HyDelta 4

WP4a – Innovations for Hydrogen Grid Balancing

D4a.1 – Grid balancing development for hydrogen distribution grids: characteristics and key gaps

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Executive summary

As hydrogen is expected to play a pivotal role in the Dutch energy transition, adequate infrastructure is needed to safely and efficiently connect hydrogen supply, storage, and demand. Alongside plans for the national hydrogen infrastructure being developed by Hynetwork, the first regional hydrogen grids are in planning and development to serve regional hydrogen offtakers (e.g. Cluster 6 industry), which will possibly be operated by Dutch distribution system operators (DSOs). Users of these regional hydrogen grids will benefit from low-threshold access to a reliable and well-functioning distribution system. A fundamental component of such a hydrogen grid is a robust balancing regime to ensure that supply and demand are safely balanced, and system integrity is maintained.

Nonetheless, a comprehensive balancing strategy for regional hydrogen grids has yet to be developed. The aim of this research is thus to **scope a suitable balancing regime for regional hydrogen grids, specify the explicit functionalities that must be present in the balancing system, explore different scenarios of role distribution amongst relevant parties, and identify key knowledge gaps.** This research is conducted in close coordination with the DSOs, that are preparing for developing and operating regional hydrogen grids and with natural gas and hydrogen experts at Gasunie, the current natural gas Transmission System Operator (TSO). It is a priority to engage with market parties (i.e., those involved in hydrogen production, offtake, and trading) in the future, to explore the topic in more depth with Gasunie, and finally with policymakers to reach a common vision of the future balancing regime for regional hydrogen grids. This report marks the conclusion of the first phase of research and provides an inventory of the existing knowledge related to balancing of regional hydrogen grids and identifies key knowledge gaps that will be investigated further in the second research phase.

This report emphasizes that regional hydrogen grids pose unique challenges to balancing due to decentral and variable hydrogen producers, smaller volumes and therefore limited linepack, absence of large-scale storage (in early grid archetypes), bidirectionality between the DSO and TSO grids (in later grid archetypes), and a need for quick response times. The unique characteristics of regional hydrogen grids suggest that they share certain similarities with both the electricity and natural gas grids. As such, the necessary balancing regime is expected to exhibit characteristics of both and will likely fall somewhere in between the two.

This report emphasizes that ***balancing*** **encompasses two fundamental realms: system and portfolio balancing**, as shown below in Figure 1. These are two distinct domains in the current natural gas and electricity systems, with a clear separation of actions and responsible parties. Nonetheless, these two are expected to be much more intertwined in early-stage hydrogen grids, particularly due to limited flexibility options and an immature hydrogen market.

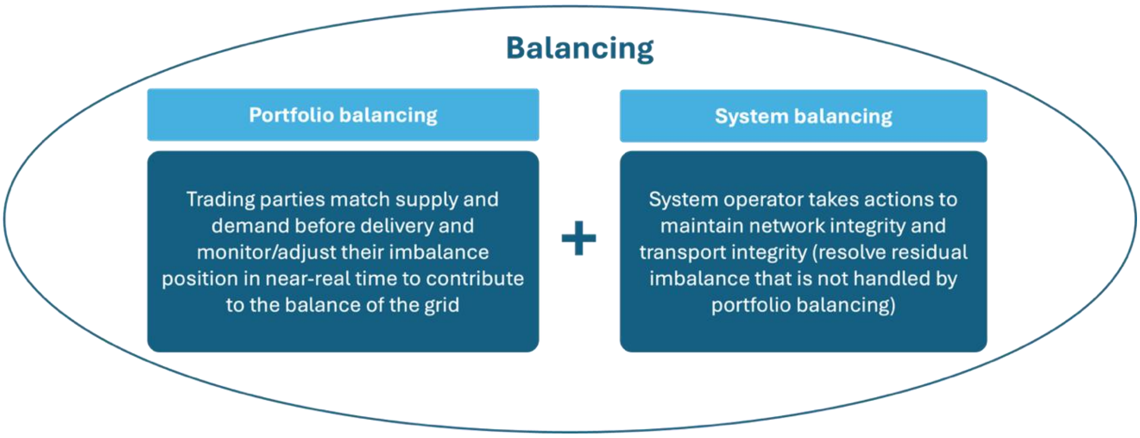


Figure 1: Distinction between portfolio and system balancing and their relationship to balancing as a whole.

A conceptual framework for balancing regional hydrogen grids is presented by first identifying key needs of the balancing regime, functionalities that must be present to meet those needs, and a series of market and technical tools that are necessary in order to carry out these functionalities (Figure 2).

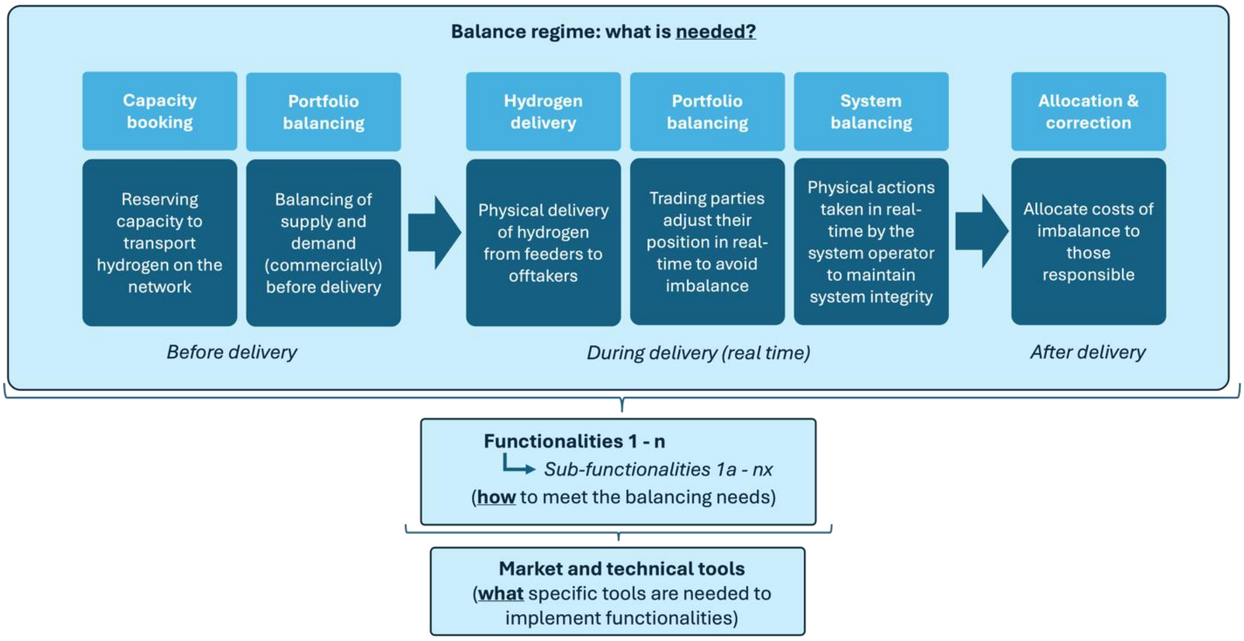


Figure 2. Conceptual framework for the needs of the balancing regime for hydrogen grids, the functionalities necessary to meet those needs, and the tools required to implement those functionalities.

It is expected that a comprehensive balancing strategy for regional hydrogen grids must contain the following components:

- A **capacity booking** process, where trading parties reserve the rights to transport hydrogen on the DSO network
- A process to facilitate the commercial matching of supply and demand via **portfolio balancing** (e.g., a trading platform to enable trade between trading parties, a penalty and incentive regime to encourage favourable balancing behaviour, etc.)
- A series of **system balancing** actions, which are needed to keep the system within its operating limits and safeguard network integrity (e.g., storage, making use of limited linepack, tapping into flexibility at feeders and offtakers through contract agreements and potentially by direct control)
- An **allocation and correction** process to assign the costs of imbalance to the trading parties who are responsible for it (and potentially compensate those who improve balance in the network)

There is a series of balancing functionalities that must be present in the system to carry out the key components of the balancing strategy defined above. These functionalities are explicitly defined and their relevance at different stages of hydrogen grid development is explored. Since regional hydrogen grids are expected to take different forms and exhibit varying levels of complexity, the balancing requirements of these distinct grid configurations are expected to be unique from one another. As such, five regional hydrogen grid archetypes are identified to examine how balancing needs and functionalities differ across the various grid types (Figure 3).

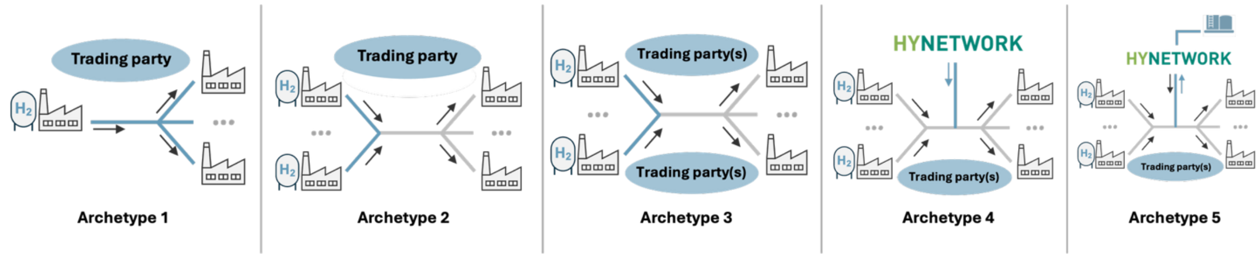


Figure 3: Future archetypes of hydrogen distribution grids (note: not all grids will move sequentially from Archetype 1 to 5).

Through this analysis, **a number of key takeaways are identified**. The results make clear that **balancing functionalities, tools, and responsibilities change depending on the grid archetype that is assumed**.

- In Archetype 1, the network is the simplest. A single feeder results in simple (top-down) flows and issues with maintaining transport integrity (i.e., ensuring hydrogen can flow through the network as intended) are not expected. However, the presence of multiple feeders in Archetypes 2 to 5 results in more complex flows and a larger role for the DSO in ensuring that the planned transports from feeders to offtakers can actually be facilitated. Furthermore, multiple feeders impact the type of control that is needed at connected parties (i.e., flow control valves or FCVs) in order to ensure that actual hydrogen flows follow the nominated volumes.
- In Archetypes 1 and 2, the presence of only one trading party means the commercial side of balancing (e.g., where trading parties trade flexibility on the market) will play a limited role. Instead, the trading party will likely rely more on physical actions to balance the grid by asking connected parties to change their behaviour. As a result, the DSO's role in balancing in Archetypes 1 and 2 is more limited, only intervening as a last resort and temporarily closing off connections to safeguard network integrity.
- In Archetypes 3 to 5, the delineation in balancing responsibilities between the DSO and the trading parties becomes more clear: the DSO handles system balancing and the trading parties handle portfolio balancing. The maturing of the hydrogen market over time will likely result in market solutions taking on a larger role, whereas in early stages, system balancing solutions, such as incentivizing (or mandating) changes in customer behaviour (feed-in/offtake), will feature prominently.
- In Archetypes 4 and 5, a connection to the Hynetwork system is realized. In this case, it must be explored how roles related to portfolio balancing are distributed between the TSO and DSO. For instance, will the DSO maintain all balancing responsibility and simply treat the connection point to Hynetwork as a new entry/exit point in the distribution grid? Or will the TSO assume primary balancing responsibility of the grid in terms of (trade of) transport capacity and nominations?

This research aims to provide an initial overview of balancing in regional hydrogen grids with the ultimate goal being the creation of a balancing vision that is suitable for the unique characteristics of the hydrogen system and agreeable to all relevant parties (i.e., system operators, market parties, regulatory bodies, etc.). Through this process, a **series of knowledge gaps are identified**, which are summarized below and explained in much greater detail in the final chapter of this report:

It is expected that response times will need to be within minutes (or less), highlighting the fact that hydrogen balancing timescales will be quicker than those in the natural gas system and therefore underscoring the importance of this research. There is a need **to quantify the timescales for balancing** and determine the necessary response times for the various sources of flexibility in the system. More work is needed to understand exactly what these sources of flexibility will be (e.g., demand-side flexibility, storage, etc.) and the order of priority for calling upon them.

The **outlook towards coupling national and regional hydrogen networks** needs considerable attention to ensure that the balancing visions of the DSOs and the TSO can be harmonized. Roles and responsibilities must be clearly assigned in way that is suitable for all parties in the periods before and after the regional and national grids are coupled.

A series of **balancing tools** have been identified in this report, but their **availability and feasibility require further research**. One of the tools that needs to be explored, for example, is the design of a market that enables the trading necessary for portfolio balancing, and related structuring of imbalance costs. Additionally, the effects of capacity limiting contracts and other new configurations needs to be researched in more detail.

Finally, the **technical operational strategy** that is needed to enable portfolio and system balancing actions requires additional attention. Practical questions relating to the minimum infrastructure requirements that are needed to carry out real-time balancing actions remain (for instance, can DSOs override setpoints on flow control valves from a regulatory and technical perspective?).

Overall, a proposed balancing regime for regional hydrogen grids is outlined, with detail given to key functionalities and their relevance in each of the five grid archetypes, respectively. In Phase 2, several of the knowledge gaps identified in this report will be further explored. In addition, the proposed balancing framework will be shared with key stakeholders (i.e. market parties and policymakers) to identify potential areas of disagreement and find a way forward to align perspectives and move towards to joint solutions.

Reading guide

Chapter 1 of this report provides a fundamental background of balancing. It begins with an overview of the proposed balancing regime for regional hydrogen grids. It draws on insights from both the electricity and natural gas grids and highlights that the hydrogen system falls somewhere in between the two. Learnings and differences with current market-driven balancing regime of the natural gas system are summarized. Key distinctions in system balancing between present-day natural gas grids and future regional hydrogen grids are identified. Relevant aspects of balancing in electricity grids are summarized. And finally, the existing regulation relevant to hydrogen balancing is explored.

Chapter 2 of this report provides a provisional assessment of what is needed for a well-functioning regional hydrogen grid balancing regime. It begins with a list of terminology before laying out the five archetypes of regional hydrogen grids and how they relate to one another. Explicit functionalities of the hydrogen balancing system are identified, and implications of role distributions for each functionality are considered. And finally, preliminary timelines are presented which show how the various balancing functionalities relate to one another (timewise).

Chapter 3 of this report identifies the specific tools that are needed to carry out the functionalities described in Chapter 2. This is done from both the market and technical perspectives.

Chapter 4 of this report provides a first look at the connected parties (feeders and offtakers) that can be expected in regional hydrogen grids to give a (preliminary) idea of how such parties can (or cannot) contribute to balancing by offering flexibility in their supply and demand.

Chapter 5 of this report summarizes the main conclusions and calls attention to the key knowledge gaps that demand further exploration in the second phase of this research.

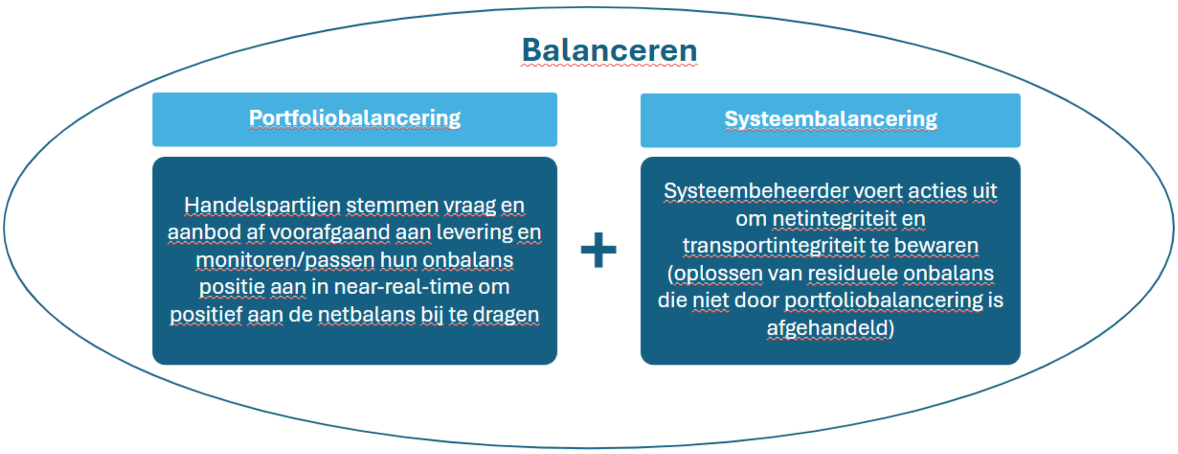
Samenvatting

Aangezien waterstof naar verwachting een sleutelrol zal spelen in de Nederlandse energietransitie, is een geschikte infrastructuur nodig om productie, opslag en vraag veilig en efficiënt met elkaar te verbinden. Naast de plannen voor een nationale waterstofinfrastructuur van Hynetwork, worden de eerste regionale waterstofnetten ontwikkeld om regionale afnemers (zoals industrie in Cluster 6) te bedienen. Deze netten zullen mogelijk worden beheerd door Nederlandse regionale netbeheerders (DSO's). Gebruikers van deze netten profiteren van laagdrempelige toegang tot een betrouwbaar distributiesysteem. Een essentieel onderdeel van zo'n waterstofnet is een robuust balanceringsregime dat zorgt voor veilige afstemming van vraag en aanbod en behoud van systeemintegriteit.

Toch ontbreekt een uitgewerkte balanceringsstrategie voor regionale waterstofnetten. Dit onderzoek heeft als doel om **een geschikt regime te verkennen, benodigde functies te specificeren, scenario's voor rolverdeling te analyseren en kennisgaten te identificeren**. Het onderzoek is uitgevoerd in nauwe samenwerking met DSO's en zowel aardgas- als waterstofexperts van Gasunie (de huidige TSO voor aardgas). Het is een prioriteit om als volgende stap dieper in het onderwerp te duiken met relevante marktpartijen, Gasunie en beleidsmakers.

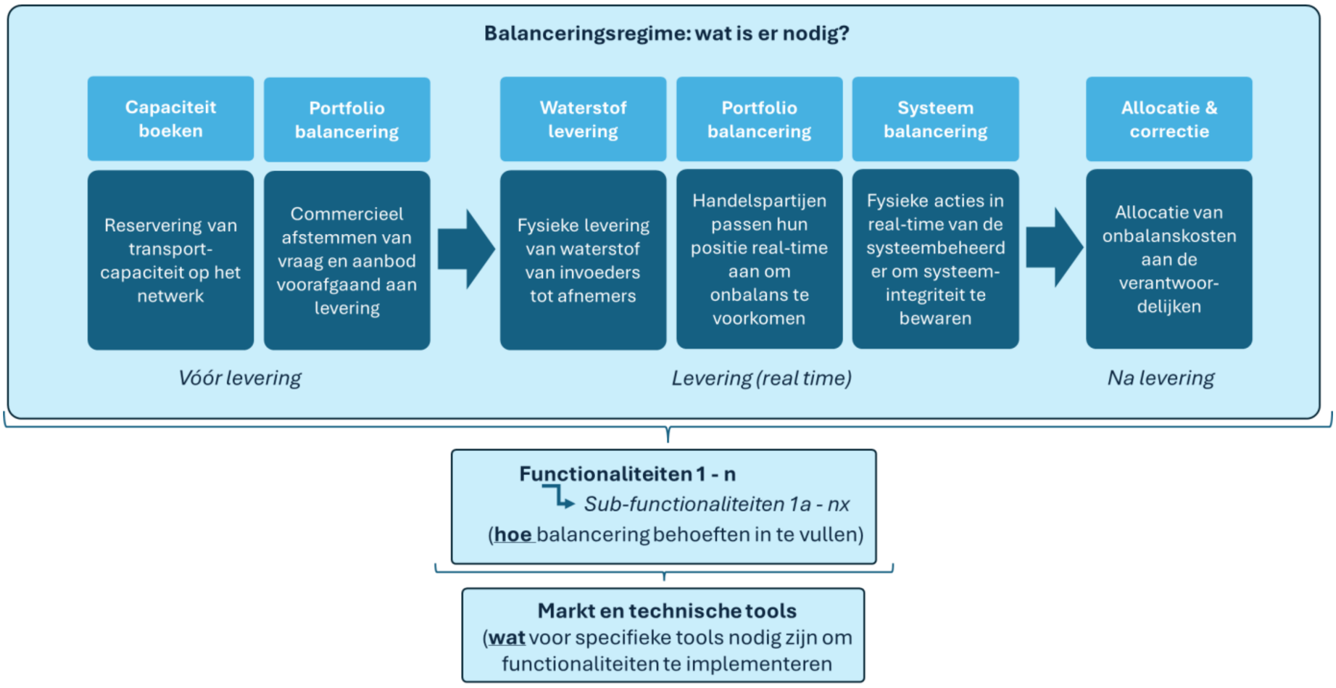
Dit rapport sluit de eerste onderzoeksfase af en bevat een inventaris van bestaande kennis over balancering van regionale waterstofnetten. Het identificeert de belangrijkste uitdagingen zoals decentrale en variabele productie, beperkte opslagcapaciteit, bi-directionele koppeling tussen DSO- en TSO-netten, en de noodzaak van snelle responstijden. Regionale waterstofnetten vertonen kenmerken van zowel elektriciteits- als aardgasnetten. Het balanceringsregime zal dus elementen van beide bevatten.

Balancering omvat **twee fundamentele domeinen: systeem- en portfoliobalancering**. Dit zijn twee aparte domeinen in het huidige aardgas- en elektriciteitssysteem, met een duidelijke scheiding van bijbehorende acties en verantwoordelijkheden. In vroege stadia van het waterstofnet zullen deze domeinen sterk verweven zijn door beperkte flexibiliteit en een onvolwassen markt.



