HyDelta 2

WP8 – Analysing digitalization in the network management

D8.1 – State of the art technologies in the current gas grid

D8.2 – Define the gap with the future hydrogen grid

Status: Final

Dit project is medegefinancierd door TKI Nieuw Gas | Topsector Energie uit de PPS-toeslag onder referentienummer TKI2022-HyDelta.

Document summary

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Document history

Version	Date	Author	Affiliation	Summary of main changes
1	31-Oct-2022	Ryvo Octaviano, Huib Blokland	TNO	First draft version
2	14-Nov-2022	Ryvo Octaviano, Huib Blokland	TNO	Second draft
3	01-Dec-2022	Ryvo Octaviano, Huib Blokland	TNO	Final draft
4	08-Dec-2022	Ryvo Octaviano, Huib Blokland	TNO	Final

Dissemination level

PU	Public	X

Document review

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Executive summary

The Dutch government's central goal with the National Climate Agreement is to reduce net greenhouse gas emissions in the Netherlands by 55% by 2030 compared to 1990 levels and 100% by 2050. Hydrogen will carry out a number of critical functions within energy and raw material systems.

The Distribution System Operators (DSO's) in the Netherlands may play an important role delivering (green) hydrogen to the built environment via their existing gas transport network for sustainable heating of homes and business.

Replacing natural gas by hydrogen in the existing DSO infrastructure will give several challenges (next to safety aspects, social acceptance, etc.) on the security of supply of energy to the end-users, related to the physical aspects of the assets in the hydrogen network. We would like to analyse where digital technology can contribute in accelerating the natural gas grid transformation. The scope of the research is limited to 100% hydrogen grids.

As a research methodology to execute work we chose for the following approach:

1. Get insight in the state of the art of digitalization of the current DSO gas grids, by sending a questionnaire and interviewing DSO representatives. The same questionnaire has been sent to TSO Gasunie to get a benchmark.
2. Get insight in the needed digitalization of the future hydrogen grid. This was done by:
    a. Literature study, mainly regarding foreign DSO's.
    b. A workshop with Dutch DSO representatives.
3. Both the literature study and the outcome of the workshop with the DSO's give an indication of the desired situation of digitalization of the (future) hydrogen grid. The concrete topics can be compared with the current situation regarding Modelling, Monitoring and Control. Within in the scope of this research, we will give a qualitatively description on the technology gap, and a (preliminary) prioritization of the gaps.

Main results from the state of the art investigation for three systems are given below.

<u>Modelling</u>

All DSO's use commercial tools for capacity calculation, designing the gas grid and determining risk levels regarding delivery. All capacity simulations are based on worst case scenario's, like maximum demand at -12 or -13 °C. No dynamic hourly demand profiles are used. For risk analysis the N-1 approach (omitting one asset) is used, in most cases for design reasons. The tools are able to work with different gas compositions, but are only used for natural gas at this moment.

For most DSO's the capacity calculation tool is validated based on pressure measurement data at district stations and total flowrates at GOS. The data from measurements in the grid is not yet directly integrated to the capacity simulation tool. Currently the data is used as a manual input of the tool or by manually comparing the value in Excel table.

<u>Monitoring</u>

Pressure is the most common parameter being measured in the network. Mostly, there is no sensor placed in the pipeline, only a limited number of stations are being measured. Need for flow data has been observed and most DSO's are working on that topic. Data from GOS and green gas suppliers is available.

Most of data is manually accessed by the DSO by sending people to onsite location or a manual download from the website. Some station data of some DSO can be retrieved automatically via Remote Terminal Unit (RTU) unit.

The use of smart meter data at small consumers is limited. Individual demand of small consumers is predicted by 'Standaard JaarVerbruik' (SJV) or by contract values for large consumer.

Control

The grid control at DSO's is autonomous on pressure. The pressure setting is changed manually. The grid is robust with respect to capacity. DSO's recognize no huge need for advanced control of the grid capacity in normal operation. More advanced control might be needed in some cases of green gas supply in the grid, e.g. boosters and dynamic pressure management.

Most activities regarding Control are on green gas feed-in. Control is done by closing the valve in case of deviating gas quality. Manual control of the GOS pressure is done by request, to allow green gas feed-in in low demand period.

From the workshop with the DSO's we found the main challenge of operating a hydrogen grid is about balancing the hydrogen grid. There are several factors that contribute to this challenge:

1. Increasing dynamics in supply and demand, like changing user profiles, increasing local supply and local storage and line-pack
2. From a stand-alone gas grid to a multi-connection grid. Observed trends are: connection to other DSO's, connection to Gasunie backbone and connection to E-grid (bi-directional)
3. Get access to real time data, on both Demand and Supply.

The workshop delivered many ideas on **how** to address the main challenges:

1. Monitoring. Real-time data of Supply, Demand and Storage. Measurements in the grid (stations, pipes): Flow, Pressure, Quality and Temperature.
2. Modelling. Real-time capacity models with coupling to externals: E-grid, Gasunie, other DSO's. And tooling for short term transition planning from natural gas to hydrogen.
3. Control. Controlling the priority of suppliers which can feed into the network.

The main results of literature study on mainly foreign DSO's are globally in line with the results from the Dutch state of the art investigation and the main outcomes of the workshop.

Both the literature study and the outcome of the workshop with the DSO's gives an indication of the desired situation of digitalization of the (future) hydrogen grid. Especially, the 'HOW' topics can be compared with the current situation to come to a qualitatively description on the technology gaps.

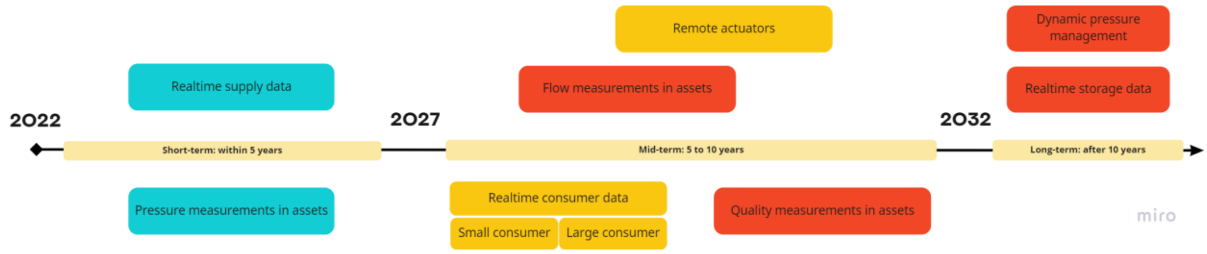
From technology point of view we come to the following summary of the technology gap in digitalization of the hydrogen grid.

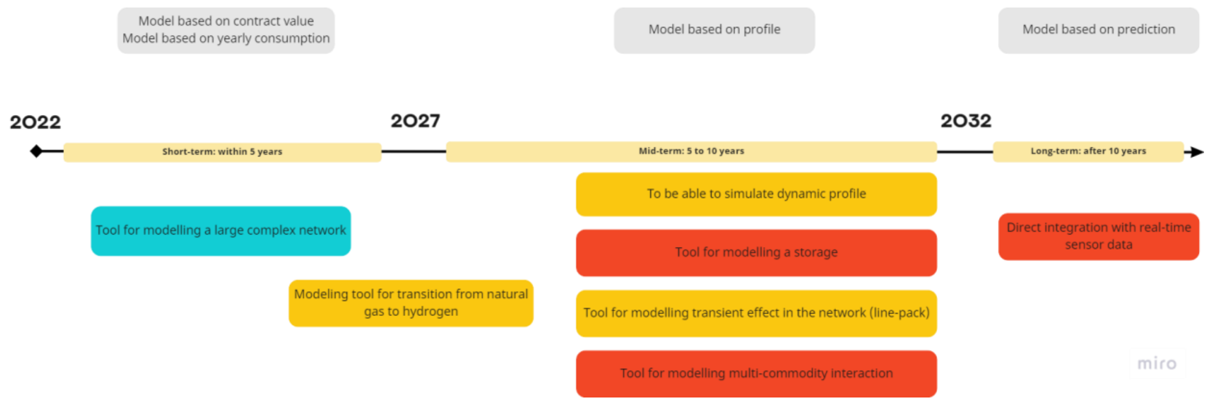
Tech	Topic	Gap
Monitoring	Realtime supply data	
	Realtime consumer data	
	Realtime storage data	
	Flow measurements in assets	
	Pressure measurements in assets	
	Quality measurements in assets	