Figuur 4: Onderscheiding tussen portfoliobalancering en systeembalancering en hun relatie tot balanceren.

Een conceptueel kader wordt gepresenteerd waarin de behoeften, functies en benodigde markt- en technische instrumenten worden beschreven.

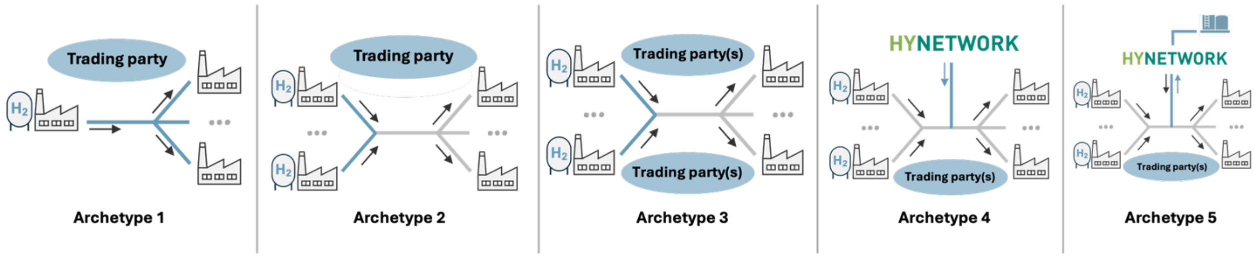


Figuur 5. Conceptueel framework voor de behoeften van een balanceringsregime voor waterstofnetten, de functionaliteiten om aan die behoeften te voldoen en de benodigde instrumenten om die functionaliteiten te implementeren.

De verwachting is geschetst dat een volledige balanceringsstrategie voor regionale waterstofnetten moet bestaan uit:

- Een proces voor het **boeken van transportcapaciteit** door handelspartijen, om recht te verkrijgen tot het transporteren van waterstof op het DSO netwerk.
- Ondersteuning van **commerciële afstemming van vraag en aanbod via portfoliobalancering** (bijv. handelsplatform, prikkels voor positieve bijdragen aan balanceren)
- **Systeemacties** om operationele grenzen te bewaken (bijv. opslag, linepack, flexibiliteit via contracten)
- Toewijzing en correctie van onbalanskosten via **allocatie en correctieprocessen**.

Een aantal functionaliteiten moet aanwezig zijn in het systeem om de belangrijkste componenten van een balanceringsstrategie uit te voeren. Deze functionaliteiten worden expliciet gedefinieerd en hun relevantie in verschillende stadia van de ontwikkeling van het waterstofnetwerk wordt onderzocht. Aangezien regionale waterstofnetwerken naar verwachting verschillende vormen aan zullen nemen en verschillende niveaus van complexiteit zullen vertonen, wordt verwacht dat de balanceringsvereisten van deze verschillende netwerkconfiguraties uniek zijn. Daartoe worden vijf archetypes van regionale waterstofnetten worden geïdentificeerd om verschillen in balanceringsbehoeften te analyseren (Figuur 6).



Figuur 6: Toekomstige archetypen van waterstof distributienetten (let op: niet alle netwerken zullen groeien van archetype 1 naar 5).

Deze analyse levert een **aantal belangrijke conclusies** op. De resultaten laten zien dat **functionaliteiten van balanceren, instrumenten en verantwoordelijkheden variëren afhankelijk van het aangenomen netwerk archetype**.

- In archetype 1 is het netwerk het meest eenvoudig. Een enkele invoeder resulteert in eenvoudige (top-down) stromen en er worden geen problemen met het handhaven van transportintegriteit verwacht (d.w.z. ervoor zorgen dat waterstof zoals bedoeld door het netwerk kan stromen).
- De aanwezigheid van meerdere invoeders in archetypen 2 tot en met 5 resulteert echter in complexere stromen en een grotere rol voor de DSO om ervoor te zorgen dat de geplande transporten van invoeders naar afnemers daadwerkelijk kunnen worden gefaciliteerd. Bovendien bepaalt de aanwezigheid van meerdere invoeders het type sturing dat nodig is bij aangesloten partijen (d.w.z. stroomregelkleppen of FCV's) om ervoor te zorgen dat de werkelijke waterstofstromen overeenkomen met de genomineerde volumes.
- In archetypen 3 tot en met 5 wordt de afbakening tussen de balancerings-verantwoordelijkheden tussen de DSO en de handelspartijen duidelijker: de DSO verzorgt voornamelijk de systeembalancering en de handelspartijen de portfoliobalancering. Naarmate de waterstofmarkt zich verder ontwikkelt zullen marktoplossingen waarschijnlijk een grotere rol gaan spelen, terwijl in de beginfase systeembalanceringsoplossingen, zoals het stimuleren (of verplicht stellen) van veranderingen in klantgedrag (invoed en afname), een prominentere rol zullen spelen.
- In archetypen 4 en 5 wordt een aansluiting op het Hynetwork-systeem gerealiseerd. In dit geval moet worden onderzocht hoe de balanceringsrollen met betrekking tot portfoliobalancering worden verdeeld tussen de TSO en de DSO. Zal de DSO bijvoorbeeld alle balanceringsverantwoordelijkheid behouden en het aansluitpunt op de nationale infrastructuur simpelweg behandelen als een nieuw entry-/exit-punt in het distributienet? Of zal de TSO de primaire portfolio balanceringsverantwoordelijkheid van het net overnemen, vergelijkbaar met het huidige aardgasnet wat betreft (handel in) transportcapaciteit en nominaties?

Dit onderzoekt geeft een eerste overzicht van balanceren in regionale waterstofnetten, met als uiteindelijke doel het creëren van een visie op balanceren die geschikt is voor de unieke kenmerken van het waterstofsysteem en die gedragen wordt door alle relevante partijen (d.w.z. systeembeheerders, marktpartijen, beleidsmakers, etc.). Door dit proces worden een aantal kennisgaten geïdentificeerd, die hieronder worden samengevat en in het laatste hoofdstuk van dit rapport in meer detail worden toegelicht:

Naar verwachting zullen responstijden binnen enkele minuten (of korter) liggen. Dit bevestigt het feit dat de tijdschalen voor waterstofbalancering korter zullen zijn dan die in het aardgassysteem en onderstreept daarmee het belang van dit onderzoek. Er is behoefte aan het **kwantificeren van de tijdschalen voor balancering** en het bepalen van de benodigde responstijden voor de verschillende flexibiliteitsbronnen in het systeem. Er is meer onderzoek nodig om precies te begrijpen welke flexibiliteitsbronnen dit zijn (bijv. flexibiliteit aan de vraagzijde, opslag, enz.) en welke prioriteit ze krijgen.

De vooruitzichten voor de **koppeling van nationale en regionale waterstofnetwerken** vereisen aandacht om ervoor te zorgen dat de balanceringsvisies van de DSO's en de TSO's op elkaar kunnen worden afgestemd. Rollen en verantwoordelijkheden moeten duidelijk worden toegewezen op een manier die geschikt is voor alle partijen in de periodes vóór en ná de koppeling van de regionale en nationale netwerken.

In dit rapport worden een aantal balanceringsinstrumenten geïdentificeerd, maar de **beschikbaarheid en haalbaarheid** ervan vereisen nader onderzoek. Eén van de instrumenten die nader moet worden onderzocht, is bijvoorbeeld het ontwerp van een markt die de handel mogelijk maakt die nodig is voor portfoliobalancering, en de bijbehorende structurering van onbalanskosten. Daarnaast moeten de effecten van capaciteitsbeperkende contracten en andere nieuwe configuraties nader worden onderzocht. Zo zijn het ontwerp van een markt die de handel mogelijk maakt die nodig is voor portfoliobalancering, de structurering van onbalanskosten (en mogelijke compensatie) en de implicaties van verschillende configuraties van transport- en aansluitcontracten slechts enkele van de instrumenten die nader moeten worden onderzocht.

Ten slotte vereist de **technische operationele strategie** die nodig is om portfolio- en systeembalanceringsacties mogelijk te maken, extra aandacht. Er blijven praktische vragen bestaan met betrekking tot de minimale infrastructuurvereisten die nodig zijn om real-time balanceringsacties uit te voeren (kunnen DSO's bijvoorbeeld setpoints op flow control kleppen overschrijven vanuit regelgeving en technisch perspectief?).

Samenvattend wordt een voorgesteld balanceringsregime voor regionale waterstofnetwerken geschetst, met details over de belangrijkste functionaliteiten en hun relevantie voor elk van de vijf netwerkarchetypen. In Fase 2 zullen verschillende van de in dit rapport geïdentificeerde kennislacunes verder worden onderzocht. Daarnaast zal het voorgestelde balanceringskader worden gedeeld met belangrijke belanghebbenden (d.w.z. Hynetwork, marktpartijen en beleidsmakers) om mogelijke meningsverschillen te identificeren en een manier te vinden om perspectieven op één lijn te brengen en te werken aan gezamenlijke oplossingen.

Leeswijzer

Hoofdstuk 1 van dit rapport biedt een fundamentele achtergrond van balancering. Het begint met een overzicht van het voorgestelde balanceringsregime voor regionale waterstofnetten. Het maakt gebruik van inzichten uit zowel de elektriciteits- als aardgasnetten en benadrukt dat het waterstofsysteem zich ergens tussen beide bevindt. Nieuwe inzichten en verschillen met het huidige marktgestuurde balanceringsregime van het aardgassysteem worden samengevat. Belangrijke verschillen in systeembalancering tussen huidige aardgasnetten en toekomstige regionale waterstofnetten worden geïdentificeerd. Relevante aspecten van balancering in elektriciteitsnetten worden samengevat. Tot slot wordt de bestaande regelgeving met betrekking tot waterstofbalancering onderzocht.

Hoofdstuk 2 biedt een voorlopige beoordeling van wat nodig is voor een goed functionerend regionaal balanceringsregime voor waterstofnetten. Het begint met een terminologielijst, waarna de vijf archetypen van regionale waterstofnetten en hun onderlinge relatie worden uiteengezet. Expliciete functionaliteiten van het waterstofbalanceringssysteem worden geïdentificeerd en de implicaties van rolverdelingen voor elke functionaliteit worden besproken. Tot slot worden voorlopige tijdlijnen gepresenteerd die laten zien hoe de verschillende balanceringsfunctionaliteiten zich tot elkaar verhouden (in de tijd).

Hoofdstuk 3 identificeert vervolgens de specifieke instrumenten die nodig zijn om de in hoofdstuk 2 beschreven functionaliteiten uit te voeren. Dit gebeurt vanuit zowel markt- als technisch perspectief.

Hoofdstuk 4 biedt een eerste blik op de aangesloten partijen (feeders en afnemers) die te verwachten zijn in regionale waterstofnetwerken. Dit geeft een (voorlopig) beeld van hoe deze partijen wel of niet kunnen bijdragen aan de balancering door flexibiliteit te bieden in hun vraag en aanbod.

Hoofdstuk 5 vat tot slot de belangrijkste conclusies samen en vestigt de aandacht op de belangrijkste kennisgaten die in de tweede fase van dit onderzoek verder onderzoek behoeven.

Contents

Abbreviations

BRP	Balance responsible party
CHP	Combined heat and power
DHNO	Distribution Hydrogen Network Operator
DSO	Distribution System Operator *(regionale netbeheerder*[1]*)*
GTS	Gasunie Transport Services B.V.
HN / HNS	Hynetwork Services B.V.
HTL	Hogedruk transportleiding
MRP	Measurement Responsible Party
OTC	Over the counter
POS	Portfolio imbalance signal (*portfolio onbalans signaal)*
RTL	Regionale transportleiding
SBS	System balance signal (*systeem balans signaal*)
TSO	Transmission System Operator *(landelijk netbeheerder*[2]*)*
TTF	Title Transfer Facility
WDBA	Within-day balancing action
WTP	Willingness-to-pay

[1] Under the new Energy law, the term 'regionale netbeheerder' is replaced by 'distributiesysteembeheerder'
[2] Similarly, the 'landelijk netbeheerder' will become 'transmissiesysteembeheerder'

Introduction

The use of hydrogen as renewable fuel and feedstock is expected to play a large role in both the European and Dutch energy transition [1]. Though costs of hydrogen production have risen in recent years, according to the Nationaal Plan Energiesysteem hydrogen is aimed to be used for decarbonisation of industry and (heavy) mobility until 2035, moving to limited deployment in the built environment and agriculture sector after that time [2]. Hydrogen use will develop from being mostly contained to the industry clusters, towards a broader distribution across sectors and geographical locations in the Netherlands.

In the effort to stimulate decarbonisation through use of hydrogen, the deployment of national infrastructure is important to make sure supply meets demand. Infrastructure including the HNS Transport System receives priority in construction and licensing and is included in the Meerjarenprogramma Infrastructuur Energie en Klimaat (MIEK) [3]. The national hydrogen network will be realised in 2032 or later through the Delta Rhine Corridor [4], whereas the first regional hydrogen grids are already in development with the aim to be fully operational by 2026 [5][6].

These upcoming regional networks are developed and operated by distribution system operators (hereafter referred to as *DSOs* or *distribution system operators*) and are non-discriminatory, with open access for multiple users. The EU Decarbonized Gas Package [7] requires system operators to provide third-party access from 2033 and to adhere to general balancing rules, ensuring non-discriminatory and efficient system operators [8]. Connected parties benefit from low-threshold access to a reliable and well-functioning hydrogen system. Keeping the hydrogen network balanced is necessary for providing customers uninterrupted access to such a system. However, a comprehensive balancing scheme is still missing, and there are significant knowledge gaps.

The Dutch electricity and natural gas systems have mature infrastructure operation schemes, being balanced by their respective transmission and distribution system operators (TSOs and DSOs). The hydrogen system is expected to behave somewhat similarly to both electricity (in its variability of supply and fast reaction times) and natural gas (in its physical properties). Thus, it stands to reason that lessons and frameworks from those systems can be applied to the subject of balancing hydrogen grids.

This work package within the HyDelta programme focuses on investigating balancing requirements for regional grids and the alignment with balancing on the national grid. The main goal is to get an overview of the joint balancing regime of the envisioned overall hydrogen system in the Netherlands. As existing knowledge is spread out over individual experts within system operators' organizations, and as knowledge gaps are still unclear and the context of the research is constantly changing, the approach is split into two phases. The first phase includes an inventory of knowledge and a high-level analysis, and the second phase focuses on in-depth analyses of the discovered knowledge gaps and constructed research questions of phase 1 (in part via consultation with market parties).

This report is the conclusion of the first phase and includes an inventory of current knowledge, the functionalities which are needed for balancing the hydrogen system and the necessary tools for their implementation. Further, network archetypes of different size and complexity are defined, first quantitative insights into timescales and potential volumes of hydrogen are presented, and properties of expected connected network parties are summarized. At the end, first conclusions are drawn, and research questions are defined for the next phase of the programme.

As the hydrogen market gradually develops, a strategic vision of future balancing systems is needed to support efficient decision-making in current hydrogen infrastructure projects and regulatory development. This initial phase of HyDelta research aims to outline such a vision by consolidating existing insights into the balancing needs of various regional hydrogen grid configurations, including both standalone and TSO-connected distribution networks. Based primarily on input from the authors and system operators, the vision presented throughout this report is still preliminary and not yet exhaustive. Instead, it is intended to serve as a foundation for dialogue with market parties, stakeholders and governments to explore and build a shared understanding of effective hydrogen balancing systems.

1. Background

Before describing the necessary balancing regime in future regional hydrogen grids, we first look to the existing balancing systems of the natural gas and electricity systems to establish a foundation and then identify the differences and challenges facing regional hydrogen grids. In this report, the term *balancing* encompasses two fundamental realms of the balancing system: system and portfolio balancing, which are explained below in Figure 7.

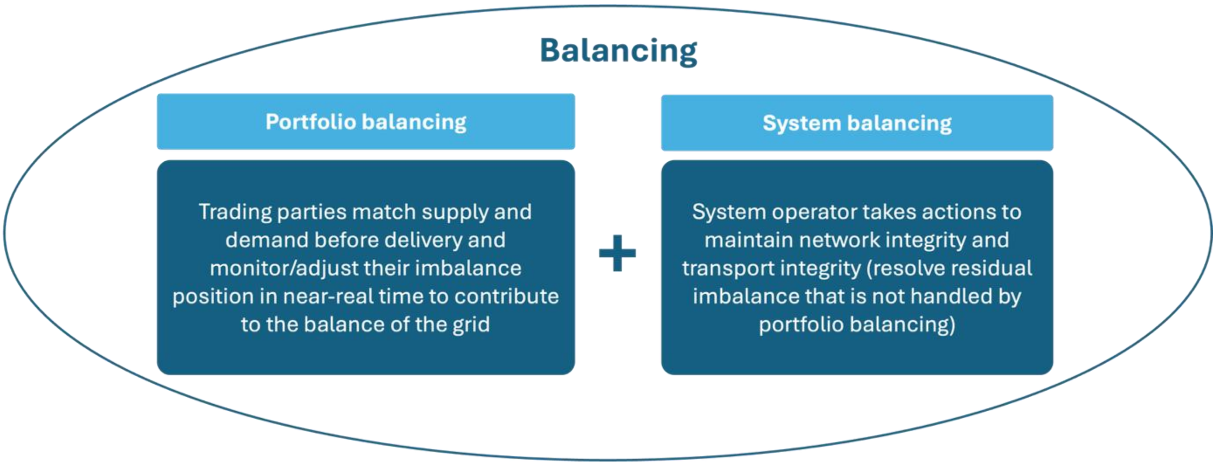


Figure 7: Distinction between portfolio and system balancing and their relationship to balancing as a whole.

This section is divided into five parts:

1. A simplified overview of the key needs for a hydrogen balancing regime is presented. It is inspired by the present-day natural gas and electricity balancing regimes, as that of hydrogen is expected to resemble characteristics of both systems.
2. Key learnings and differences with current market-driven balancing regime of the natural gas are summarized.
3. Key distinctions in system balancing between present-day natural gas grids and future regional hydrogen grids are identified.
4. Relevant aspects of balancing in electricity grids are summarized.
5. The existing regulation relevant to hydrogen balancing is explored.

This chapter lays the groundwork for examining the necessary functionalities of a hydrogen balancing system in Chapter 2.

1.1 Overview of the envisioned hydrogen balancing regime

A simplified overview of the balancing process that will be necessary for balancing hydrogen grids is depicted in Figure 88. This process is inspired, in part, by the current market-driven balancing regime of the Dutch natural gas) and electricity grid (see [9] and Appendix CC for further explanation). However, the regional hydrogen grid balancing regime will have many distinguishing characteristics and system needs, which will be elaborated further in the second chapter. Additionally, Hynetwork was contacted to discuss their strategic plans for hydrogen grid balancing. Though not much could be shared on their vision for balancing at this time, input was taken into account during the analytical phase of this study.

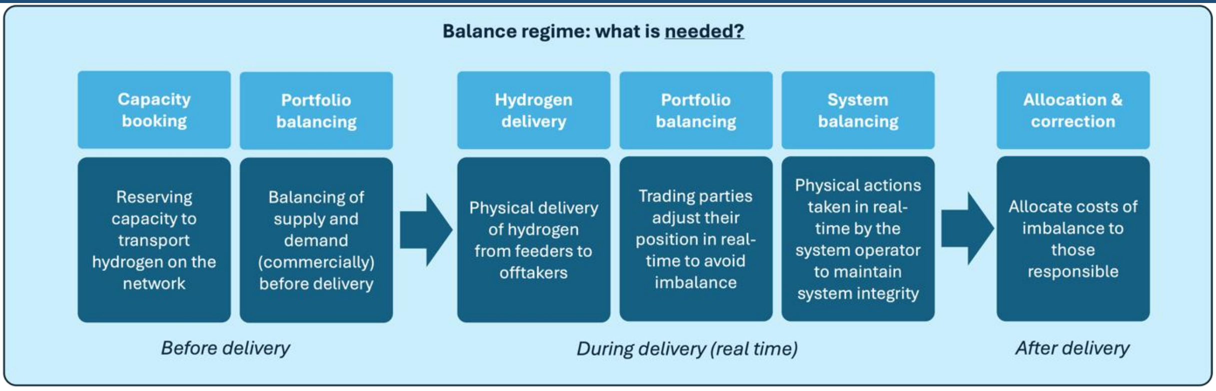


Figure 8: Simplified overview of balancing needs.

Before delivery of hydrogen, trading parties who trade in hydrogen commodity must reserve transport capacity with the system operator via a **capacity booking** process, in which the system operator ensures that the total transport capacity of the network is not exceeded.[3] After this point, trading parties can begin matching supply and demand within their portfolio of feeders and offtakers, as well as trading amongst themselves (**portfolio balancing**).

In real time, hydrogen is delivered from feeders to offtakers via the network (**hydrogen delivery**). **Portfolio balancing** continues in real-time, as trading parties are able to monitor their current imbalance position and that of the network in aggregate and adjust their position as needed to avoid imbalance.[4] Simultaneously, the system operator monitors the physical state of the network (mainly system pressure) and intervenes if necessary with actions to maintain network and transport integrity (**system balancing**) and resolves any residual imbalance that is not handled by portfolio balancing. In more advanced grid archetypes, the roles of the trading party and the system operator become clearly/more distinct: the former is responsible for portfolio balancing, while the latter handles system balancing. In contrast, early grid archetypes—particularly when only one trading party is involved—often show a blurred line between these roles. In such cases, system and portfolio balancing actions are closely intertwined, and a single party may hold responsibilities on both sides.