Modelling	Tool for modelling a large complex network	Blue
	Tool for modelling multi-commodity interaction	Red
	Tool for modelling transient effect in the network for high pressure	Orange
	Tool for modelling storage	Red
	Direct integration with real-time sensor data	Red
	Modeling tool for transition from natural gas to hydrogen	Orange
	Tool to enable simulation of dynamic profiles	Orange
Control	Optimization algorithm for producer priority allocation or network operational strategy	Red
	Actuators that can be controlled remotely	Orange

Red: Not available
Orange: Rarely available
Blue: Available, but should be extended

Combining the technology readiness and timing, results in a preliminary prioritization of the technology gaps for modelling, monitoring and control.





To provide more quantitively information regarding the development of the main technologies for digitalization of the hydrogen grid, in the second part of the current HyDelta2 project we will investigate a selection of the gaps in use cases:

1. Investigation on the number of flow sensors and pressure sensors needed in the grid. Investigate the added value of flow sensors?
2. Investigation on the added value of using demand profiles and intermittent supply profiles for balancing the hydrogen grid using storage by utilizing producer priority and grid pressure regulation.

Samenvatting

Het centrale doel van de Nederlandse overheid met het Nationaal Klimaatakkoord is om de netto uitstoot van broeikasgassen in Nederland in 2030 met 55% te verminderen ten opzichte van 1990 en 100% in 2050. Waterstof zal een aantal kritische functies vervullen binnen energie- en grondstofsystemen.

De Regionale Netbeheerders (RNB's) in Nederland kunnen een belangrijke rol spelen bij het leveren van (groene) waterstof aan de gebouwde omgeving en (kleine) industriële gebruikers via hun bestaande gastransportnet voor duurzame verwarming van woningen en bedrijven.

Het vervangen van aardgas door waterstof in de bestaande RNB-infrastructuur zal verschillende uitdagingen opleveren (naast veiligheidsaspecten, maatschappelijke acceptatie, enz.) op de leveringszekerheid van energie aan de eindgebruikers, gerelateerd aan de fysieke aspecten van het waterstof netwerk. We willen analyseren waar digitale technologie kan bijdragen aan het versnellen van de transformatie van het aardgasnet. De scope van het onderzoek is beperkt tot 100% waterstofnetten.

Als onderzoeksmethode is gekozen voor de volgende aanpak:

1. Inzicht verkrijgen in de stand van zaken op het gebied van digitalisering van de huidige RNB-gasnetten door een vragenlijst te sturen en RNB-vertegenwoordigers te interviewen. Dezelfde vragenlijst is naar Gasunie gestuurd om een benchmark te verkrijgen.
2. Inzicht verkrijgen in de benodigde digitalisering van het toekomstige waterstofnet. Dit is gedaan door:
    a. Literatuurstudie, voornamelijk met betrekking tot buitenlandse RNB's.
    b. Een workshop met Nederlandse RNB vertegenwoordigers.
3. Zowel de literatuurstudie als de uitkomst van de workshop met de RNB's geven inzicht in de gewenste situatie van digitalisering van het (toekomstige) waterstofnet. De concrete onderwerpen kunnen worden vergeleken met de huidige situatie op het gebied van Modelleren, Monitoring en Control. In het kader van dit onderzoek zullen we een kwalitatieve beschrijving geven van de technologiekloof en een (voorlopige) prioritering van de hiaten.

De belangrijkste resultaten van het state-of-the-art onderzoek worden hieronder weergegeven, hierin zijn drie systemen onderscheiden: Modelleren, Monitoren en Control.

<u>Modelleren</u>

Alle RNB's gebruiken commerciële tools voor capaciteitsberekening, het ontwerpen van het gasnet en het bepalen van risiconiveaus met betrekking tot levering. Alle capaciteitssimulaties zijn gebaseerd op 'worst case' scenario's, zoals de maximale vraag bij -12 of -13 °C. Er worden geen dynamische vraagprofielen gebruikt. Voor risicoanalyse wordt de N-1-benadering (weglaten van één asset) gebruikt, in de meeste gevallen om ontwerp redenen. De tools kunnen met verschillende gassamenstellingen werken, maar worden op dit moment alleen voor aardgas gebruikt.