Allocation is the process by which the costs of balancing actions for the imbalance caused in the hydrogen grid are assigned to the responsible trading party. If applicable, compensation could be allocated to trading parties that carry out corrective actions in favour of reducing imbalance. This process occurs after delivery.[5] The data used for allocation can also be used to settle the transactions between trading parties and connected parties for the transported hydrogen volumes (though this does not directly relate to balancing). If the validated hydrogen flows shown by the measurement responsible party (MRP) are different than what was determined via the allocation process (e.g., due to measurement errors or missing data), then financial **corrections** are made (the process that is currently known as reconciliation).

As mentioned, the simplified hydrogen balancing overview depicted in Figure 88 draws inspiration from the existing balancing systems of the electricity and natural gas grids. As such, the balancing system for regional hydrogen grids will likely resemble aspects of both these two systems. Balancing

[3] The exact details of this process still need to be worked out from both a technical and market perspective.
[4] This is made possible by near-real time data sharing between the system operator and the trading parties. A process similar to the portfolio imbalance signal (POS) and system balance signal (SBS) used by GTS will likely need to be developed for balancing regional hydrogen grids. See Appendix C for more information.
[5] It is important to note that the allocation process defined here differs slightly from that of the natural gas system (which occurs in near-real time). More information on the GTS process can be found in Appendix C.

regional hydrogen grids will present a series of unique challenges, namely decentralized production, faster time scales, and few sources of flexibility. Further, an immature hydrogen market will likely make system balancing actions more prevalent in early stages, rather than being able to leave balancing mostly up to the market (portfolio balancing). Overall, the characteristics of the hydrogen balancing system require further investigation. In some respects, it might fall between the electricity and natural gas systems, while in others it might be entirely unique. Relevant details of both the natural gas and electricity balancing systems are explained further in the following sections.

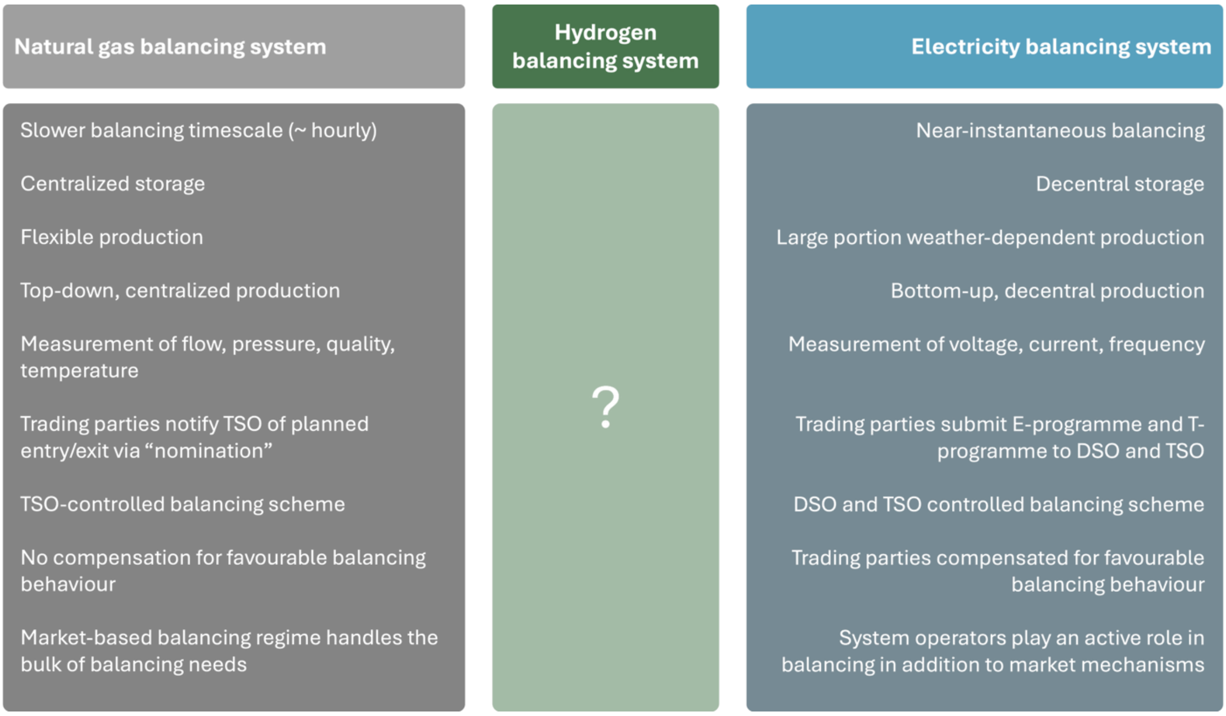


Figure 9: Distinct characteristics of the natural gas (left) and electricity balancing systems (right). The characteristics of the hydrogen balancing system require further investigation. The hydrogen balancing system will likely share certain characteristics with each of these two systems and also be unique in its own way. Note: GTS refers to trading parties as shippers, but here we use the term trading party to remain consistent with the proposed hydrogen balancing regime terminology. In the electricity grid, the term BRP is used in place of trading party.

1.2 Market-driven balancing regime in the current natural gas system

The discovery of natural gas reserves in Groningen in 1959 quickly led to Dutch dominance in gas supply, holding more than 50% of the market share in the early 70s [10]. Due to the scale and geophysical characteristics of the gas field in Groningen it was a key source of long- and short-term flexibility, which in turn contributed significantly to security of supply. Therefore, in this centralized (top-down) system, balancing was largely handled by simply adjusting the supply from the Groningen field (with additional flexibility in the form of linepack and the growing use of gas storage facilities such as the Gasunie-owned salt cavern storage at Zuidwending [10]. For hydrogen, this will be completely different, as more decentral production, bidirectional flows, and limited access to storage in the early stages necessitates a larger role for the DSOs.

Currently, balancing of the natural gas system is fully managed by the TSO, with the DSO responsible only for the investing in, maintaining, and safeguarding their respective distribution grids, as well as holding measurement responsibility, which is necessary for facilitating the balancing task of the TSO. In the future, the role of the DSO will be much greater, as they will be expected to hold primary balancing responsibility in regional hydrogen grids.

The unbundling requirements in the European gas directives in 2000 led to a considerable shift in the natural gas industry structure in the Netherlands post-2004 when many of these changes were instituted (see Table 44 in Appendix C). It resulted in the growing participation of market parties interested in trading gas (i.e., by *shippers*), which eventually developed into a robust commercial balancing scheme coordinated by GTS that now accounts for the vast majority of balancing in the system.[6]

This is expected to be a **key difference with balancing in regional hydrogen grids,** where market-driven balancing will likely play a diminished role in early stages due to a nascent hydrogen market and limited sources of flexibility. **Instead, system balancing actions will likely play a much greater role than they do in the current natural gas balancing regime (which is principally handled by the market via portfolio balancing).**

In early stages, the future hydrogen system could resemble the pre-2004 natural gas system, with only one (or few) dominant suppliers, pricing arranged via long-term contracts, and overall little market liquidity. With the future development of the HNS Transport System and the maturing of the hydrogen market, hydrogen commodity trading might become more attractive, and the hydrogen market might come to resemble the current natural gas and electricity wholesale market with various trading parties, competition, and considerable liquidity.

While the natural gas system provides useful insight, future hydrogen grids are expected to present a series of unique challenges, including decentralized and more variable production (e.g., from electrolysers following a wind profile), no connection to underground storage facilities (in beginning phases) and bidirectional flows. This makes replicating the gas balancing system to regional hydrogen grids undesirable. Nonetheless, five key insights from the current natural gas balancing regime and their relevance to future hydrogen grids are highlighted in Figure 10.

Figure 10: Key insights from the current gas balancing regime and their applicability to future regional hydrogen grids.

Insight from natural gas system related to balancing	Applicability for regional hydrogen grids
Portfolio (market) balancing constitutes the majority of balancing in the natural gas grid. This requires a mature market with sufficient market liquidity and price volatility for price arbitrage.	System balancing will likely play a larger role than portfolio (market) balancing until hydrogen market matures.
GTS established a new market based-balancing regime in 2011, where trading parties had to pay a fine for imbalance (regardless of market value), whereas now the imbalance price is based on the bid and supply curves [10], which increased market attractiveness.	Participation in regional hydrogen grids might be less attractive for trading parties in immature markets with a fixed imbalance price rather than mature ones where the imbalance price follows market-driven bid and supply curves. Estimating imbalance price is difficult in the absence of a market-driven price setting.
GTS's market-driven balancing regime from 2011 included a provision to compensate trading parties for having a favourable position (in the eyes of the system operator) during periods of imbalance. These "helpers" were rewarded for their contribution of "assistance gas,"	Although this provision was removed for natural gas in 2014 with the implementation of the European network code, it could be an interesting model to look to in early-stage

[6] GTS uses the term "shipper" to refer to entities that transport gas on their system and "trader" to refer to those who only have license to trade gas. In the hydrogen balancing system, we adopt the term *trading party* to refer to entities that contract transport capacity to transport or trade hydrogen on the regional network.

which is the portion of their position that is on the opposite side of the network imbalance [11]. This is then sold to the "causers" of imbalance at the market price [12].

hydrogen grids to incentivize participants to positively contribute to balancing.

Trading parties (i.e., shippers) that transport gas to domestic physical exit points can transfer imbalance risk to another trading party (*balance supplying shipper*) who is willing to take on that risk in exchange for some form of compensation. In this case, a dedicated *balance receiving shipper* and *balance supplying shipper* agree that a certain amount of gas (either percentage, maximum volume, etc.) can be transferred over a virtual trading point specifically for sharing balance (see [13] for further explanation).

This could be an interesting model to keep in mind for balancing regional hydrogen grids, particularly in cases where certain market parties are hesitant to take on risks of imbalance.

Operational Balancing Agreements (OBAs) are used between neighbouring TSOs to perform behind-the-scenes physical balancing that does not impact portfolio (market-driven) balancing, by tapping into the flexibility in the neighbouring networks and shifting times in delivery as needed [14].

When regional hydrogen grids eventually connect to the HNS Transport System and if a bidirectional connection is deemed feasible and necessary, the current model between TSOs of neighbouring networks and the agreements they share could be inspiration for arranging balancing responsibilities between the TSO (Hynetwork) and the DSO, with the latter maintaining balancing responsibility of the regional grid.

1.3 System balancing in natural gas vs. hydrogen distribution grids

Network configurations: natural gas vs. hydrogen

The current natural gas grids in the Netherlands are built and divided based on pressure levels. The high-pressure networks, between 40-80 bar(g) (HTL) and 16-40 bar(g) (RTL), are managed by GTS as the TSO, while the low-pressure networks, below 8 bar(g), are managed by the DSOs. Gas mainly flows unidirectionally from the TSO network to the DSO networks, with a pressure regulator located at the city gate to feed gas from high pressure network to low pressure network. Some DSO networks may also have a local biomethane injection point (known as *groengas invoeding* in Dutch) in their grid and/or a booster compressor (reverse flow station) to feed gas into a higher-pressure network (Figure 1111). This results in the network becoming bidirectional.

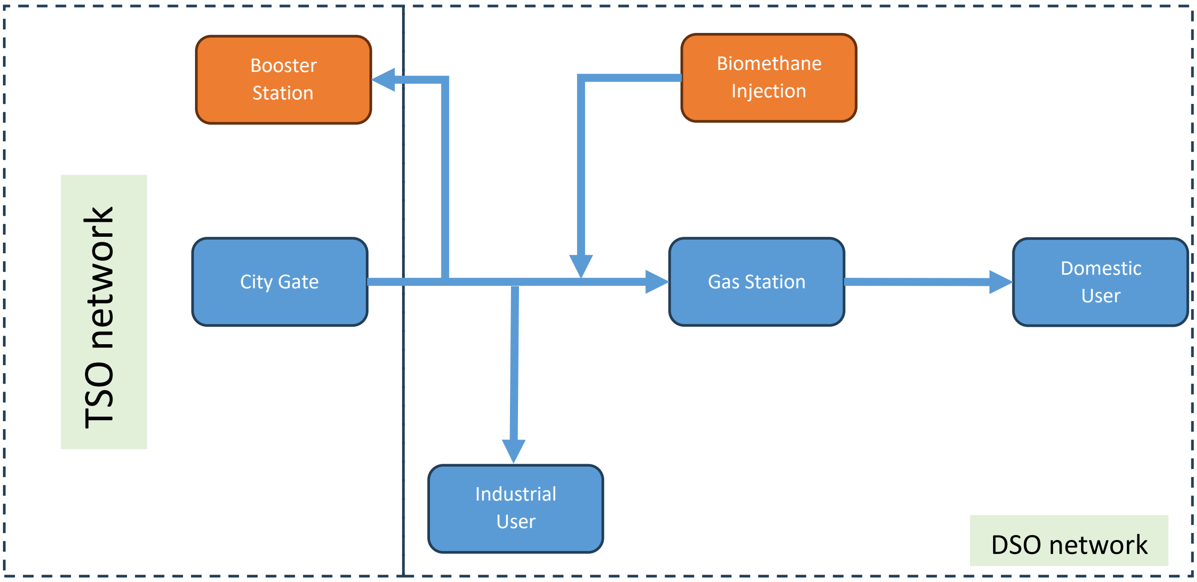


Figure 11. Schematic of the current natural gas distribution network connected to the TSO network. Orange box is an optional asset.

The future hydrogen DSO grid can be directly connected to the TSO network or initially be built as a standalone network: a network without connection to the TSO network. Maintaining balance between entry and exit points will therefore be crucial to keep pressure between maximum and minimum limits for ensuring network integrity. Flexibility in supply and demand or system flexibility (e.g., linepack or storage) will be essential for ensuring safe operation and preserving pipeline integrity.

For the hydrogen DSO network connected to the TSO network, the configuration may include a bidirectional station (combining a city gate and a booster compressor) when hydrogen needs to be delivered to a higher pressure grid or it may only require a city gate if the total local hydrogen injection is always lower than the total demand (Figure 12). The network then looks similar to the current natural gas system with possibility of an additional storage in the DSO network as a balancing tool. However, the valve control mechanism could be different between standalone and TSO connected network configuration.

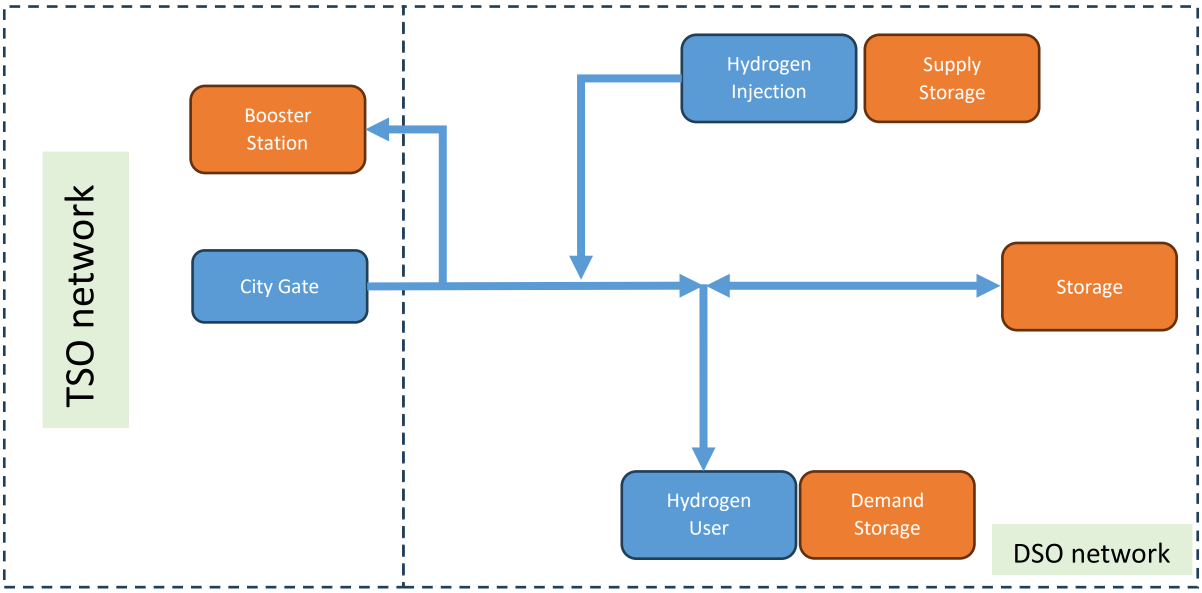


Figure 12. Schematic of a future hydrogen distribution network. There are two possible configurations: a standalone hydrogen distribution network and TSO-connected hydrogen distribution network. Orange box is an optional asset.

Valve mechanism: pressure vs. flow control

In the sub-section below, we will discuss the different control mechanism of the valve at an entry- or exit-point of the network.

Pressure control

The natural gas DSO network is mostly regulated by pressure at city gates using a pressure regulator valve (PRV), as there is an abundant supply of gas from the TSO network. The flow from a city gate is driven by consumer demand ensuring that the total supply flow from the city gate is always balanced with the total demand flow. When there are multiple city gates (for example in the big network), the flow distribution between these stations is determined by pressure setpoints and network configurations.

An additional local biomethane injection is currently contracted based on capacity and are equipped with PRV. As long as the network pressure remains below the setpoint, the injected biomethane injection is absorbed by the pipeline. However, during periods of low demand (summer), the network pressure may reach the pressure setpoint limit, resulting in the shutdown of local biomethane injection. When multiple local biomethane injection points are present, managing and prioritizing these injections via PRV setpoints becomes increasingly complex from an operational standpoint, particularly when precise flow profiles are required for each injection point.

Flow control

For the future hydrogen DSO network without connection to the TSO network, there is no city gate to balance the grid using a pressure setpoint. Therefore, the DSO will need to carefully monitor pipeline pressure, as any imbalance between supply and demand will directly cause the pipeline pressure to increase or decrease. At the connected party (entry or exit), a flow control valve (FCV) is needed to regulate the flow based on a flow setpoint. Unlike PRVs that don't require external control signals, FCVs receive signals from external devices like programmable logic controllers (PLCs) to adjust a valve's position.

FCVs offer the advantage of directly regulating the flow entering and exiting the pipelines. However, a pressure monitoring system is still required to ensure network integrity. When pipeline pressure rises, the issue can be mitigated by reducing the supply flow at the entry point or increasing the demand flow at the exit point, and vice versa when the pressure drops.

Conclusion

In a future standalone hydrogen grid, where local hydrogen injection is intermittent, a flow control system would be beneficial for balancing supply and demand. By directly setting the flow according to the nominated setpoint, it ensures that flow at entry and exit remain aligned. A flow control system consists of a flow meter, PLC and FCV installed at the connected party. The real-time flow metering is needed at each entry/exit point of the pipeline and the data should be accessed also by connected party and the system operator. The connected party is responsible to regulate the flow based on the nomination of the trading party. The system operator continuously monitors the pipeline pressures for network integrity and operating safety control valves that shut off the connection in emergency situations.

For future TSO connected hydrogen grids, there are 2 possibilities:

1. Using flow control mechanisms and treat TSO as an additional entry point that must balance their supply.
2. Using similar architecture like natural gas by using PRV without any balancing mechanism at DSO level if there is an abundant supply of hydrogen for all users.

1.4 Balancing in the electricity system

As the physical properties of electricity are very different to those of natural gas and hydrogen, the balancing system characteristics are not as directly applicable to hydrogen. In the Dutch electricity system, Balancing Responsible Parties (BRPs) are accredited by transmission system operator TenneT and are required to inform them on a daily basis of the exchanges with other BRPs planned for the following day. This is called the 'E-programma'. This information is used to perform a day-ahead check to ensure the portfolio is balanced.

The T-programma is a prognosis of the exchanges per physical connection with the public grid (either infeed or offtake) and is submitted to the TSO or DSO that it is connected to. This gives the system operators insight into expected flows and is used to prevent transmission bottlenecks. Where the E-programma is used to check the energy balance for the system, the T-programma focuses on location-specific information of electricity trades, in order for transmission bottlenecks (congestion) to be solved by the system operator. In the natural gas system, transmission bottlenecks are solved mostly through the use of compressors in the system by the TSO. For hydrogen, however, the availability of compressors is expected to be limited, which might lead to location-specific data being a necessary requirement in nominations. Both E- and T-programmas are submitted for every 15 minutes in the balancing day.

Reaction times necessary to respond to imbalance situations and maintaining system frequency, are much shorter for electricity than for natural gas. The electricity system needs to be balanced with reaction times in seconds, rather than minutes and hours for natural gas. Where in the latter the operational pressure range provides the system with what can be considered as linepack 'storage', the electricity system imbalance needs to be restored almost instantaneously. To that end, frequency reserves (i.e., FCR, aFRR, mFRR – see [15] for more information) of different response times are procured by TenneT to stabilize the grid. Additionally, market parties can contribute to balancing on the balancing market, receiving financial compensation for their contribution to reduce the system imbalance. The deployment of reserves or market mechanisms can be applicable to hydrogen balancing, where reaction times are expected to be much lower than in the natural gas system.

A final point of interest is the contract structures in place for electricity connections. Capacity limiting contracts are already available, where financial compensation is given by the system operator in return for a temporary limiting of electricity exchange. Additionally, the use of capacity control contracts is rising, in which the operation of energy storage systems is disclosed. Both contract types alleviate transport difficulties in times of congestion, through scaling down demand or scaling up supply depending on the system needs. These contract models could inspire similar contractual arrangements between DSOs and connected parties in regional hydrogen grids. This allows for faster response times in interventions by the DSO and possible compensation, e.g. through reduced tariffs, for the connected party's contribution of flexibility services necessary for balancing.