De capaciteit rekentool is gevalideerd op basis van drukmeetgegevens op stations en totaaldebieten bij het GOS. De gegevens van metingen in het net zijn nog niet direct geïntegreerd in de capaciteit simulatietool. Er wordt gebruik gemaakt van handmatige invoer.

<u>Monitoren</u>

Druk is de meest voorkomende parameter die in het netwerk wordt gemeten. Er is geen sensor ín de leiding geplaatst, er wordt slechts in een beperkt aantal stations gemeten. Er is behoefte aan flow data waargenomen en de meeste RNB's werken aan dat onderwerp. Gegevens van de GOS en groengasleveranciers zijn beschikbaar.

De meeste gegevens zijn handmatig toegankelijk voor de RNB door mensen naar de locatie te sturen of door ze handmatig te downloaden van de website. Sommige stationsgegevens van sommige RNB's kunnen automatisch worden opgehaald via de Remote Terminal Unit (RTU)-eenheid.

Het gebruik van de slimme meter bij kleinverbruikers is beperkt. De individuele vraag van verbruikers wordt voorspeld door 'Standaard JaarVerbruik' (SJV) of door contractwaarden voor grootverbruikers.

Control

De netaansturing bij RNB's is autonoom op druk. De drukinstelling wordt handmatig gewijzigd. Het net is robuust qua capaciteit. RNB's hebben geen grote behoefte aan geavanceerde controle van de netcapaciteit bij normaal bedrijf. Bij levering van groen gas in het net is in sommige gevallen een meer geavanceerde sturing nodig, b.v. boosters en dynamisch drukbeheer.

De meeste activiteiten op het gebied van Control vinden plaats op de invoeding van groen gas. Regeling vindt plaats door het sluiten van de klep bij afwijkende gaskwaliteit. Handmatige regeling van de GOS-druk gebeurt op aanvraag, zodat groen gas kan worden ingeleverd in een periode met weinig vraag.

Uit de workshop met de RNB's ontdekten we dat de belangrijkste uitdaging van het bedrijven van een waterstofnet ligt in het balanceren van het net. Er zijn verschillende factoren die bijdragen aan deze uitdaging:

1. Toenemende dynamiek in vraag en aanbod, zoals veranderende gebruikersprofielen, toenemende lokale invoeding, lokale opslag en line-pack.
2. Van een stand-alone gasnet naar een multi-connection gasnet. Waargenomen trends zijn: aansluiting op andere RNB's, aansluiting op de Gasunie backbone en aansluiting op het electriciteitsnet (bidirectioneel).
3. Toegang verkrijgen tot realtime gegevens, zowel aan de vraag- als invoedzijde.

De workshop leverde veel ideeën op voor de concrete aanpak van de belangrijkste uitdagingen:

1. Monitoring. Realtime gegevens over vraag, aanbod en opslag. Metingen in het net (stations, leidingen): Flow, Druk, Kwaliteit en Temperatuur.
2. Modelleren. Realtime capaciteitsmodellen met koppeling naar externen: E-grid, Gasunie, overige RNB's. En tooling voor de korte termijn transitieplanning van aardgas naar waterstof.
3. Control. Het sturen van de prioriteit van lokale invoeders die in het netwerk kunnen voeden.

De belangrijkste resultaten van literatuuronderzoek naar voornamelijk buitenlandse RNB's zijn globaal in lijn met de resultaten van het Nederlandse state-of-the-art onderzoek en de belangrijkste uitkomsten van de workshop.