1.5 Regulatory landscape for hydrogen balancing

Having laid the background for balancing through lessons learned from the electricity and natural gas grid, we turn to hydrogen. An overview of the regulatory landscape provides a starting point for what is required in a hydrogen balancing system. There is little concrete regulation in place for hydrogen balancing. The most relevant legislation comes from the EU hydrogen and gas decarbonisation package, consisting of the Directive 2024/1788 and Regulation 2024/1789 [16]. Here it is stated that:

- *"Network users shall be responsible for balancing their balancing portfolios in order to minimise the need for transmission system operators and hydrogen transmission network operators to undertake balancing actions"* and *"balancing actions shall be performed on the basis of standardised products in accordance with the network code on balancing established pursuant to this Regulation and conducted on a trading platform or by means of balancing services in accordance with that network code"* – Article 3 (e) (f)

Additionally, in the Implementatie Energiewet, it is stated that a distribution system operator will similarly need to ensure system balance, starting January 1st, 2033 [17].

The responsibility of balancing their portfolios is therefore left with the network users themselves. Without the presence of a liquid market, portfolio balancing will likely entail bilateral agreements between trading parties. Additionally, balancing actions need to be in the form of standardised products and conducted on a trading platform.

- *"Hydrogen network operators shall offer their services on a non-discriminatory basis to all network users …"* and *"The maximum capacity of a hydrogen network shall be made available to market participants, taking into account system integrity and efficient and safe network operation."* – Article 7 (1) (2)

This appears to impose restrictions to system operators on whether or not they can reject access to parties. However, this is only applicable to the situation from 2033 onwards. Until then, negotiated access applies, on terms of the system operator. In the earliest stages, where allowing a connection to a party with an intermittent profile could make balancing the system very difficult, it could prove necessary for a DSO to reject access.

- *"Each (…) hydrogen transmission network operator (…) shall take reasonable steps to allow capacity rights to be freely tradable and to facilitate such trade in a transparent and non-discriminatory manner."* – Article 12

Article 12 requires the TSO to allow capacity rights to be freely tradable. This is already the case in the natural gas system and is logical in a large network with many trading parties participating in trading natural gas. Whether distribution grids need to allow trade of capacity rights and at what time, is open for debate, as regional hydrogen grids in early archetypes will likely have only one trading party. In more complex grid archetypes, multiple trading parties could be present, at which point trading of capacity rights might become prudent.

- *"In order to enable network users to take timely corrective action, the transmission system operator shall provide sufficient, timely and reliable on-line based information on the balancing status of network users."* – Article 13 (2)

The TSO is required to provide information on the imbalance position of network users. To aid the network users in their responsibility to balance their own portfolios, it could be desirable for the DSO to provide similar information in stand-alone networks.

- "*Transmission system operators shall ensure firm capacity for the access of production facilities of renewable gas and low-carbon gas connected to their grid. To that end, transmission system operators shall, in cooperation with the distribution system operators, develop procedures and arrangements, including investments, to ensure reverse flow from the distribution network to the transmission network.*" – Article 20 (2)

Finally, of interest is the mention of reverse flow from the distribution network to the transmission network in Article 20. Once the regional and transmission network are connected, the Decarbonized Gas Package requires the possibility for the connection to be bidirectional. Whether every connection will actually be made bidirectional, depends on the situational need and it is not an obligation.

2. Hydrogen balancing needs

Based on existing knowledge related to balancing, a series of key steps are needed to build a comprehensive balancing regime for regional hydrogen grids. In this report, a series of functionalities are defined in order to meet those needs and specific market and technical tools are identified that are required to implement those functionalities. Figure 13 highlights the conceptual relationship between balancing needs, functionalities, and tools.

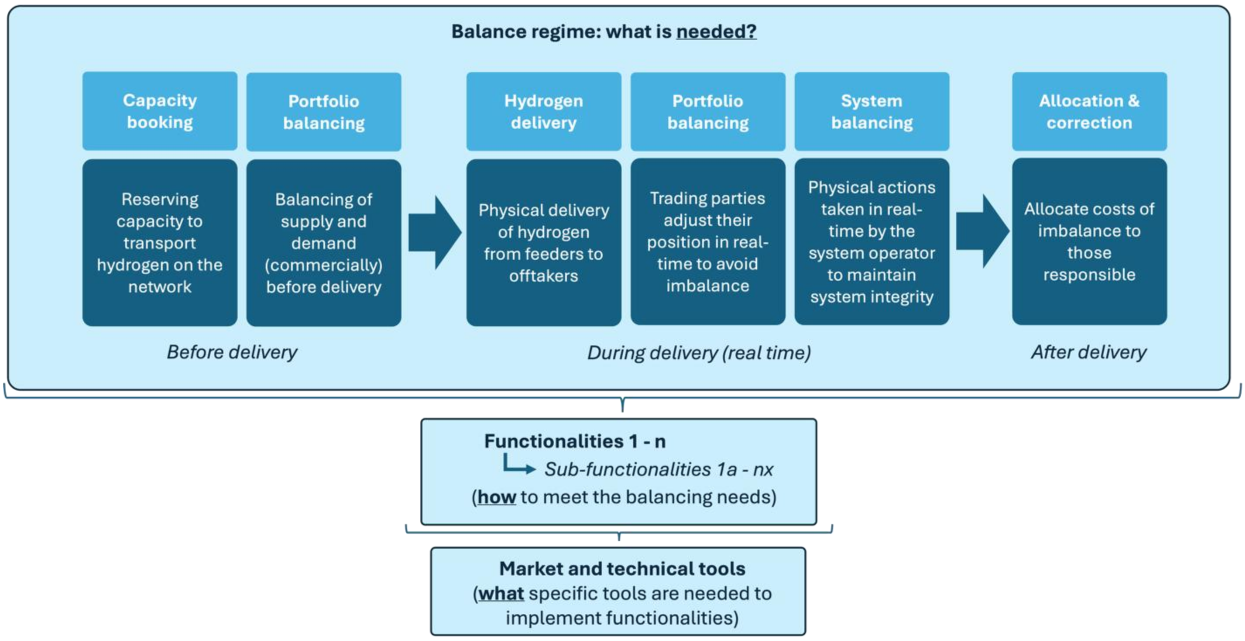


Figure 13: Conceptual framework for the needs of the balancing regime for hydrogen grids, the functionalities necessary to meet those needs, and the tools required to implement those functionalities.

2.1 Balancing regional hydrogen grids: terminology

In this section, we will provide a brief list of relevant terminology that will be used to describe the proposed balancing regime for regional hydrogen grids. In some cases, the terminology overlaps with that used in the gas world and in other cases it is distinct. Further, we include here the corresponding term in Dutch to alleviate confusion.

Table 1: Relevant terminology to the regional hydrogen grid balancing regime.

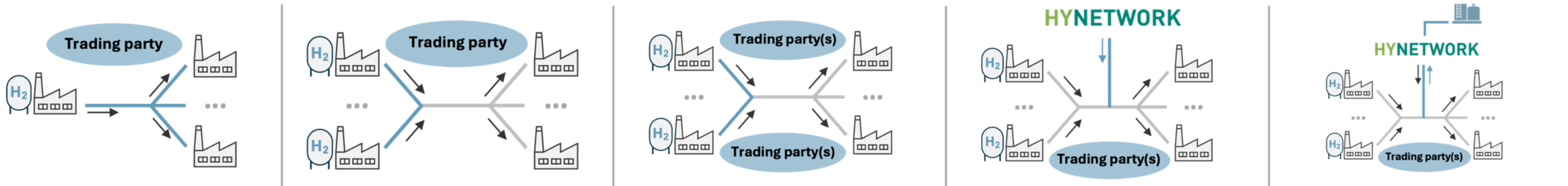
Term	Dutch	Remarks
Trading party	Handelspartij	Entities that transport hydrogen on the network (equivalent to “shipper” in the GTS world). The term *trading party* is adopted in lieu of balance responsible party (BRP) or supplier (*Dutch: leverancier*) as the distinction between these roles remains unclear. It is also not yet known whether the roles of BRP and supplier will be held by a single party or different parties. For these reasons, *trading party* is used to describe the responsibilities that fall under both roles in an attempt to maintain simplicity and allow for further specification. Additional guidance on how these roles will be assigned is expected to be provided in future legislation .

Connected party	Aangeslotene	A party connected to the network via a connection capacity contracted with the DSO.
Feeder	Invoeder	A connected party that feeds hydrogen into the network (can include storage, imports, or connections with neighbouring networks).
Offtaker	Afnemer	A connected party that consumes hydrogen (can include storage).
Portfolio balancing	Portfolio balancering	Actions (can be administrative) taken by trading parties to maintain balance in their portfolios.
System balancing	Systeem balancering	Actions taken by the system operator to maintain grid integrity and resolve residual imbalance that is not handled by portfolio balancing.
Nominations	Nominaties	Information that a trading party must submit to the system operator (i.e., location-specific planned entry, exit, and trades (including counterparts) at a frequency that still must be determined (e.g., hourly, 30-minute, 15-minute intervals) for the coming day of hydrogen delivery).[7]
Portfolio	Handelsprogramma	A collection of entry (in-feed) and exit (offtake) transactions (including trades) that pertain to a single trading party. Each day, the trading party is expected to balance their portfolio and notify the system operator (day-ahead and within-day, if necessary) of their planned entry, exit, and trades for the coming hydrogen delivery day via a *nomination* (above).
Connection agreement	Aansluitovereenkomst or AO	A contract between the DSO and a connected party that dictates the terms and tariffs associated with *connection capacity*.
Transport agreement	Transportovereenkomst or TO	A contract between the DSO and a trading party that dictates the terms and tariffs associated with *transport capacity*.

[7] In the GTS system there is a distinction between *programmes* and *nominations*. Trading parties (i.e., shippers) have been historically required to submit both a programme (which were largely used to see if damping had been applied correctly but this is not expected to be relevant in most regional hydrogen grids for the foreseeable future [26]) and a nomination to GTS. Nominations will effectively replace programmes in the GTS system in the future. Therefore, we adopt the term *nominations* to refer to all information that a trading party must submit to the system operator regarding their planned entry, exit, and trades.

2.2 Regional hydrogen grid archetypes

The makeup of regional hydrogen grids (and the associated balancing scheme that is required) is expected to take different forms and some networks will go through various phases of development. Therefore, it is crucial to understand how balancing requirements will differ between grids with different connected parties and infrastructure characteristics. We define five *archetypes* to assess the balancing requirements of future network designs in greater detail to ensure that connected parties are optimally supported as the network (in some cases) changes over time. These archetypes are shown in Figure and include typical aspects of projected future hydrogen grids, though it is also possible for certain networks to exhibit characteristics of more than one archetype as they evolve. Furthermore, not all networks should be expected to develop fully from Archetype 1 to 5, hence the term *archetype* is used rather than *growth stage*. These archetypes are useful for exploring balancing requirements in greater detail, as the balancing regime can be expected to differ given the different stages of development.



Archetype 1	Archetype 2	Archetype 3	Archetype 4	Archetype 5
RESPONSIBILITY FOR NETWORK				
System operator operator constructs distribution network and monitors/maintains network integrity	Same as Archetype 1	Same as Archetype 1	Same as Archetype 1	Same as Archetype 1
NUMBER OF OFFTAKERS IN THE SYSTEM				
One or more off-takers is connected to the network	Same as Archetype 1	Same as Archetype 1	Same as Archetype 1	Hynetwork is an additional source of offtake
NUMBER OF SUPPLIERS IN THE SYSTEM				
Single feeder supplies hydrogen for the entire network (including cushion gas)	Multiple feeders supply hydrogen for the entire network (including cushion gas)	Same as Archetype 2	Hynetwork is an additional source of feed-in	Same as Archetype 4
NUMBER OF TRADING PARTIES IN THE SYSTEM				
A single trading party contracts transport capacity with system operator and connects supply and demand for the entire network	Same as Archetype 1	Multiple trading parties are responsible for balancing supply and demand in the network	Can be either one or multiple trading parties responsible for balancing supply and demand in the network	Same as Archetype 4
FLOW COMPLEXITY				
Gas flow is unidirectional, limited buffer is assumed in the grid, storage possible at connected parties	Same as Archetype 1, but multiple feeders mean complex flows thus real-time transport integrity management by the DSO is needed	Same as Archetype 2	Same as Archetype 2	Same as Archetype 2
BALANCING ROLES				
Balancing is mainly responsibility of trading party – system operator only safeguards network integrity if absolutely necessary by limiting feed-in/off-take of connected parties directly	Same as Archetype 1	Multiple trading parties means system operator will take over system balancing role from trading party to adjust feed-in/off-take as needed to maintain operational limits or take action directly if needed	Same as Archetype 3	It must still be explored whether Hynetwork will take over **part** of the balancing role in most advanced development stages
MARKET PLATFORM AND DATA SHARING				
No market is needed due to presence of only one trading party. Nomination to grid operator is not needed.	Same as Archetype 1 but trading party must share some information about planned transports so system operator can perform transport integrity management	Market necessary to facilitate trades between trading parties and also for trading booked transport capacity. Trading parties must submit nominations to system operator.	Same as Archetype 3	Additional market integration needed if trading parties also become active on the Hynetwork grid

Figure 14: Summary of future archetypes of hydrogen distribution networks.

Archetype 1

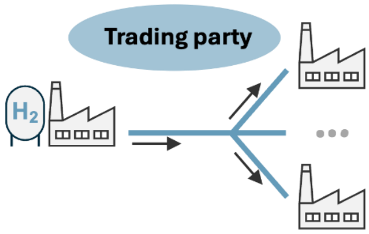


Figure 145: Distribution network with one regional feed-in point and connection to one or more connected parties via one trading party.

This archetype is the simplest of all hydrogen distribution network design variants, with one feed-in point, one trading party, and one or more connected customers (offtakers). Key characteristics include:

- **Responsibility for network:** System operator constructs distribution network, maintains network integrity, and is responsible for the monitoring necessary for balancing (whether the system operator is also responsible for measurements needed for balancing and invoicing or if that is handled by another party remains unknown).
- **Number of offtakers:** One or more offtakers are connected to the network.
- **Number of feeders:** One single feeder supplies hydrogen for the entire network (including cushion gas, which refers to the volume of gas needed to be permanently present in the network in order to maintain adequate pressure and flow rates).
- **Number of trading parties:** A single trading party contracts transport capacity with the system operator and connects supply and demand for the entire network. This situation seems inconsistent with the free-market access required by regulation. However, an immature market could make it less attractive for additional trading party(s) to join, therefore a network with only one trading party is expected in the early stages (Archetypes 1 and 2).
- **Flow complexity:** Gas flow is unidirectional and therefore system operator is not expected to have to perform real-time transport integrity management (assuming the trading party stays within its booked transport capacity).
- **Balancing roles:** System balancing responsibility mainly with trading party and system operator only safeguards network integrity if absolutely necessary by performing emergency actions (disconnecting connected parties). Trading party is also responsible for balancing supply and demand within their portfolio (which includes all connected parties).
- **Market platform:** No market is needed for exchange of hydrogen or transport capacity between trading parties since there is only one trading party present.[8]
- **Data sharing:** Nominations to the grid operator are not necessary.
- **Flexibility sources:** Limited buffer is expected in the network due to limited linepack and (though some storage at the connected parties could be present).

[8] *Market* refers to a place where trading parties can exchange volumes of gas with one another if needed. For example, if a trading party has a supply surplus in their portfolio, they can offer that on the *market* in hopes that another trading party has a deficit and wishes to buy it. This market opens up additional opportunities for trading parties to balance their portfolios but **only becomes relevant in later archetypes when more than one trading party is present**. In some cases, an additional market might develop for the purpose of exchanging booked capacity amongst trading parties. A trading party must reserve transport capacity with the DSO, but they might not use all of it all the time. In the event that a trading party has excess transport capacity already reserved but does not need all of it, they could offer the unused transport capacity on the market in hopes that another trading party is in need of additional transport capacity and will buy it. This ensures that the available network capacity is used an efficient manner but **is only relevant if multiple trading parties are present.**

Intern/Internal

Archetype 2

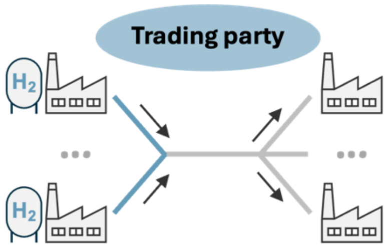


Figure 16: Distribution network with more than one regional feed-in point and connection to multiple connected parties via one trading party.

The second archetype represents a network similar to Archetype 1 with only one trading party but with the presence of more than one regional feeder. Key differences with Archetype 1 include:

- **Number of feeders:** Multiple feeders supply hydrogen for the entire network (including cushion gas – though it remains unknown how these costs will be distributed amongst the trading parties active in the network). The single trading party must manage additional complexity in balancing supply and demand between multiple feeders and offtakers.
- **Flow complexity:** Multiple feeders result in more complex flows.
- **Data sharing:** More complex flows means that the trading party must provide some information to the system operator regarding planned entry and exit so the system operator can check whether the planned transports can be facilitated and perform transport integrity management.

Archetype 3

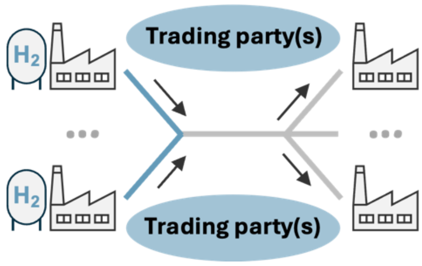


Figure 157: Distribution network identical to Archetype 2 but with the presence of more than one trading party.

This archetype is identical to Archetype 2 but is distinguished by the presence of more than one trading parties. Key differences with Archetype 2 include:

- **Number of trading parties:** Multiple trading parties are present.
- **Balancing roles:** Multiple trading parties means that the system operator must take over the role of system balancing – portfolio balancing remains the responsibility of the trading parties
- **Market platform:** Trading parties can now manage imbalances between supply and demand by directing feeders and/or offtakers in their portfolio to change their behaviour or via exchange with other trading parties. In advanced stages of this archetype a hydrogen exchange market could be developed, though sufficient size and liquidity are requisites for proper market functioning. A market model could also be needed for trading parties to exchange booked transport capacity (this refers to a market whereby trading parties can exchange the transport capacity that they have booked with the system operator amongst themselves as needed).
- **Data sharing:** Trading parties must nominate expected entry and exit the day before delivery each day (renominations are possible in the event of changed forecasts) and share that

information with the system operator. The system operator subsequently uses it to check whether portfolios are balanced, whether transports can be facilitated, and whether the nominated flows are within the trading parties' booked transport capacity.

Archetype 4

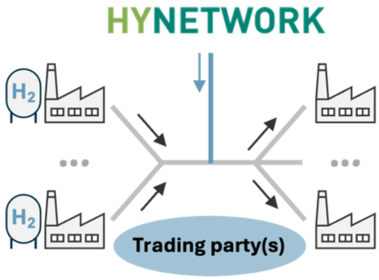


Figure 18: Distribution network similar to Archetypes 2 and 3 but with a unidirectional connection to the HNS Transport System (presence of more than one trading party is possible but not a requisite).

This archetype introduces a unidirectional connection to the HNS Transport System (i.e., Hynetwork connection is an additional source of feed-in into the network) and otherwise remains similar to Archetype 3 (with the possibility of having more than one trading party but not as a requirement). Key differences with Archetype 3 include:

- **Number of feeders:** Unidirectional connection to the HNS Transport System serves as an additional source of feed-in (though in this archetype the HNS Transport System is assumed to remain under development and flows cannot always be guaranteed and large-scale storage is not yet expected in the earliest stage).
- **Data sharing:** Trading parties must also include planned offtake from the Hynetwork entry point in their nominations as trading parties can make use of other parties on the Hynetwork grid to balance their portfolios.
- **Flexibility sources:** Balancing regime largely looks similar to previous archetypes (i.e., Hynetwork is not expected to take over balancing responsibility in the early development stages of the HNS Transport System). The main difference is the additional flexibility provided by the HNS Transport System, which can either be included in nominations by trading parties or used by the system operator to maintain stable network pressure (assuming adequate supply in the HNS Transport System).

Archetype 5

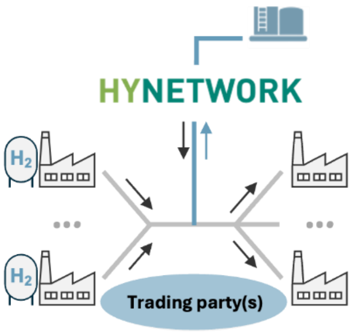


Figure 16: Distribution network largely the same as Archetype 4 but with a bidirectional connection to the HNS Transport System, which is eventually expected to have access to large-scale storage.

This archetype is largely the same as Archetype 4 but introduces a bidirectional connection to the HNS Transport System and assumes that in later development stages the HNS Transport System will have access to large-scale hydrogen storage (thereby providing more stable and reliable flows from the HNS Transport System). The key differences with Archetype 4 include:

- **Number of offtakers:** The regional network grid now has the option to feed into the HNS Transport System (i.e., national infrastructure is an additional source of offtake), which would require trading parties to book entry capacity with Hynetwork and also submit nominations day-ahead.
- **Balancing roles:** In the most advanced stages of development, it still needs to be explored whether Hynetwork will take over balancing of regional networks via passive pressure balancing if deemed appropriate or is a requirement by regulation, similar to how current regional natural gas grids are balanced. There is also the opportunity for regional system operator to assist Hynetwork with balancing via operational balancing agreements (OBAs) (and vice versa) similar to current practice of balancing between international grids via arrangements between TSOs of neighbouring countries [14].
- **Market platform:** Market integration between the Hynetwork market for exchanging hydrogen commodity and that used by trading parties on the DSO network is likely needed.
- **Flexibility sources:** Improved supply in the HNS Transport System and access to large-scale storage is assumed making it a more reliable source of flexibility to be used by trading parties for portfolio balancing or for the system operator for emergency actions needed to maintain stable network pressure.

Intern/Internal

2.3 Functionalities of a hydrogen balancing system

Building on the high-level characterization of the system for the different archetypes, this chapter addresses the question of what the future hydrogen balancing framework needs. These needs are outlined in a list of *functionalities,* formulated to keep crucial decisions open, while at the same time incorporating certain preliminary decisions to enable identification of system requirements, challenges and knowledge gaps. The functionalities aim to form a list of system needs with a factual basis, including decisions already taken in regulation.

The list of functionalities gives an estimate of expected roles per functionality. In a separate chapter (Potential distribution of roles per functionality), possible role distributions are laid out, as well as the foreseen consequences of these decisions. Instead, the functionalities describe actions taken by *parties* (e.g., system operator, trading party).

The functionalities are described loosely in order of appearance when considering a standard day of hydrogen delivery. A visual overview of this order of appearance and the relation between functionalities is given afterwards in the Balancing Timelines chapter. The main functionalities discussed are:

1. Investment in and maintenance of hydrogen infrastructure
2. Assignment of transport capacity to trading parties
3. Connecting feed-in and offtake – nominations
4. Nomination review and approval
5. Measurement and data management
6. Maintaining transport integrity real-time
7. Real-time portfolio balancing
8. Maintaining system integrity real-time
9. Delivery – sales and purchases
10. Allocation and correction
11. Flexibility services

F1	Investment in and maintenance of hydrogen infrastructure
Sub-functionalities	1a. Provide connection and transport capacity through investments 1b. Provide hydrogen booster 1c. Provide collective storage 1d. Process requests for connection capacity 1e. Assign connection capacity to connected parties
Description	The starting point of hydrogen balancing naturally is the consideration of the infrastructure. Investments and maintenance of hydrogen infrastructure are responsibilities of the system operator, according to the Gasverordening (Art 7, lid 5.), as likewise with electricity (see Elektriciteitswet (Art. 16)) and natural gas. Its relevance to balancing is the interrelation between the available connection capacity to connected parties on the network, and the volumes transported in daily operation (including balancing) of the network. The invested capacity of the network (1a) determines the possible transports, while daily operation reaching its limits calls for new investments by the system operator. Additionally, requests for connections to the network need to be handled by the system operator (1d). After determining the needed investments, a decision needs to be made on whether or not to connect a party based on request (1e). Being granted *connection capacity* gives no right to any amount of *transport capacity.*[9] This is instead assigned in 2b. For requests of parties with a supply or demand profile that is in conflict with the task of balancing the network, it may be desirable for the system operator to have the ability to refuse access. Finally, in addition to the pipeline capacities of the network, the availability of a booster for transport to the TSO network (1b), and the availability of a collective storage unit for use in balancing (1c), are identified as potential functionalities.
Expected roles	Investment and maintenance of hydrogen infrastructure on the regional grids (1a), as well as connection capacity assignment (1d, 1e) likely falls under the responsibility of the DSO. Provision of hydrogen boosters (1b) and collective storage (1c) could be provided and maintained by either the TSO and DSO in later archetypes. Exploitation of storage will be left to the market. Investment and operation of a collective storage could potentially be done by a market party as well.

[9] In this report, it is assumed that *connection capacity* is issued to connected parties via a connection agreement (*aansluitovereenkomst* or AO) and *transport capacity* is issued to the trading party via a transport agreement (*transportovereenkomst* or TO). In the natural gas system, DSOs enter into combined connection and transport agreements (or ATOs) with the connected parties. However, in certain regional hydrogen grids that are in development (namely the H2avennet project in the Port of Amsterdam and the GROHW project in Deventer), the decision has been made to split the ATO into an AO with the connected parties and a TO with the trading party. As such, this report adopts a similar assumption with the main caveat being that this item requires additional exploration in Phase 2, particularly to understand how such contract designs enable (or limit) the DSO's ability to implement certain balancing tools that are proposed in this report (such as interruptible contracts).

Intern/Internal

F2	Assignment of transport capacity to trading parties
Sub-functionalities	2a. Process requests for transport capacity 2b. Assigning transport capacity (firm or interruptible) 2c. Trade of transport capacity
Description	Whereas connection capacity is often assigned to a location years in advance (relative to a specific moment of network balancing), the assignment of transport capacity relates to the available transport volumes at entry and exit points *for a given moment in time*. Requests for transport capacity (2a) by trading parties can be done for different time periods (e.g. minutes, days, years) and can apply to a part of the total available transport capacity on the entry or exit point. The assignment of transport capacity (2b) is done within the total available transport capacity of the network, as assessed by the system operator using the appropriate simulation tools. A possible functionality of the hydrogen balancing system, as with natural gas, can be to offer both firm and interruptible transport capacity to be booked. Finally, trade of booked transport capacity (2c) allows for a more liquid market in archetype 3, 4 and 5 of the hydrogen grid where multiple trading parties are active. As with the more mature natural gas system, a platform could be provided for trade of booked transport capacity. An example would be if one trading party has additional transport capacity already booked with the system operator, but they do not intend to use it. They could then put this transport capacity on the market so that other trading parties who desire additional capacity make use of it. The existing capacity is thus used more efficiently. Otherwise, bilateral trade between trading parties is an option.
Expected roles	Assigning transport capacity (2a, 2b) is expected to fall under the responsibility of the DSO for transport capacity on the distribution network. As for the transport capacity booked on entry/exit points, the exact distribution of roles between the DSO and TSO is to be determined. This will depend on whether portfolio balancing is mostly done by the TSO comparable to the current gas network, or the regional network is a separate balancing zone under DSO control in Archetypes 4 and 5. This is a situational choice to be made for each network connected to the HNS Transport System. Trade of transport capacity is expected to be carried out by trading parties, but the facilitation of trade falls under the responsibility of the TSOs by legislation according to the EU hydrogen and gas decarbonisation package (2c). In Archetypes 1 to 3, the DSO fulfils this role and in later Archetypes this is still up for debate.

F3	Connecting feed-in and offtake – nominations
Sub-functionalities	3a. Match of feed-in and offtake within portfolios 3b. Match of feed-in and offtake with other trading parties 3c. Internal establishment of expected trade between parties

Intern/Internal

	3d. Nominate – communicate results to system operator
Description	Trading parties are responsible for the administrative matching of expected feed-in and offtake within their portfolios (3a). This ultimately results in the matching of supply and demand profiles, to achieve a balance of feed-in and offtake flows at any given moment in time. Trading parties can accomplish this via long-term contracts in the years, months, weeks, etc. leading up to delivery. In addition, trading parties are able to trade with one another and match the feed-in and offtake between each other's customers (3b). When those steps are completed, internal establishment of all expected trade within their portfolio is done by the trading party (3c). Finally, the expected (location and time-specific) feed-in and offtake within this portfolio must be passed along to the system operator via a *nomination* (3d). This includes the information to which entry/exit points the feed-in and offtake relate, which is used for location-dependent transport integrity calculations of functionality 4c. The actions taken for this functionality are happening sometime during the day-ahead (D-1) and have multiple goals: to offer information to the system operator on expected transactions and thus flows, and to minimise the number of needed physical actions to maintain system integrity by matching flows between trading parties. The deadline for finalizing these trades, exactly when this information is passed along to the system operator and the degree to which they can be modified still needs to be defined.
Expected roles	Matching of feed-in and offtake and nominations are all expected to be the responsibility of the trading party (3a, 3b, 3c, 3d)

F4	Nomination review and confirmation
Sub-functionalities	4a. Review of nominations on feed-in and offtake 4b. Renomination based on review 4c. Review of nominations on transport facilitation 4d. Modification of trading party's nomination and/or impose restrictions to connected party
Description	The system operator checks the volumes of feed-in and offtake in the nominations for correctness. This includes: i) checking whether feed-in and offtake are balanced; ii) checking whether a traded volume of gas nominated by the trading party supplying the gas is accompanied by a matching nomination from the counterparty that is receiving the gas; and iii) checking whether the nominated flows are within the trading party's booked transport capacity and communicates back to the trading party whether it is correct or needs adjustments before being accepted (4a). The trading party receives this message and is able to renominate within the allotted time (4b). If this renomination is not done (in time) within the contracted transport capacity, the system operator assumes a zero nomination. This means a non-zero flow will be treated as an imbalance. It is important that the constraints of the renomination process are strict enough to encourage accurate initial nominations where possible but flexible enough to enable renomination to still take place when needed (the exact conditions must still be defined). Additionally, the system operator checks the consequences of all nominations on their ability to facilitate transports on the network (4c). This consists of

	calculations and network simulations of the projected transports and uses the location-dependent information on feed-in and offtake from the nominations. Finally, functionality 4d allows the system operator to direct trading parties to modify (the expected feed-in and offtake in) their nomination based on this transport review. Whether this is done through an interruptible contract or otherwise is examined more closely in the chapter Market tools. This is different from balancing in the natural gas grid, where transport issues can be solved within the larger system (e.g. turning on compressors). Possibilities will be limited in the first archetypes of the hydrogen grid, requiring a functionality to maintain facilitation of transports.
Expected roles	Reviewing the nominations on feed-in and offtake and on transport facilitation (4a, 4c), as well as directing trading parties to make changes based on this transport review (4d) is the responsibility of the DSO and TSO. Renomination based on review (4b) is the trading party's responsibility.

F5	Measurement and data management
Sub-functionalities	5a. Measurement of data for portfolio balancing 5b. Measurement of data for system balancing actions on net integrity 5c. Measurement of data for allocation and correction 5d. Aggregation, processing and transparency of data
Description	To facilitate balancing actions as well as administrative and financial processes, measurements are required. Firstly, portfolio balancing actions at connected parties need measurement of flow on the connection points (5a) and this information must be shared with the trading party(s). It is important to note that the trading party must also receive pressure data in Archetypes 1 and 2, since the trading party has primary balancing responsibility in these first two archetypes. Additionally, balancing actions for remaining net integrity need measurements of pressure throughout the network (5b): on connections but also in later stages on the interconnections to other grids. Measurements for allocation and correction are also necessary (5c). This financial processing of changes between projected transport and realized transport is discussed in functionality 10. Finally, aggregating data, processing it and making it available for transparency reasons is necessary (5d). This data should be shared remotely. In early archetypes this can be done more pragmatically (bilaterally between the Measurement Responsible Party (MRP) and the trading party), andn later archetypes, a data sharing platform is likely to be necessary.
Expected roles	The responsibility of measurement of data for portfolio balancing actions, and for allocation and correction (5a, 5c) can possibly fall under an MRP or by the DSO. This does pose the risk of a conflict of roles. Measurement of data for balancing actions on net integrity, and aggregation and distribution of data (5b, 5d) are the responsibility of both/either? the TSO and DSO.

F6	Maintaining transport capacity in real-time
Sub-functionalities	6a. Monitoring transport capacity and signalling when capacity issues arise 6b. Changing gas flows to maintain ability to facilitate transports
Description	Moving from the day-ahead to (near-)real-time, the system operator must monitor transport capacity to ensure that intended flows of hydrogen can be facilitated. If issues arise, the system operator directs the trading party(s) and/or their connected parties to change gas flows to restore transport integrity (6a). The trading party(s) and/or connected parties then must adjust flows accordingly (6b). This can be done in several ways: deployment of flexibility services, imposing restrictions on trading parties with interruptible contracts, etc. These tools will be more thoroughly explored in the following chapter.
Expected roles	Monitoring of transport capacity and sending a signal in case of issues in transport capacity (6a) is the responsibility of the DSO and TSO. The process of changing gas flows to facilitate transports will be executed by the trading party(s) and their connected parties at the direction of the DSO and TSO (6b).

F7	Real-time portfolio balancing
Sub-functionalities	7a. Monitoring and reacting to near-real-time imbalance signal to avoid imbalance 7b. Deliberate deviation from nominations to improve total system imbalance
Description	There are two sub-actions within the real-time portfolio balancing functionality. First, the trading party(s) use the near-real-time imbalance signal to monitor their own imbalance position (comparable to the portfolio imbalance signal or POS in the natural gas system – see Appendix C) received from the system operator. The trading party(s) must respond and restore their own imbalance position to remain in line with their nominated flows by directing connected parties in their portfolio to adjust their flows as needed (7a). This imbalance signal will later be used to calculate imbalance penalties, providing trading parties a financial incentive to prevent imbalance on the network and associated interventions from the system operator. Additionally, a system imbalance signal (comparable to the SBS in the natural gas system – see Appendix C) consisting of the total system imbalance needs to be available, so trading parties know the likelihood of intervention by the system operator and whether they should perform any corrective action.[10] However, a second sub-functionality that can be useful in preventing imbalance is to provide a financial incentive to trading parties that purposely deviate from their nominations in order to contribute positively to the system imbalance (7b).[11]

[10] For example, a situation could arise where a trading party sees in their individual imbalance position that they are out of balance, looking at their nomination. The system balance signal then shows that the network as a whole is in balance, which means the system operator will not need to take any corrective action. Therefore the trading party is not at risk of incurring any imbalance fees. In this case, the trading party might not direct the connected parties in its portfolio to change their behaviour as a result.
[11] For example, a trading party could see in their individual imbalance position is balanced but that the system imbalance signal as a whole is out of balance. If they have some flexibility in their portfolio, the trading party could direct their connected parties to deviate from their nominated flows in such a way that improves the overall system balance. If it turns out in the end that the trading party did indeed improve (and did not exacerbate) the imbalance situation, they could be compensated for their contribution.

	This has been part of the natural gas balancing system in the past but has since been abandoned [11]. Provided the right incentives are there and the risk of 'gaming the system' is mitigated, this could provide a needed tool for balancing hydrogen grids.
Expected roles	Monitoring of imbalance signal and following nomination adjustments (7a, 7b) are carried out by the trading party

F8	Maintaining system integrity real-time
Sub-functionalities	8a. Deployment of flexibility services to maintain system integrity 8b. Gradual and incremental intervention 8c. Physical intervention based on projected system integrity loss
Description	The system operator has the ability to deploy several tools to maintain system integrity. When pressure levels cross the boundaries of desired or allowed pressure range, there is a sequential list of steps to take, in order of severity of the pressure problem. Firstly, when pressure levels are still within operational bandwidth the trading party is expected to take action. If they fail to do so (in time) and intervention is necessary to prevent further problems, the system operator is able to deploy flexibility services to maintain system integrity (8a). This requires time to contact the relevant connected party. Additionally, an automated system is in place when quicker response times are needed. In principle, the action taken in case of integrity risk is to close valves. However, in order to prevent a cascading shutdown of the whole system, it could be desirable to use a more stepwise approach. In that case, the system operator would deploy a gradual and incremental closing of the valve at connection points when pressure is still within the operational bandwidth (8b). This can be done based on prioritization (location of pressure problem). However, it is heavily dependent on the connected party whether their asset is able to operate in these conditions. Furthermore, the feasibility and necessity of this sub-functionality are still unknown and require further research. The final and most severe intervention is to deploy safety mechanisms such as closing valves, as pressure levels rise beyond the outermost levels (8c). This requires either local mechanical pressure safety systems or an automated disconnection system, and is the final intervention method available for system operators.
Expected roles	Maintaining system integrity in real-time (8a, 8b, 8c) is the DSO's responsibility by regulation.

F9	Delivery – sales and purchases
Sub-functionalities	9a. Effectuation of trade transactions (feed-in and offtake)
Description	After portfolio balancing has taken place (i.e., supply and demand are matched, trades are conducted, information is shared with system operator via the nomination process, nominations are confirmed, and trading parties potentially deviate from their nominations to avoid imbalance) as explained in the previous

	functionalities, here the effectuation of the projected trade transactions is made explicit.
Expected roles	Effectuation of trade transactions (9a) is done by the trading party.

F10	Allocation and correction
Sub-functionalities	10a. Allocation of imbalance 10b. Aggregation of allocation data: transactions of transported hydrogen 10c. Correction: correction process of measurement errors or missing data
Description	After delivery, allocation of imbalance costs to the causers of imbalance is done based on earlier measurement data (10a). If applicable, a financial renumeration is done to those trading parties that contributed to improving system balance at the time. In the natural gas system, this process occurs online, in near-real time. Additional discussion is needed on whether this will be the same for hydrogen or whether allocation will happen at a later time. The trading parties themselves then aggregate the data relevant to distributing the costs to the connected parties that are under contract (10b). Finally, the correction process consists of correcting possible measurement errors, missing data, etc. (10c) If there is a difference between the validated flow measurements and those that were measured in near-real time, a financial settlement is made between system operator and trading party.
Expected roles	Allocation and correction (10a, 10c) are expected to be the DSO's or TSO's responsibility. The aggregation of allocation data (10b) could be done by either an MRP or the DSO/TSO.

F11	Flexibility services
Sub-functionalities	11a. Contracting of flexibility services 11b. Balancing action carried out by Flexibility Service Provider
Description	Finally, to support the functionalities that make use of flexibility services (i.e., storage) to restore balance or prevent imbalance situations, an explicit functionality is made for the arrangement of flexibility services. Contracting of flexibility services (11a) requires an agreement on the capacity, time scales and response time between the contracting party and flexibility provider making temporary changes to the way they consume, generate, or store hydrogen. Within the day of balancing, the Flexibility Service Provider then carries out the balancing action when necessary (11b).
Expected roles	Contracting of flexibility services for system balancing will be the responsibility of the DSO (11a, 11b). Whether or not trading parties can also contract flexibility providers to support in real-time portfolio balancing, is as of yet uncertain.

2.4 Potential distribution of roles per functionality

Each functionality has been assigned possible expected roles in the descriptions above. A detailed examination of roles per sub-functionality and archetype is included in Appendix A. Most uncertainty stems from the decision on responsibility for portfolio balancing actions. The system balancing actions taken on the distribution network will fall under the DSO's responsibility. Portfolio balancing actions throughout the country can be assigned to one central party (e.g. the TSO), comparable to the current natural gas system. This applies to Archetypes 4 and 5 when a Hynetwork connection is available. The alternative is to leave responsibilities to the DSO, as in earlier archetypes.

A consideration to be made here is the moment of connecting a regional network to the HNS Transport System. A nationally operated portfolio balancing system could provide more efficiency and consistency in use, but setting up individual balancing systems by the DSOs only to have to discard them at the point of connection seems inefficient. On the other hand, regional networks will have different characteristics and different intended end-points. No uniform decision has to be made at this time, but rather a case-by-case assessment for each network. Furthermore, further alignment is needed on the plans of DSO and TSO organizations, to ensure risks as mentioned above are mitigated.

Additionally, the assigned roles for carrying out measurements for allocation purposes are still open. Measurement for system balancing actions are carried out by the DSO for system integrity, and by the trading party for flow measurements at the connection. Measurements for allocation of imbalance need to be done by an independent party, which can be the DSO or a Measurement Responsible Party (MRP).

A more detailed overview of possible roles per functionality for each archetype is given in Appendix A.

2.5 Balancing Timelines

In this section, the functionalities described in the previous section are presented in a preliminary timeline to help conceptualize the order of events. Since many uncertainties remain, these figures should be interpreted as merely a first concept of how such functionalities are arranged in time. This will need to be worked out further in the second research phase.

The balancing timeline is expected to change depending on which of the five different grid archetypes is assumed. Therefore, this chapter presents two different potential timelines meant to highlight some of the key differences between a timeline for **early grid archetypes** and one for the **most advanced grid archetype**.

Further explanation of the mechanics of the timeline visual is provided below in Figure 20. The order of events in the timelines can be followed by starting at the green circle and following the arrows through to the end.

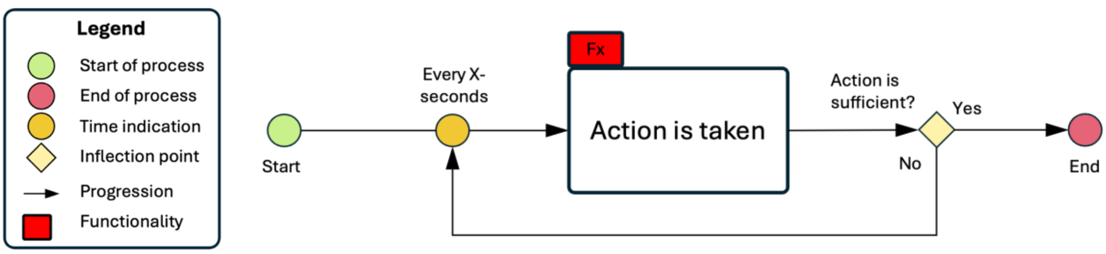


Figure 20: Example timeline demonstrating timeline mechanics.

The process shown in Figure 220 begins at the *Start* point and then *Every X-seconds* the *Action* occurs (which corresponds to *Functionality x* – see Functionalities of a hydrogen balancing system for additional information on the individual functionalities). If the *Action* is sufficient, then the process ends. If not, then the process returns to the beginning and is repeated *Every X-seconds*.

On the subsequent pages, the following two balancing timelines are presented:

1. An approximate version of a timeline for **early grid archetypes** (most relevant to Archetypes 1 and 2, which have only one trading party present in the system) (Figure).
2. An approximate version of a timeline for the most **advanced grid archetype** (most relevant to Archetype 5, which is expected to have multiple trading parties, a more mature and liquid hydrogen market, and a bidirectional connection to Hynetwork) (Figure 18).

A further explanation of how to interpret these timelines is provided in Figure 171.