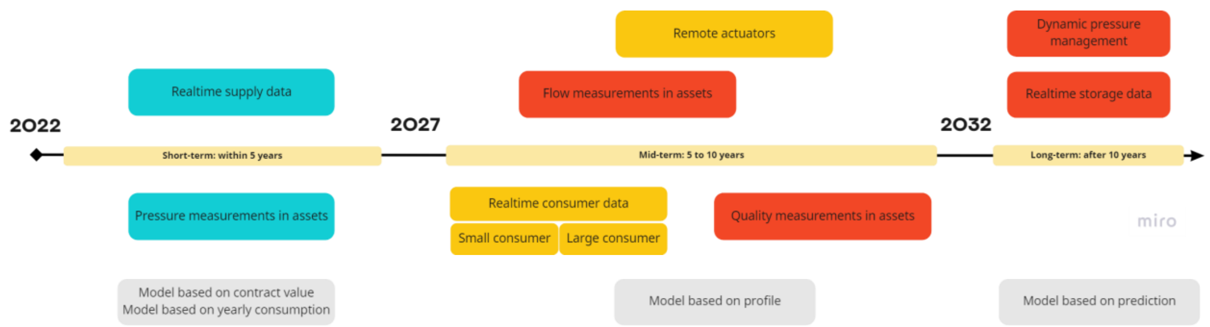
Zowel de literatuurstudie als de uitkomst van de workshop met de RNB's geeft een indicatie van de gewenste situatie van digitalisering van het (toekomstige) waterstofnet. Vooral de 'HOE'-onderwerpen kunnen worden vergeleken met de huidige situatie om tot een kwalitatieve beschrijving van de technologische lacunes te komen.

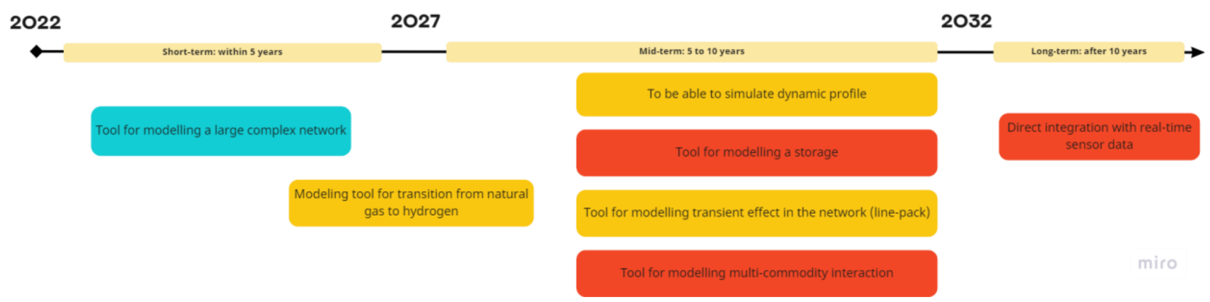
Vanuit technologisch perspectief komen we tot de volgende samenvatting van de technologiekloof in de digitalisering van het waterstofnet.

Tech	Onderwerp	Gap
Monitoring	Realtime invoeder data	[blauw]
	Realtime afname data	[oranje]
	Realtime opslag data	[rood]
	Flow metingen in de assets	[rood]
	Druk metingen in de assets	[blauw]
	Gaskwaliteitsmetingen in de assets	[rood]
Modelling	Tool voor het modelleren van grote en complexe netwerken	[blauw]
	Tool voor het modelleren van interactie met andere netwerken	[rood]
	Tool voor het modelleren van tijdsafhankelijke effecten in het netwerk, voor hoge druk	[oranje]
	Tool voor het modelleren van opslag	[rood]
	Directe integratie van real-time sensor data	[rood]
	Tool voor de korte termijn transitie van aardgas naar waterstof	[oranje]
	Tool om de simulatie van dynamische profielen mogelijk te maken	[oranje]
Control	Optimalisatie algoritme voor prioritering van invoeders en operationele strategiën	[rood]
	Op afstand gestuurde actuatoren	[oranje]

Rood: Niet beschikbaar
Oranje: Nauwelijks beschikbaar
Blauw: Beschikbaar, maar moet worden uitgebreid

De combinatie van technologische gereedheid en timing resulteert in een voorlopige prioritering van de technologische gaps.





In het tweede deel van het HyDelta2-project zullen we een selectie van de gaps in use-cases onderzoeken en meer kwantitatieve informatie verschaffen over de ontwikkeling van de belangrijkste technologieën voor de digitalisering van het waterstofnet. Het betreft de use cases:

1. Onderzoek naar het benodigde aantal flow- en druksensoren in het netwerk. Inclusief een studie naar de meerwaarde van flow sensoren.
2. Onderzoek naar de meerwaarde van het gebruik van vraagprofielen en intermitterende productieprofielen voor het balanceren van het waterstof netwerk. Gebruik makend van opslag, van de mogelijkheid om prioritering aan te brengen in producenten en van netwerk druk regulatie.

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1 Introduction

1.1 Background

Hydrogen will be a key component of the global energy system aiming at net zero greenhouse gas (GHG) emissions by 2050. Besides decarbonized hydrogen produced from natural gas, green hydrogen produced with an electrolyser powered by sustainable electricity has been proposed (among others) for sector coupling (Power-to-Gas) and for large-scale storage of renewable energy.

In the Dutch situation, the starting point is the Climate Agreement [1]. The Climate Agreement is part of the Dutch climate policy. The government's central goal with the National Climate Agreement is to reduce net greenhouse gas emissions in the Netherlands by 55% by 2030 compared to 1990 levels and 100% by 2050. According to this document, Hydrogen will carry out a number of critical functions within energy and raw material systems with focus on:

1. A carbon-free feedstock for the process industry
2. Carbon-free energy carriers for high temperature heat for the process industry
3. Dispatchable carbon-free capacity, energy storage for prolonged periods and energy transport over longer distances.
4. Mobility, especially with regard to passenger transport for greater distances and road transport for e.g. trucks as a focus ahead of 2025
5. Built environment, possibly for buildings and districts that cannot easily be made more sustainable in other ways.

The Distribution System Operators (DSO) in the Netherlands will be responsible for delivering green hydrogen to the built environment and hard to electrify industry via their existing gas transport network for sustainable heating of homes and business.

<u>Hydrogen Transport</u>

Gaseous hydrogen can be transported through pipelines as natural gas is today. For example, there is currently approximately 2600 km operating hydrogen pipelines in the United States (Figure 1), many of which are retrofitted from natural gas [2]. The high initial costs for building a new hydrogen pipeline is becoming a major barrier for expanding hydrogen delivery. Converting existing natural gas pipelines into dedicated hydrogen pipelines could reduce hydrogen transmission costs by 20% to 60% compared to constructing new hydrogen pipelines [3]. With a few adjustments, hydrogen can be injected into existing natural gas pipelines and delivered to a wide range of end-point applications.

Figure 1 United States Gulf Coast active hydrogen pipelines in 2020.

In the Dutch situation, there is a study called HyWay 27 created by The Ministry of Economic Affairs and Climate Policy, together with Gasunie and TenneT [4]. This study concluded that the current natural gas transmission network provides a cost-efficient basis for safe hydrogen transmission and has been transferred to a concrete investment plan.