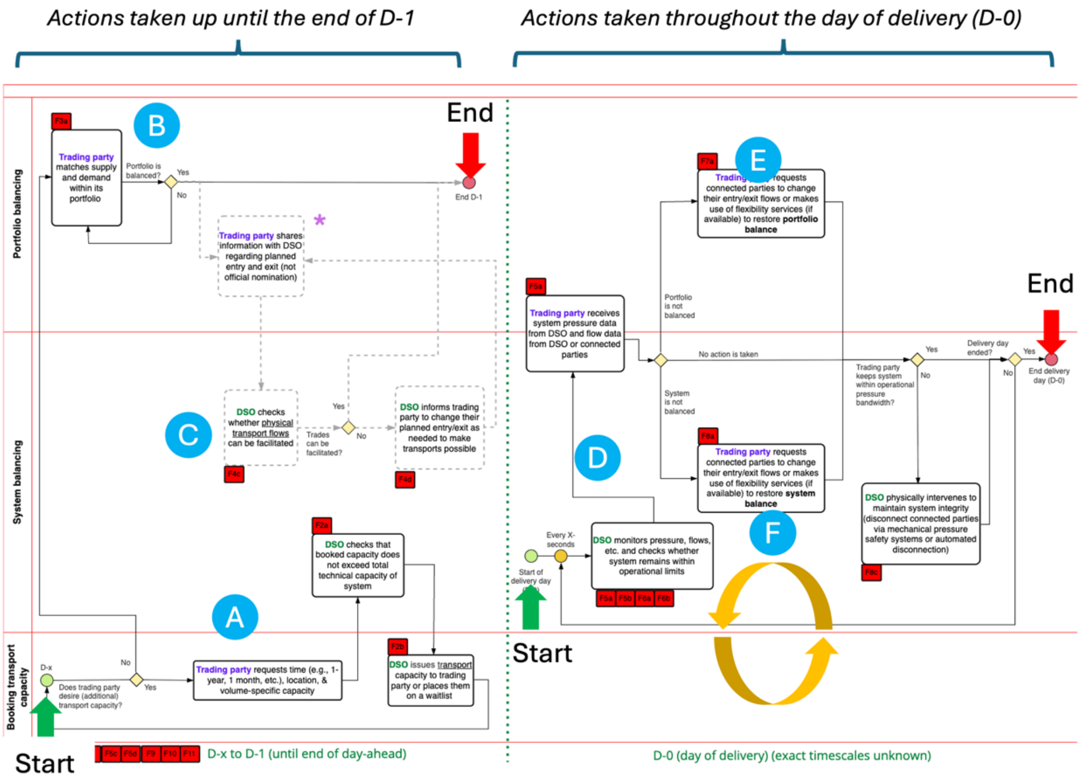


Figure 17: How to interpret the balancing timelines (note: the early grid archetype timeline is shown here but the advanced grid archetype layout remains largely the same). Two processes are shown. On the left-hand side, the D-x to D-1 actions are depicted. These include the process of booking transport capacity (A), the commercial matching of supply and demand (B), and a series of pre-delivery system checks by the DSO to ensure that planned entry and exit is possible (C). On the right-hand side, D-0 actions are shown. These include the monitoring and sharing of pressure and flow data (D), real-time portfolio balancing actions (E), and system balancing actions (F). Note: these 3 sub-processes (D, E, and F) are looped every X-seconds until the end of the delivery day.

In each of the timelines on the following pages, the left-hand side of the figure presents actions that take place some period of time before the day of hydrogen delivery (D-x) and up until the day-ahead (D-1). The right-hand side of the figure presents a timeline of actions taken within the hydrogen delivery day (D-0). It includes a loop that is repeated every *X-seconds* throughout the day (timescales remain undetermined) until the day of delivery is complete.

The timeline is divided into three distinct categories (rows) based on the type of action to be taken: the top row includes actions related to <u>portfolio balancing,</u> the middle row includes actions related to <u>system balancing</u>, and the bottom row includes actions related to <u>booking of transport capacity</u>.

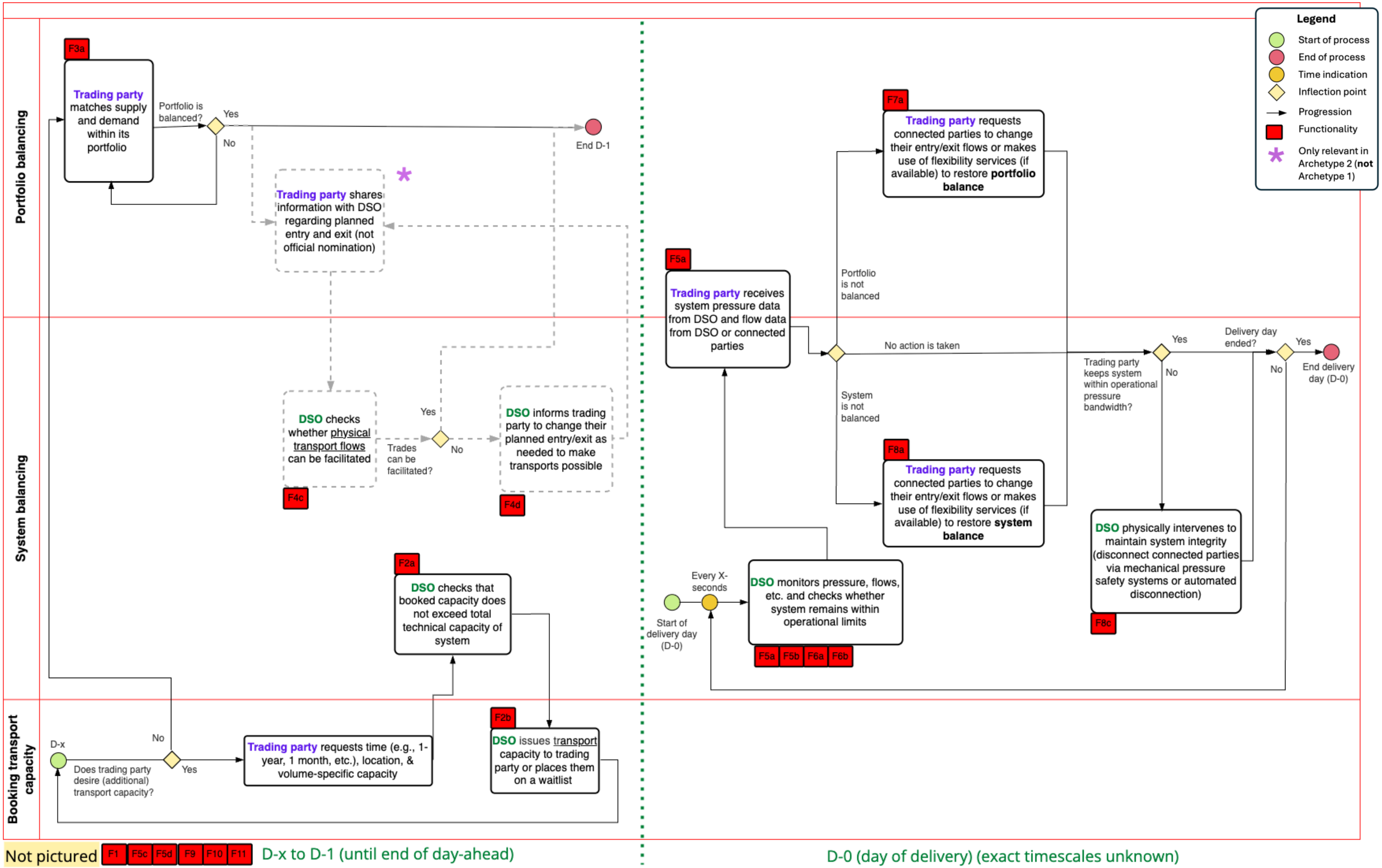


Figure 22: Approximate timeline of balancing actions to be taken in early grid archetypes (mostly relevant to Archetypes 1 and 2).

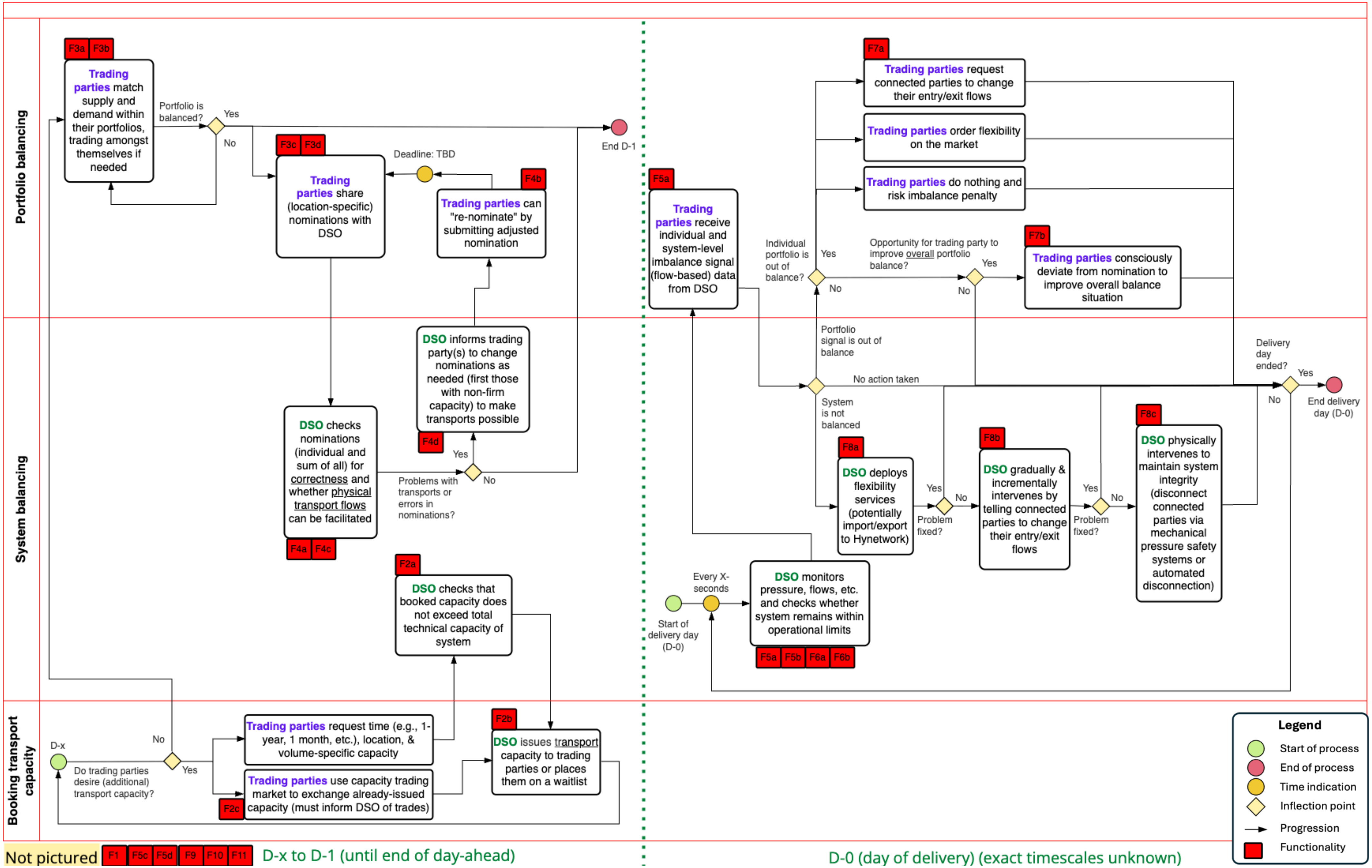


Figure 18: Approximate timeline of balancing actions to be taken in later regional hydrogen grids (Archetypes 3 to 5).

Key distinctions between the timeline for **early grid archetypes** (Figure) and the timeline for the **most advanced grid archetype** (Figure 18) are outlined below:

Main balancing responsibility (system and portfolio balancing) is held by the trading party in early grid archetypes. In Archetypes 1 and 2, the single trading party takes on the majority of balancing responsibility, and the DSO has a limited role (only intervening by disconnecting parties to maintain network integrity when the trading party fails to balance the system). The DSO shares pressure (and possibly) flow data in real-time with the trading party, who is expected to balance the system accordingly. In Archetypes 3 to 5, the DSO takes on the role of system balancing based on pressure and the trading parties take on the role of portfolio balancing (acting on a flow-based individual and system-wide balance signal).

No market for exchanging booked transport capacity amongst trading parties in early grid archetypes. In the bottom left corner of the timelines, the booking of transport capacity begins at D-x. This means that trading party(s) can book capacity with the DSO starting some unspecified period of time before the day of delivery. The main difference between the two timelines is that in the early archetypes timeline the trading party can only request transport capacity from the DSO and if none is available, they are put on a waitlist. In the advanced archetype timeline, there is another option to exchange already issued transport capacity amongst the trading parties in the system.

Day-ahead data sharing and checks of transport flow are simpler in the earliest grid archetype due to only one feeder. In the centre left of the timelines, it is notable that the DSO performs a check of the planned entry and exit flows for the coming delivery day to ensure that transports can be facilitated. The dotted line indicates that this process is only relevant for Archetypes 2 and higher when there is more than one feeder in the system. In Archetype 1, there is only a single feeder, and flows are unidirectional making such a transport integrity check not necessary.

Lack of nominations in early grid archetypes. Since the trading party takes on the majority of balancing responsibility in Archetypes 1 and 2, they are not required to submit a nomination to the DSO (who only intervenes if absolutely necessary). In Archetypes 3 to 5, when there are multiple trading parties active, trading parties are required to submit a nomination to the DSO so the DSO can check their planned entry and exit against the measured flows and allocate imbalance costs accordingly to the responsible trading party (or compensate those responsible for improving balance).

Portfolio balancing expected to play a larger role in advanced grid archetype. In the top left-hand part of the timelines, trading parties match supply and demand within their portfolios prior to the day of delivery. In the advanced grid archetype timeline, they are also able to trade with other trading parties, which is not relevant in the early archetypes timeline as only one trading party is present. Furthermore, the real-time portfolio balancing process (top right-hand side of the figures) in the advanced archetypes timeline is more involved, as it is assumed that a liquid market enables trading parties to trade amongst themselves and order flexibility as needed to adjust their imbalance position. There is also the option for trading parties to consciously deviate from their nomination in an attempt to improve the overall (portfolio) imbalance in the system.

Access to the HNS Transport System in advanced grid archetype offers more flexibility. On the system balancing side (bottom right-hand side of the figures), the advanced archetypes timeline highlights that there are additional measures available to the DSO to perform system balancing. This includes deploying flexibility sources and importing or exporting to/from the HNS Transport System. It is also assumed that if market integration will enable trading parties on the regional network to balance their portfolios by trading with other parties on the Hynetwork grid.

3. Available tools for balancing

The functionalities described above provide an answer to the question 'what does a hydrogen balancing system need?'. Several (sub-)functionalities call for use of certain tools to restore balance or prevent future imbalances but are still quite open as to what tool can be used. In this section, we will describe the tools from both the market and the technical side that could be available to the system, and for which functionalities they provide an option. It is highly likely that there will not be a single tool providing the balancing, for earlier as well as later archetypes, but rather a combination of multiple tools.

3.1 Market tools

1. Conscious deviation from nomination to improve total system imbalance [F7]

To operate an efficient market, encouraging the trading parties - as much as acceptable - to prevent or reduce (their own) imbalance is preferable. Furthermore, there could be situations in which it is favourable for trading party(s) to consciously deviate from their nomination in order to improve the imbalance situation on a system level. The first 'tool' to meet the system needs (Functionalities) is therefore **conscious deviation from nominations**.

To enable such behaviour and effectively use this tool for balancing, near real-time data needs to be shared, which includes: an insight into the trading party's own imbalance (similar to the POS in the natural gas system – see Appendix C), as well as insight into the total system imbalance (similar to the SBS in the natural gas system – see Appendix C).[12]

System balancing actions by the DSO are only taken when the system imbalance goes past a certain threshold, and trading parties responsible for causing the imbalance will pay the associated costs. Trading parties can monitor their individual imbalance position and that of the system as a whole and decide whether to change their behaviour (by contracting flexibility or directing connected parties in their portfolio to do something) to avoid imbalance penalties.

Furthermore, a system can be in place where financial remuneration is given to those trading parties that contributed positively to restoring balance on the system level, regardless of their individual balance position. This does pose a risk, however, of parties 'gaming the system' (i.e., purposefully creating an imbalance situation in order to help solve it). Therefore, it is important that the necessary measures are in place to mitigate this risk.

A simplified summary of the potential actions a trading party might take based on their individual imbalance position and the status of the system-wide imbalance signal is provided in Table 12.

[12] The distinction between the system-level imbalance signal and an individual signal only becomes relevant in Archetype 3 and beyond when there is more than one trading party active on the system.

Table 22: Summary of trading party actions given different imbalance scenarios.

Is the trading party's portfolio balanced?	Is the system balanced?	Trading party action	Implication
Yes	Yes	No action needed	Individual portfolio and system are in balance, so no corrective action is needed.
No	Yes	No action needed	Although the trading party's individual portfolio is not in balance, the system balance signal shows the system is balanced. Thus, no balancing actions will be needed, and it is not desirable for the trading party to take corrective action to resolve their own portfolio imbalance (as it could inadvertently worsen the imbalance situation on the system level) and there is no risk of imbalance penalty.
No	No	Resolve individual imbalance	Trading party must take corrective action to resolve imbalance within their portfolio if they want to avoid a penalty. Otherwise balancing actions will be needed to resolve the system-level imbalance and the cost of such actions will be allocated to the trading party(s) responsible for the imbalance.
Yes	No	Option to take action	Although the trading party's portfolio is in balance, the system balance signal shows the system is not in balance. Therefore, the trading party could purposefully deviate from its nominated flows in an attempt to improve the overall system balance (assuming there is some degree of flexibility in its portfolio). If it turns out that the trading party improved (rather than exacerbated) the imbalance situation, they could be compensated for their assistance.

2. Request to modify trading party's nomination by system operator [F4, F6, F8]

In case day-ahead simulations of the received nominations show issues in the ability to facilitate transports, and in case real-time intervention is needed to maintain pressure levels and the ability to facilitate transports, an available tool for the system operator can be to **request trading parties to modify their nominations**. This can be done in three ways:

1) Offering interruptible transport capacity. When this capacity is booked by a trading party, the system operator withholds the right to no longer allow transports at a certain time.
2) Offering interruptible connection capacity. Similar to Capacity Limiting Contracts in the electricity network, this allows system operators to restrict part of a connected party's connection capacity at any given time, with an agreed limit to the number of hours that are restricted within a certain time period (year, month, etc.). This offers a solution to frequent imbalance situations at a certain point in the network but may be difficult to find offtakers flexible enough to agree to such a contract.
3) Countertrading (redispatch): DSO instructs trading parties to create balanced modifications to their nominations that mitigate transport capacity limitation (and subsequently submit a re-nomination)

In Archetypes 1-3, or in cases where the availability of storage and flexibility providers is still limited, these flexible contract structures could be a necessary condition to connect parties or to assign transport capacity to them. A large benefit in early stages of using this tool to prevent deployment of flexibility services or physical intervention, is that it can be seen as 'in-kind' payment for balancing, in volume of hydrogen as opposed to a monetary payment for balancing. In the absence of a wholesale market, pricing hydrogen is difficult and uncertain. Disputes over costs made and the value of the hydrogen used from flexibility services, can be prevented this way.

3. Market platform for trading between portfolios [F2c, F3, F4b]

As mentioned earlier, an efficient and low-cost balancing system has a large share of the needed modifications in portfolio, interventions and balancing actions happening on-market, to prevent (costly) intervention from the system operator. To facilitate this need illustrated by the Functionalities above, a **market platform** can be constructed for Archetypes 3 and higher. When bilateral trade and agreements are no longer effective due to market size, setting up a platform for trade between trading parties could result in nominations and renominations that lead to less imbalance.

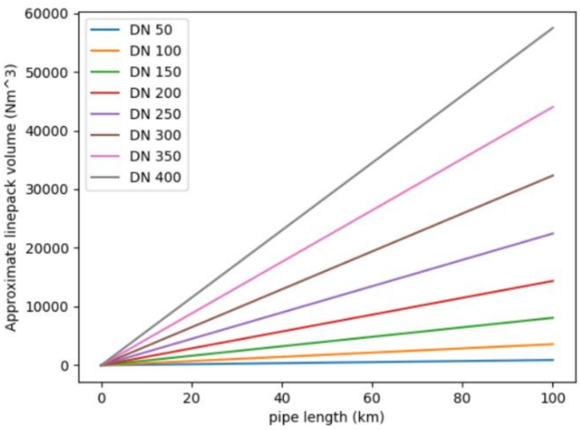
3.2 Technical tools

Hydrogen is a compressible gas whose density changes with variations in pressure or temperature. It means that the gas can be squeezed into a smaller volume by applying pressure. This behaviour can be utilized for balancing mechanisms by using buffering through linepack or tank storage.

1. Balancing network through buffering (linepack) [F6, F8]

Any imbalance between the gas entering and exiting the pipeline will cause the pressure to either increase or decrease. **Linepack** refers to the volume of gas that can be stored or subtracted in a pipeline within its normal operating range. When the network is not operated at full capacity (i.e. not at maximum pressure drop), the pipeline still has room to absorb imbalances within normal operating range, it is called "usable linepack".

Assuming a 16 bar hydrogen grid, the left side of Figure 23 shows the calculation of linepack volume for different network sizes with upper and lower pressure limits of 14 bar(g) and 9 bar(g), respectively (5 bar pressure difference). To estimate the imbalance volume required to increase or decrease the pressure by 1 bar, the calculated linepack volume should be divided by 5 (Figure 24, right side), the difference between the pressure limits. A detailed formula is given in Appendix A.