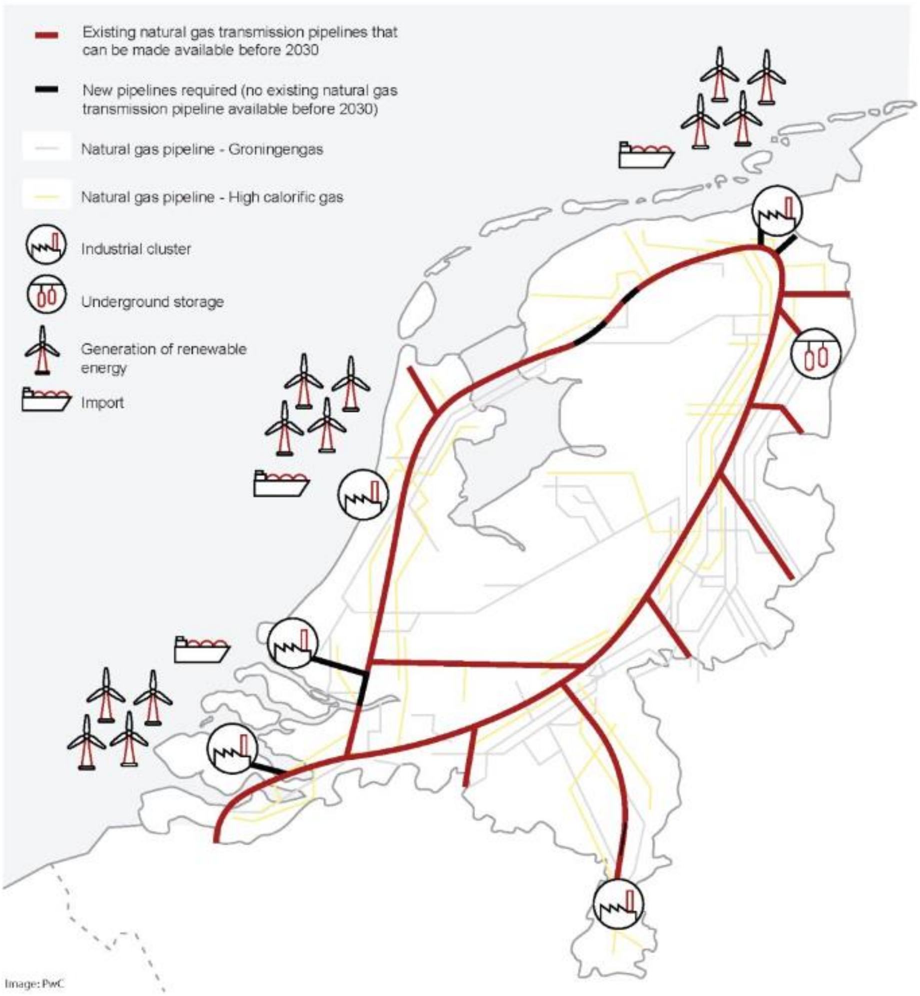

Figure 2 Plan of hydrogen backbone based on HyWay 27 study.

The natural gas volumes will be dropped by around 40% in 2030 compared to today's levels, due to the gas extraction from the Groningen gas field is phased out. Currently, there are multiple parallel pipelines in the Dutch gas backbone. One of these pipelines will be converted into a hydrogen pipeline (Figure 2). The HyWay study and Kiwa report [5] also described that current natural gas pipelines in principle can be used for transporting hydrogen. However, it still requires a few changes to the pipeline especially in these following areas:

- replacement of valves
- thorough pipeline cleaning (depending on the required level of purity)
- replacement or configuration of metering equipment
- new pipeline operation methods, including pressure fluctuation control
- new management and maintenance methods.

Converting natural gas by hydrogen in the existing DSO infrastructure will give several challenges (next to safety aspects, social acceptance, etc.) on the security of supply of energy to the end-users, related to the physical aspects of the hydrogen network. This study gives an investigation where the digital technology can contribute in accelerating the natural gas grid transformation and tackle several challenges mentioned before.

The potential benefit of digitalization of the gas grid will be described in work package 8 within the frame of the HyDelta2 program. This analysis will start with an inventory on the State of the Art as a starting point to define the gap in needed digitalization of the gas grid for a future transition to hydrogen grids. The “Smart Grid” terminology is currently widely used in the transmission and distribution of electricity network. Here, we will present another perspective of a smart grid for another commodity, which is a gas network. (Figure 3)