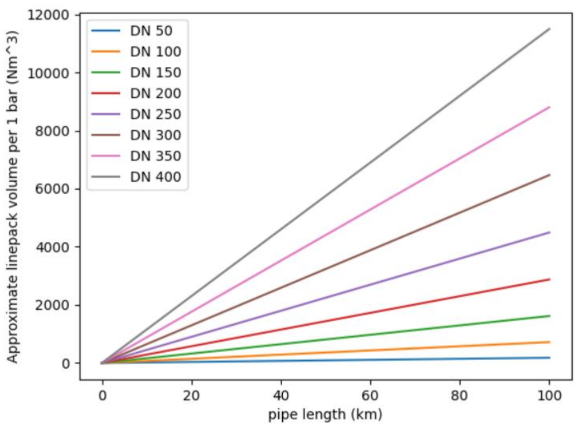


Figure 24: The linepack volume of a network depends on its size (left). The approximate volume imbalance needed to increase or decrease the pressure by 1 bar (right).

DN size (mm)	Length (km)	Pipe volume (m^3)	Linepack volume (Nm^3)	Volume / 1 bar (Nm^3)
100	10	79	359	72
200	10	314	1437	287
300	10	707	3232	646
400	10	1257	5747	1149

The linepack volume can also be expressed as energy by multiplying it by the gross calorific value, or Higher Heating Value (HHV), which is 142 MJ/kg, and by the normal density of hydrogen, which is 0.089 kg/m³.

Example:

Case 1: The DN100 network with a length of 10 km is not operating at full capacity and experiences pressure drops of 2 bar from 14 bar(g) to 12 bar(g). This means the pipeline still has a "usable linepack" of 3 bar before reaching the lower limit of normal operating range. In the event of a sudden failure of a 5 MW PEM electrolyzer producing hydrogen at a flow rate of 1000 Nm³/h, it would take approximately 13 minutes for the pressure at the exit point to decrease from 12 bar(g) to 9 bar(g).

$$\mathrm{t} = \frac{P_{\mathrm{margin}} \times V_{\mathrm{imb}}}{Q_{\mathrm{imb}}} = \frac{3 \times 72}{1000} = 0.22 \text{ hours} = 13 \text{ minutes}$$

During this period, balancing actions are required to restore the pipeline pressure to its initial state. If the imbalance volume is larger or the network is smaller, a faster balancing reaction time than 13 minutes will be required.

Case 2: Another example if we use DN400 network with a length of 10 km with a sudden loss of 1000 Nm^3/h hydrogen injection, the reaction time would be 3,45 hours.

$$\mathrm{t} = \frac{P_{\mathrm{margin}} \times V_{\mathrm{imb}}}{Q_{\mathrm{imb}}} = \frac{3 \times 1149}{1000} = 3.45 \text{ hours} = 207 \text{ minutes}$$

Case 3: However, with a larger diameter (DN400), it is more likely that the systems have a larger feed-in. Now, assuming there is a 50 MW PEM electrolyzer with a flow rate of 10000 Nm³/h that suddenly stops, it would require a reaction time of less than 21 minutes to balance.

$$\mathrm{t} = \frac{P_{\mathrm{margin}} \times V_{\mathrm{imb}}}{Q_{\mathrm{imb}}} = \frac{3 \times 1149}{10000} = 0.35 \text{ hours} = 21 \text{ minutes}$$

Note: these calculations show an upper limit for the calculated linepack and response times. Effects of linepack position, reaction time and contamination are not taken into account.

2. Balancing network through storage [F6, F8]

When linepack volume is too small or unavailable (e.g. pipeline is operated at full capacity), storage can be used as a tool to balance the network and/or extend reaction time for balancing. This helps maintain pipeline pressure within a safe operating range. Several methods and technologies exist for storing hydrogen such as compressed gas tanks, liquid hydrogen tanks, metal hydrides, or stored as other chemical carrier like ammonia or LOHC.

Storage can be classified into three functional categories:

1) Storage located at the connected party to increase the flexibility of supply and demand.
2) Storage located at the connected party and offered as a flexibility service to other party.

3) Storage within the distribution network, used by the system operator to create more volume and extend the balancing reaction time (For example, emergency balancing can be performed without relying on the trading party, allowing the DSO to avoid disconnection).

Various types of storage can be used at connected party facilities. Compressed gas tanks are particularly suitable for system balancing because they are simple, well-developed, and capable of handling intermittent hydrogen charging and discharging. However, when operated at pressures higher than the operating network pressure, this type of storage requires a compressor and significant physical space, which can be a limiting factor.

The primary reason for implementing storage within the distribution network for system balancing is to address situations where market mechanisms cannot resolve imbalances within the required reaction time, which would otherwise force the disconnection of connected parties.

The storage size needed can be calculated using the following steps:

1. **Calculate the required volume** by multiplying the imbalance flow rate by the duration of the imbalance.

$$V_{\mathrm{req}} = Q_{\mathrm{imb}} \times t \qquad (\mathrm{Nm}^3)$$

2. **Account for operating flexibility around the mid-level**. A common planning rule is to assume that only half of the storage capacity is available for either charging or discharging. This means the working volume is twice the required volume:

$$V_{\mathrm{work}} = 2 \times V_{\mathrm{req}} \qquad (\mathrm{Nm}^3)$$

3. **Determine the pressure vessel volume**. The working volume is then converted into the actual tank volume based on the operating pressure range, i.e., between the minimum pressure and the maximum pressure.

$$V_{\mathrm{tank}} = V_{\mathrm{work}} \frac{P_N}{\left[\frac{P_{\max}}{Z_{\max}} - \frac{P_{\min}}{Z_{\min}}\right]} \frac{T}{T_N} \qquad (\mathrm{m}^3)$$

Example:

Case 1: If the storage system needed to cover the imbalance of a 5 MW PEM electrolyzer producing 1000 Nm³/h of hydrogen for reaction time of 1 hour (assuming you can't react within 15 minutes based on previous example), the required tank storage volume is:

$$V_{\mathrm{req}} = 1000 \times 1 = 1000\ \mathrm{Nm}^3$$

Applying the mid-level flexibility rule, the working volume becomes:

$$V_{\mathrm{work}} = 2 \times 1000 = 2000\ \mathrm{Nm}^3$$

For a hydrogen storage system with a minimum pressure of 9 bar(g), the corresponding storage tank size are depending on the maximum pressure:

Pressure (barg)	Tank Volume (m³)
16	311
30	103
350	7.6
700	4.5

Case 2: If we need to address the imbalance over an extended period (e.g., 8 hours), this is because the operating time of the PEM electrolyzer is limited by the electricity grid's overcapacity. Consequently, the required storage tank volume increases by a factor of approximately 8.

Pressure (barg)	Tank Volume (m^3)
16	2494
30	826
350	61
700	36

If the imbalance volume becoming large, it means that the bigger storage is needed. If there is not enough space for surface tank storage, underground hydrogen storage can be an option if the network is connected to TSO network.

3. Balancing network through entry/exit flexibility [F7, F8]

Another flexibility option, in addition to system flexibility, comes from connected parties. This imbalance is mainly addressed through portfolio balancing with flexible assets, either on the supply side (e.g., electrolyzers) or the demand side (e.g., dual-fuel installations). More in-depth information is provided in Chapter **Fout! Verwijzingsbron niet gevonden.**.

4. First look at connected parties

In early archetypes, an immature hydrogen market and relatively few sources of flexibility (such as storage) are expected. Therefore, the connected parties (feeders and offtakers) that will be present in regional hydrogen grids could potentially play an important role in providing the flexibility necessary for balancing. This section looks to the likely customer typologies on both the supply and demand sides of future regional hydrogen grids and provides an initial look at the amount of flexibility they are able (and willing) to offer to contribute to balancing.

4.1 Supply-side connected party typologies

Supply-side connected parties could be a promising source of flexibility alongside other sources of flexibility such as storage and linepack. These supplier are able to scale up or scale down the production level of their asset, and in doing so changing the amount of hydrogen they feed into the network. The ability of the trading party to help balance the network depends on if their assets are flexible. Below is a list of ramp rates for several hydrogen production technologies. A ramp rate is the speed at which production can be scaled up or down.

Table 3: Start-up times and ramp rates for different hydrogen production technologies

Type	Cold Start up	Ramp rates
Alkaline electrolyzer [18]	1 hour	±18% / minute
PEM electrolyzer [18]	10 minute	±10% / second
AEM electrloyzer [18]	30 minute	+28% / minute, -10% / seconds
Steam Methane Reforming (SMR)	15 hours	±3% / minute
Biomass gassification [19]	1 day	+3% / minute, - 5% / minute
Ammonia cracking [20]	1 day	±3% / minute
Methanol cracking [21]	20 minutes	±4.9% / minute
Vaporization liquid hydrogen	-	instantaneous

Based on the ramp rates displayed in Table 33, all assets are capable of contributing to supply balancing. No technical limitations are anticipated once the assets are operational. Given their rapid start-up capability, PEM electrolyzers have the most potential to respond on a very short time-scale (seconds to a minute). The other supply technologies would provide flexibility at a slower rate, but larger capacity installations could provide a more significant contribution to balancing.

Another possibility is for a connected party to have storage located next to the asset, as part of the (production) installation. This storage can be used by the connected party to contribute to balancing both from the supply and demand side. Integrating such a storage unit into their installation would provide a feed or demand-side buffer. These buffers could be included in connection agreements to ensure enough flexibility in the system.

4.2 Demand-side connected party typologies

When designing market tools and other penalty (or incentive) regimes to encourage regional hydrogen grid users to contribute positively to balancing, it is important to understand which types of hydrogen offtakers can be expected in hydrogen grids and their willingness and capacity to contribute to balancing. In phase 2 of this research, a more detailed analysis of connected party typologies and their relevant impact on balancing will be carried out by consulting directly with market parties. This section provides a preliminary outlook on the likely connected party types and sizes in future regional hydrogen grids and makes a first assessment of their potential contribution to balancing by offering flexibility in their hydrogen demand profiles.

The analysis is based on data from the HyRegions report [22].[13] It is important to note that the HyRegions research focuses on decentral industrial demand in Cluster 6, and therefore excludes the five main industrial clusters, which are mostly expected to be directly connected to the HNS Transport System. For instance, hydrogen use as feedstock (e.g., fertilizer industry) or in blast furnaces (e.g., in steel production [23]) is not included in the HyRegions analysis, as it is assumed these end-users will be directly connected to the HNS Transport System. However, certain regional networks (e.g., H2avennet in the Port of Amsterdam) will be situated within industrial clusters and therefore the data from HyRegions paints an incomplete picture. Nonetheless, this section offers a first look at potential regional hydrogen grid connected party typologies based on the most-likely regional hydrogen connected parties identified by HyRegions, and this topic will be explored in greater detail during the second research phase.

Expected offtaker demand volumes in regional hydrogen grids

Firstly, it is important to understand the expected hydrogen demand volumes for individual offtakers that will connect to regional hydrogen grids. The results of the HyRegions research suggest the majority of offtakers are expected to consume less than 50 GWh annually. For reference, a fairly constant demand profile (e.g., 8000 full load hours) amounting to 50 GWh per year would yield an hourly demand of approximately 6.25 MW per hour or less for most expected connected parties (equivalent to approximately 2111 Nm^3 per hour and 188 kg per hour). In the H2avennet project, customers up to 30 MW are possible.

Most important sectors in expected regional demand clusters

The HyRegions [22] report identifies eleven concentration areas of potential hydrogen demand to give insight into future regional infrastructure needs. Figure 19shows the connected party typologies that can be expected in each of these concentration areas based on connected parties with the highest expected willingness-to-pay (WTP) and most likelihood of deployment in the 2030-2035 period [22]. The total volume of annual hydrogen demand, as well as the breakdown by sector, is represented for each of the regional concentration areas.

[13] <u>In this report, we look mostly to industrial end-users.</u> This is because previous HyDelta research [31] and the HyRegions report [22] both identify that regional hydrogen demand could be driven by decentral industry use as a (partial) replacement for natural gas as a heating source. It is highly uncertain whether mobility customers would directly connect to regional grids given the high-purity and high-pressure requirements (and potential issues with odorants introducing impurities) and low-volumes (which likely make anything but very short pipeline connections financially unattractive). Instead, refuelling stations could be supplied by tube trailer and thus receive purified and compressed hydrogen from centralized facilities that benefit from economies of scale. Similarly, HyRegions does not consider the built environment in its analysis due to low-cost alternatives (i.e., electrification) (though it could be connected to regional grids in very specific cases).

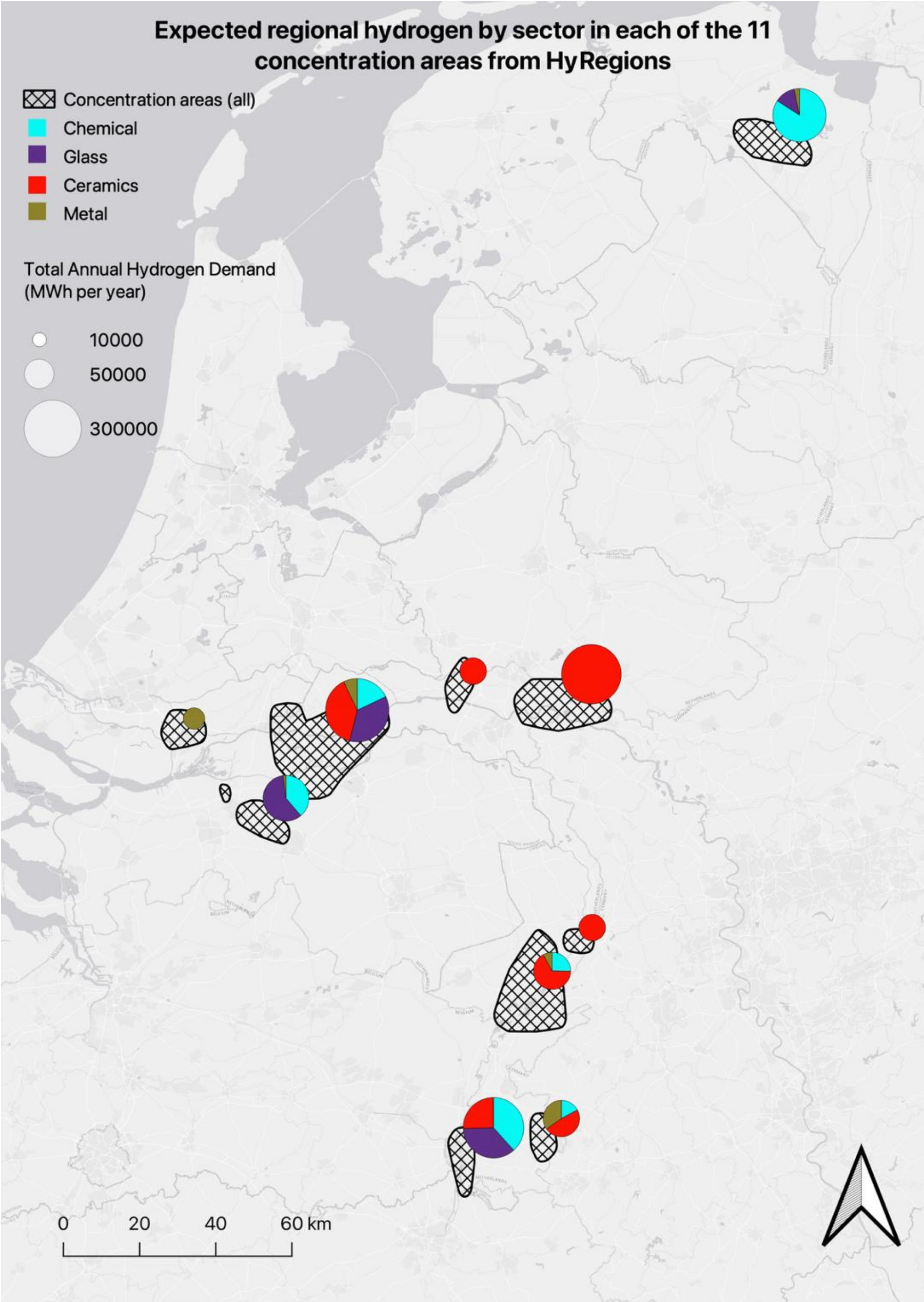


Figure 19: Expected regional hydrogen demand by sector in each of the "concentration areas" identified in the HyRegions report [22]. The data shown represents connected parties with "A Demand," which refers to demand among connected parties with highest willingness-to-pay (WTP) and most likelihood of deployment in 2030-2035 period.

Four important sectors stand out as likely connected party typologies based on the HyRegions analysis: **chemical, glass, ceramics, and metal**. The first three of these sectors have uninterruptible processes that require very-high temperature (VHT) or peak heat (see Box 1 in Appendix D), for which electrification is not expected to be a suitable alternative. These processes typically cannot be interrupted without causing considerable harm and therefore limited flexibility is expected.

Regional metal companies (note: this does not include steel production in Ijmuiden) are also likely to be seen in regional grids and they will similarly require VHT heat for melting and forming (which is not expected to be flexible). However, some amount of electricity and/or hydrogen could be used for low-temperature processes. This suggests that there might be some flexibility if hydrogen heat pumps are utilised, which enable variable inputs of hydrogen and electricity.

Connected parties in the building materials sector (e.g., concrete production) are less likely, but potential connected parties in regional grids according to the HyRegions analysis. Though kiln processes that require HT heat are continuous and uninterruptible, drying processes could provide some degree of flex through scheduling and or load shifting. In the HyRegions analysis, connected parties in the asphalt sector are deemed to be unlikely connected parties in early-stage regional grids due to a low willingness-to-pay. However, some regional hydrogen grids are seeing interest from potential connected parties in the asphalt sector. In this case, industrial processes in this sector requiring only medium temperature (MT) heat might provide some degree of flexibility.

Overall, **limited demand-side flexibility is expected amongst likely hydrogen connected parties** (primarily ceramics, glass, and chemical industries). Due to uninterruptible processes, flexibility cannot be provided by changes in scheduling, volumes, or production output (see Table 664 in Appendix D for different types of industrial demand-side flexibility).

However, a **considerable opportunity for flexibility could be realised if these consumers are able to make use of dual-fuel furnaces that consume variable amounts of hydrogen and natural gas or hydrogen heat pumps which consume variable amounts of hydrogen and electricity.** This sort of fuel flexibility could introduce flexible demand into sectors that are otherwise inflexible. Though continued reliance on fossil alternatives might seem counter-productive, in certain cases such flexibility could improve balancing and security of supply in early-stage regional hydrogen grids until hydrogen supply increases and large-scale hydrogen storage becomes available. Incentivizing such investments in these flexibility measures could be imperative in early grid archetypes where other sources of flexibility are expected to be quite limited and connected parties (offtakers and feeders) will be expected to contribute significantly to balancing the grid.

5. Conclusions and further research

5.1 Conclusions

This report finalizes the first phase of the project and contains an overview of current knowledge on hydrogen grid balancing. Since the first phase has primarily focused on gathering knowledge, defining key concepts, and identifying knowledge gaps, most conclusions relate to areas where further research is required. This has led to the following findings, summarized below.

A comparison to the existing balancing systems shows that **hydrogen balancing will share characteristics of both the electricity and natural gas system**, placing it somewhere between the two. Physically, the hydrogen system resembles more that of natural gas, but in contrast to natural gas early (stand-alone) hydrogen grids with fewer connected parties will contain a higher degree of variability in supply, lower total volume in the system and limited access to central storage. This leads to system balancing likely playing a larger role than the current natural gas system, as well as the control strategy at the valve possibly being flow-controlled instead of pressure-controlled. The intermittency and variability of the electricity system, as well as its congestion issues, offer insights into possible solutions for balancing the hydrogen system: capacity restricting contracts, location-dependent nominations and the availability of containment reserves for balancing.

The definition and detailing of archetypes for hydrogen grids highlights the diversity of future regional hydrogen grid configurations. The functionalities of a future balancing system for regional hydrogen grids, defined for these five archetypes, highlight the **need to quantify timescales and amount of flexibility that is necessary**. The list presented in this report is only an inventory of what the hydrogen system will need, and it is clear that balancing of hydrogen grids will prove to be challenging due to its variability of supply. However, a quantification of that challenge is missing: what are the relevant timescales, how much flexibility should there be in the system and what implications does that have for the functionalities of the system? These aspects can change from situation to situation, but a rough estimate is needed.

Furthermore, the detailing of archetypes is made difficult by the **uncertainty about the endpoint of the system** (for those grids expected to grow towards an HNS Transport System coupling). Besides that, the distribution of roles between DSO and TSO, as well as the operation of the systems as separate balancing zones or as one, are at this time unknown. As these archetypes are still several years away from realisation, a decision is not yet required. However, choices made at this stage may influence the design of balancing systems in earlier archetypes. For example, how to prevent the redundant development of different parallel systems, that need connection in the future? Alignment between TSO and DSO is needed throughout this process towards coupling the systems.

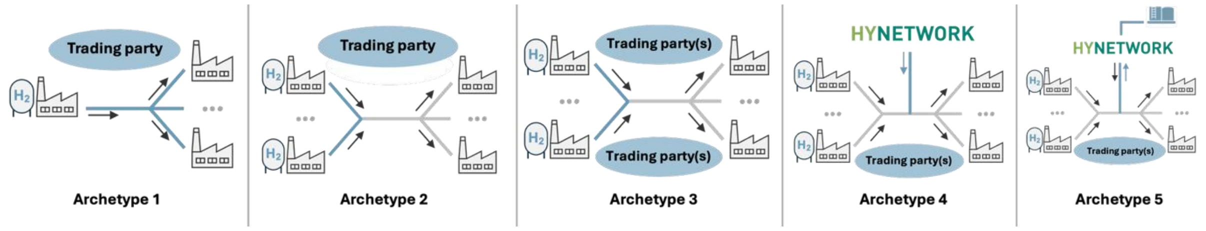


Figure 20. The five archetypes defined to investigate the effects of different grid complexities, size of the system and infrastructure coupling on hydrogen balancing.

Next, an initial exploration of the wide range of market and technical tools available to support balancing reveals a knowledge gap regarding their **availability and practical feasibility**. Interruptible transport capacity booking, interruptible contracts, and measures to encourage supply and demand-side flexibility seem to be necessary in earlier archetypes, as linepack and storage availability will be limited. A delayed delivery or otherwise 'in-kind' balancing will also prevent the need to price the hydrogen used in balancing actions, which will be difficult in absence of a spot market. However, the regulatory viability as well as a quantitative substantiation are missing for most tools.

Additionally, **daily operational strategy considerations** need to be further investigated. Technical measures including real-time network monitoring systems, remote control systems such as flow control valves, and safety valves providing pressure protection were studied. Also, the consideration of flow-controlled versus pressure-controlled valve operation indicates that in earlier archetypes flow-control is likely beneficial to balancing. The pros and cons of daily operational strategies need to be worked out. For instance, is flow valve control by the DSO at the connected party possible, and what are further technical constraints of operating the valve on flow measurements?

Finally, the content of this report has been the result of work from the three research organisations and supported with input from a number of system operators. As such, it still presents a limited point of view. To get a complete outlook towards balancing regional hydrogen grids of the future, a **broader discussion with relevant stakeholders is needed**. Both to build a shared understanding of effective hydrogen balancing and to effectively incorporate all needs and possible contributions related to balancing.

To conclude, the first phase of the project has entailed a preliminary exploration and design of the contours of a future regional hydrogen grid balancing system. The challenge of balancing has been further illustrated, and the work has resulted in a first understanding of *what* the system needs and functionalities are. However, much work is still to be done in detailing *how* those functionalities need to be met, with what tools and their measure of availability. In the next phase, we will further research a number of these key knowledge gaps, which are described below.

5.2 Key knowledge gaps

Most of the conclusions above already highlight the largest knowledge gaps resulting from the first phase of this research. In the next phase, these knowledge gaps will be addressed with further (desk) research while at the same time, we will actively engage with relevant stakeholders to share and discuss the first results. Their perspectives and expertise will be essential in validating our findings, ensuring alignment with market needs, and guiding the development of effective solutions.

Quantification of time scales and needed flexibility

First, a quantification is needed to determine the difficulty of the challenge of balancing regional hydrogen grids. Diving into the timescales of how small the necessary response time is in different archetypes, as well as that of the available tools, will determine how severe the intervention needs to be. This will have implications for the timely design of balancing mechanisms and required investments in technical tools. The underlying research questions are as follows:

- What are the response times for balancing functionalities from the technical and market perspective?
- What is the time scale associated with available tools, in terms of response time and duration of use?
- What customers are able to provide flexibility in their profiles? Is prioritization necessary, depending on likeliness to exacerbate imbalance?

Outlook towards coupling national and regional networks

The evolution of archetypes is detailed, but there is uncertainty about the expected or desired endpoint (Archetypes 4 and 5) in terms of functionalities and role distributions. As some decisions in the earlier archetypes are impacted by the endpoint, it is sensible to align early on the viewpoints of both TSO and DSOs. The following research questions will aid that alignment:

- How do functionalities and role distribution change across the different archetypes?
- Should there be one combined balancing zone in Archetypes 4 and 5 when there is connection with Hynetwork, or separate ones?
- How are roles and responsibilities designated between DSO and TSO in Archetypes 4 and 5?

Availability and feasibility of tools

The needs for balancing are detailed in the functionalities, and several tools have been proposed to meet those balancing needs. However, their feasibility and availability are unknown. Detailing these with quantitative substantiation will show in what measure they can be expected to contribute to balancing, in each archetype. The research questions:

- How should an imbalance penalty and/or incentives to contribute be designed? What types of contracts are needed (e.g. interruptible capacity, balance-supplying vs. balance-receiving trade party)?
- How does the distinction between transport agreements and connection agreements and the fact that they are entered into by different parties (trading party or connected party) influence the possibilities for incentives for solving congestion?
- How should a trading platform for transport capacity be designed? What is needed to ensure a liquid market, both in technical terms and contractual?

Technical operation strategy

Both portfolio balancing and system balancing requires technical operational strategy and tools to support this balancing action.

- What are the minimum technical and infrastructural requirements necessary to enable real-time portfolio and system balancing within DSO-operated gas networks?
- In scenarios of network imbalance, is an incremental shutdown required for the stability of the system? Currently, the connection is directly shut off in emergency situations when the pressure exceeds the allowable limit.

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Appendix A

Detailed matrix of possible role assignment per functionality, per archetype (note: the term *trading party* used in the report encompasses *BRP* and *supplier* roles)

Functionality	Description	ARCHETYPE 1		ARCHETYPE 2		ARCHETYPE 3		ARCHETYPE 4		ARCHETYPE 5	
		Executing	Responsible	Executing	Responsible	Executing	Responsible	Executing	Responsible	Executing	Responsible
F1	**Investment in and maintenance of hydrogen infrastructure**										
a	Provide connection and transport capacity through investments	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Provide hydrogen booster	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	DSO or TSO	DSO or TSO
c	Provide collective storage	n.a.	n.a.	market or DSO	TBD	market or DSO	TBD	market or DSO	TBD	market or DSO	TBD
d	Process requests for connection capacity	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
e	Assign connection capacity to parties	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
F2	**Assignment of transport capacity to connected parties**										
a	Process requests for transport capacity	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Assigning transport capacity (firm or interruptible)	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
c	Trade of transport capacity	n.a.	n.a.	n.a.	n.a.	BRP / DSO	DSO	BRP	DSO/TSO	BRP	DSO/TSO
F3	**Connecting feed-in and offtake – nominations**										
a	Match of feed-in and offtake within programmes	BRP	BRP	BRP	BRP	BRP's	BRP's	BRP's	BRP's	BRP's	BRP's
b	Match of feed-in and offtake with other trading parties	n.a.	n.a.	n.a.	n.a.	BRP's	BRP's	BRP's	BRP's	BRP's	BRP's
c	Internal establishment of expected trade between parties	BRP	BRP	BRP	BRP	BRP's	BRP's	BRP's	BRP's	BRP's	BRP's
d	Nominate – communicate results to system operator	BRP	BRP	BRP	BRP	BRP's	BRP's	BRP's	BRP's	BRP's	BRP's
F4	**Nomination review and approval**										
a	Review of nominations on feed-in and offtake	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Renomination based on review	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP
c	Review of nominations on transport facilitation	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
d	Modification of trading party's nomination and/or impose restrictions	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP
F5	**Measurement and data management**										
a	Measurement of data for portfolio balancing	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Measurement of data for system balancing actions on net integrity	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
c	Measurement of data for allocation and reconciliation	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
d	Aggregation, processing and transparency of data	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
F6	**Maintaining transport capacity real-time**										
a	Monitoring realtime transport capacity and signalling when capacity issues arise	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Changing gas flows to maintain ability to facilitate transports	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP
F7	**Real-time portfolio balancing**										
a	Monitoring and reacting to near-real-time imbalance signal to avoid imbalance	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP
b	Deliberate deviation from nominations to improve total system imbalance	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP	BRP
F8	**Maintaining system integrity real-time**										
a	Deployment of flexibility services to maintain system integrity	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Gradual and incremental intervention	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
c	Physical intervention based on projected system integrity loss	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
F9	**Delivery – sales and purchases**										
a	Effectuation of trade transactions (feed-in and offtake)	Supplier	Supplier	Supplier	Supplier	Supplier	Supplier	Supplier	Supplier	Supplier	Supplier
F10	**Allocation and reconciliation**										
a	Allocation of imbalance	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
b	Aggregation of allocation data: transactions of transported hydrogen	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
c	Correction: correction process of measurement errors or missing data	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO	DSO
F11	**Flexibility services**										
a	Contracting of flexibility services	n.a.	n.a.	DSO	DSO	DSO	DSO	DSO or TSO	DSO	DSO or TSO	DSO
b	Balancing action carried out by Flexibility Service Provider	n.a.	n.a.	FSP	DSO	FSP	DSO	FSP	DSO	FSP	DSO/TSO

Appendix B

Linepack calculation

Analytical linepack volume can be calculated using equation (eq. 1) below:

$$V_{\text{linepack}} = V_{\text{pipe}} \left[\frac{P_{\text{m}}}{Z_{\text{m}}} - \frac{P_{\text{m}'}}{Z_{\text{m}'}}\right] \frac{1}{P_N} \frac{T_N}{T} \quad \text{(eq. 1)}$$

Where,

- linepack volume (Nm^3)
- geometric volume (m^3)
- upper and lower pressure (Pa)
- upper and lower compressibility factor
- pressure (Pa) and temperature (K) at normal condition
- average temperature (K)

Appendix C

Historic developments in the Dutch natural gas industry

Table 44: Relevant historical developments of Dutch natural gas industry.

Before 2004 unbundling (as required by EU gas directive)		Post-2004
Gasunie is owned by DSM (later EBN), Dutch government, and Shell/Exxon/Mobil.	→	Gasunie is restructured to be fully state-owned, with the regulated subsidiary GTS receiving the designation of TSO.
Gasunie participates in gas purchase, transport, and sale of gas.	→	Gasunie's responsibilities are split such that newly created GasTerra takes over trading of domestically produced gas and sells to private parties, and Gasunie (now government owned) is responsible for transmission [24].
Local municipal gas companies responsible for distribution to small-scale consumers.	→	Regulated (and government-owned) DSOs responsible for distribution.
Gas trading arranged between few private and public actors via bilateral contracts [25].	→	Private actors join incumbents on the gas market to increase competition and lower cost of energy supply. Trading takes place via Title Transfer Facility (TTF), which consists of the anonymous market (spot market and futures market) as well as over the counter (bilateral) trades.
Gas price mostly set by oil price (less liquid) [25].	→	Gas price set by the gas market, which has become a more global and interconnected market due to the role of liquified natural gas (LNG). Access to such a liquid market made it more attractive for private parties to participate in the market (allowing them to "buy low" and "sell high").

Introduction to balancing in the natural gas grid

The principal components of the natural gas balancing regime process are explained below. For a detailed explanation of the GTS market-driven balancing regime, see [9].

Before discussing the main steps outlined above, a few definitions are needed. A **shipper** is a market party responsible for trading gas commodity. Shippers bring supply and demand together by connecting **offtakers** of gas with **feeders** of gas (which can include storage).

Capacity booking is the process by which shippers reserve capacity with the TSO to allow them to transport gas on the network. The TSO is responsible for ensuring that the booked capacity does not exceed the network limits and expanding the network as needed. Booked capacity is a take-or-pay principle, which means that the shipper pays for the capacity regardless of whether they use it. Transport capacity can be firm (which is guaranteed capacity) or interruptible (which is only sold when all firm capacity is sold out and has a certain chance of being interrupted). Capacity can be booked for different time periods: yearly, quarterly, monthly, daily, and within-day and it can also be traded amongst shippers.

Portfolio balancing is the responsibility of shippers and is the commercial process by which they match supply and demand in their portfolios. Shippers have a collection of feeders and offtakers in their portfolios and each day they are responsible for informing the TSO of their planned in-feed and outflow of gas into or out of the network for each hour of the coming gas day. Historically, this has been done by submitting a *programme,* which shows the expected flow and any trades for each hour per portfolio.

The programme must be balanced, which means that the net of in and outflow should always be zero for each hour (unless "damping" is applied, in which case it must be balanced over the course of the entire gas day – see [26]).

Shippers must also submit a *nomination* the day ahead of gas delivery, which has largely replaced programmes and includes much of the same information and some additional information (i.e., planned hourly gas flows at each entry and exit point where the shipper has booked capacity for the coming gas day).[14] Since shippers are also able to trade with one another to balance their portfolios, they must include a nomination of all trades and the counter party of the trade (who is also required to submit a nomination for the same amount at the same time indicating that they have agreed to accept/offer the determined volume of gas – otherwise the TSO will either reject the nomination or apply default rules such as the "lesser rule"). Trades take place either over the counter (OTC) between shippers or via the Title Transfer Facility (TTF), which is the virtual trading point for gas in the Netherlands [27]. The TSO is informed of any gas that is traded via the gas exchanges ICE ENDEX and EEX via a single-sided nomination that is submitted by the exchanges to the TSO.

On the day of gas delivery, the balance of the network is monitored by the TSO in near-real time (5-minute basis). The TSO shares this information with the shippers via the portfolio imbalance signal (POS) and, after all POSs have been added together, the system balance signal (SBS). These signals are purely based on the flows (in kWh) of gas that were expected based on the submitted programmes versus what is being observed from near-real time measurements (i.e., this is not based on pressure). The POS represents each shipper's individual imbalance position compared to their own programme and is shared with them individually. The sum of all individual POSs is used to create the SBS. Shippers must use both their individual POS and the aggregate SBS to gain insight into their current estimated imbalance position, the approximate aggregate imbalance of the network, and make decisions on whether to intentionally deviate from their programmes to avoid imbalance. This is accomplished via a new trade or directing connected parties within their portfolio to adjust their in-feed/offtake (both of which require a renomination to the TSO).

Over the course of each gas hour, if the forecasted SBS has remained outside of the acceptable range for 20-minutes, the TSO will place an order on the ICE ENDEX trading platform for a within-day balancing action (WDBA).

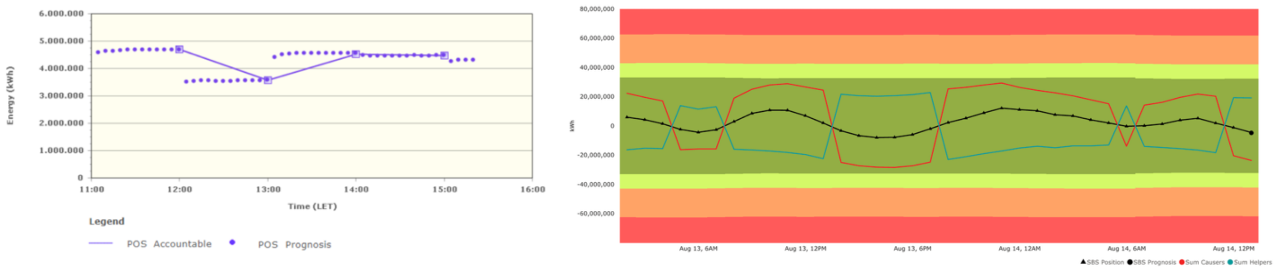

Figure 21: POS (left) of an individual shipper versus the aggregate SBS (right) of the network [32].

System balancing is the responsibility of the system operator and refers to the actions that the system operator takes (or directs others to take) to keep the system within the acceptable limits (i.e., maintaining network integrity). An important caveat is that in the GTS system, these actions do not fall

[14] One key distinction is that programmes were used by the TSO to check to see if damping had been applied correctly [26]. However, damping is not expected to be relevant in most regional hydrogen grids for the foreseeable future.

within the scope of "balancing," since balancing is handled by the market-driven regime (portfolio balancing). However, we include these actions under the name system balancing, as that is the terminology we use for the hydrogen system. These actions include monitoring the system, controlling actions by market participants, and using compressors, flow valves, storage, tapping into linepack, etc. as needed to maintain network integrity. If an emergency action is needed, the TSO can require feeders to change their feed-in and as a last result, require offtakers to adjust their offtake (all in a pre-established order of priority). Emergency actions are incredibly uncommon and portfolio balancing typically handles the bulk of the supply and demand matching.

Allocation refers to the process of assigning the measured volume of gas at a specific network point to the shipper(s) who were active on that point. Allocation happens both in near real time and at other times after the gas day. If a WDBA was ordered to restore the balance of the SBS, the cost of the balancing action is therefore passed along pro-rata to the causers in a roundabout manner by assigning the volume of additional gas that was needed to them.

Measurement of gas flows is the process necessary for accounting the allocation of gas and attributing that to the affiliated parties. This data is then passed on to the shippers who use it to invoice their customers (feeders and offtakers) for the delivered commodity (though this does not directly relate to balancing).

Settlement is a process that is needed when there is a difference between the validated flow measurements and those that were allocated in near-real time. If so, a financial settlement is made.

Appendix D

Hydrogen application in industry by heating needs

It is relatively likely that hydrogen will be used for higher temperature heating demands that lack suitable sustainable alternatives (e.g., electrification). Though these applications are likely applications for hydrogen, they also often offer limited flexibility due to continuous processes (e.g., firing). Heating needs where there are alternatives to hydrogen (typically those <500°C) might be able to offer some degree of flexibility by changing the fuel source (feedstock flex) or through scheduling batch processes (scheduling flex). However, these uses also are least likely to be first connected to regional hydrogen grids if lower-cost solutions are already available. Box 1 provides additional details on the different applications of hydrogen in industry based on the type of heat demand.

Box 1: Application of hydrogen in industry characterized by heating temperature [22].

Low-temperature (LT) heat (<100°C): Likely a low willingness-to-pay (WTP) for hydrogen and therefore less likely to connect to regional grids in early stages due to suitable low-cost alternatives such as electrification via heat pumps.
Mid-temperature (MT) heat (100-250°C): Similar to low-temperature heat, low-cost alternatives are available (e.g., high-temperature heat pumps could be used for industrial processes such as drying), thus hydrogen initially not the most suitable sustainability alternative but could become relevant as hydrogen price becomes more competitive.
High-temperature heat (HT) (250-500°C): Generation of high-pressure steam or thermal oil processes (e.g., distillation) could potentially be electrified without considerable process modifications.
Very high-temperature heat (VHT) (>500°C): Processes that are very difficult to electrify without considerable process modifications (e.g., furnaces in glass and ceramics industry and process furnaces in chemical industry).
Peak heat: Heating processes that have a very variable demand profile, which makes investment in sustainable alternatives difficult due to low operating hours (e.g., peak units for energy supply or certain batch processes in the food industry).

Relevant customer types for regional hydrogen grids by sector

Based on the expected demand from HyRegions, Table 55 outlines certain key sectors that could represent future regional hydrogen grid customer types. They are characterized by the relative importance of security of supply (which is used as a proxy for understanding their willingness to provide flexibility) and their likelihood to be present in regional hydrogen grids. If some degree of flexibility is expected in the relevant processes, the type of flexibility is noted.

Table 5: Inventory of potential hydrogen customer types in regional hydrogen grids adapted from [22].

Customer-type	Notes	Importance of security of supply	Likelihood of demand in regional H_2 grids	Type of flexibility
Building materials (e.g., concrete)	Clinker production and kilns are normally continuous processes, and unscheduled interruption can impose high cost on equipment [28]. Drying processes could provide some degree of flex by scheduling or shifting drying.	Mid	Potential	Scheduling
Chemical	Chemical companies typically require VHT heat (which is very difficult to electrify) and HT heat (for which electric boilers are an option). Security of supply is crucial.	High	Likely	n.a.
Paper	MT heat is needed for drying. Hydrogen could be used in industrial heat pumps (flexible electricity versus hydrogen input) and CHPs. Additional flex available by scheduling batch processes.	Mid	Potential	Feedstock, scheduling

Food sector	Blanching, drying, cooking, and sterilization processes. Steam and LT heat. Many companies have batch processes with HT heat but few operating hours (i.e. flex can be scheduled)	Mid	Potential	Scheduling
Glass	Melting process requires VHT and covers majority of demand. Melting process could be hybridized with some combination of electricity and hydrogen meeting energy needs. Remaining demand is MT heat. Production is very inflexible, as interruption in electricity supply can result in unusable glass and issues with the furnace.	High	Likely	n.a.
Ceramics	VHT heat required for firing (flue gas content is also important which makes it hard to fully electrify without big process changes – though some portion of heat could be provided with electricity). Continuity of firing process is imperative. Drying process requires MT heat.	High	Likely	n.a.
Metal	Regional metal companies (both basic and specialized metals) need VHT heat for melting and forming (limited alternatives so hydrogen is likely alternative). Electrification could compete with hydrogen for LT heat needs.	Mid	Likely	Feedstock (electricity and hydrogen for LT heat)
Greenhouse	Large natural gas demand currently using CHPs. CHPs in greenhouse can operate flexibly based on electricity prices – but this also suggests they can respond to system operator signals for balancing needs.	Mid	Potential (greenhouses have low WTP thus demand is highly uncertain)	Volume

A series of sectors, including food & dairy and paper & carton, are unlikely to be present in early-stage regional grids due to their low WTP and abundance of suitable alternatives. However, these sectors require MT heat for many batch processes that could provide some degree of scheduling flexibility and also feedstock flexibility by changing the energy supply if they do appear in future grids. Similarly, greenhouses could offer flexibility by producing electricity with hydrogen in their combined heat and power units (CHPs) only at moments when it is favourable from a balancing perspective. However, they similarly are expected to have a very low WTP and therefore should only be expected to connect to regional hydrogen grids if hydrogen price decrease significantly.

Types of industrial demand flexibility

In order to understand whether these customers will be able to offer flexibility services to contribute to balancing, it is important to look to the type of application and the type of flexibility that can be provided. Table 66highlights four different types of demand-side flexibility.

Table 66: Types of demand-side flexibility adapted from [29].

Flexibility type	Concept	Examples
Feedstock	Flexible use of different inflow materials (e.g., hydrogen, biomass, natural gas, electricity)	Dual-fuel hydrogen/natural gas boilers, hydrogen/electricity heat pumps, etc.
Volume	Flexible volume of production or throughput	Scale production up or down to meet available capacity needs (more variable than simply on/off) – potentially making use of storage to decouple variations in gas capacity from production outputs
Scheduling	Flexibility in scheduling of production processes	Schedule batch processes in production in to meet flexibility needs
Production	Change in production scheme	Design equipment and production process such that it can be turned on or off upon request