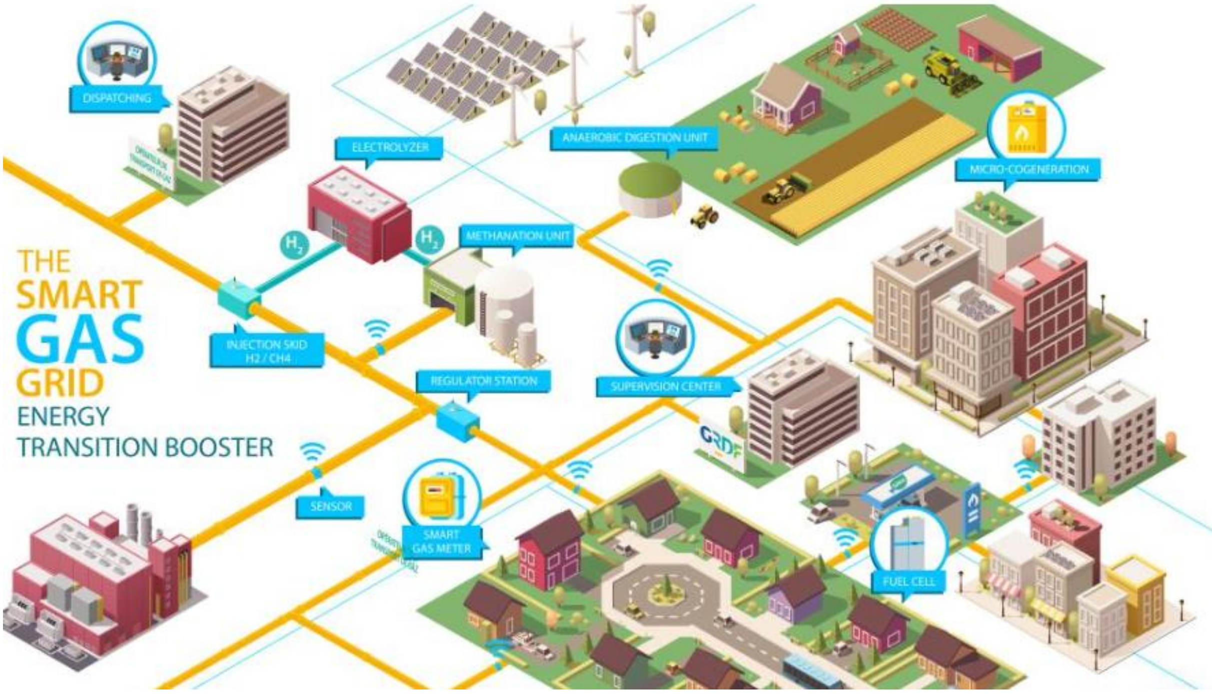

Figure 3 Smart gas grid concept of GRDF [5].

The definition, scope of work, objectives and methodology are first presented in this report. Then, the report is divided into three chapters: Current state of the art of the technology at Dutch DSOs, the future ideal technology for hydrogen grids, and the link between the current state of the art and the ideal required technology (gap analysis). This report will be closed by a summary, prioritizing the gaps and recommendations on how to approach the next steps in quantification of the main gaps.

1.2 Definition

There are many digital terminologies becoming a buzzword in the past years related to technology development. It can be difficult to distinguish what they all mean and the difference between them. The word digitization, digitalization, and digital transformation are used interchangeably. The meaning of each word is different. In this section we will explain the definition of Digitization, Digitalization, Digital Transformation (Figure 4) and including Digital Twin based on these references [6] [7] [8] [9].

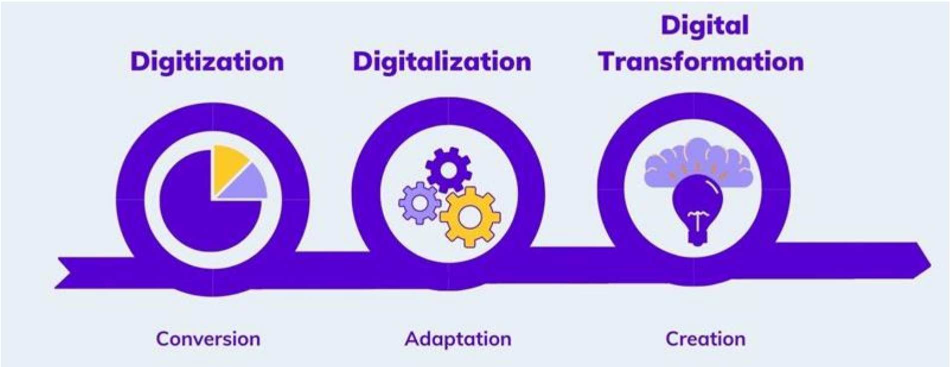

Figure 4 Digitization, digitalization and digital transformation process.

1.2.1 Digitization

Digitization refers to converting physical information / analogue data into a digital format that is accessible through technology. It can be anything from images, videos, audio, or text. For example:

- Creating a digital documentation to replace paper documentation with scanning a letter is a simple example of digitization
- Automating data acquisition from the plant equipment instead of reading by the engineer on site. The digital data point has larger sampling frequency compared to the occasional data recorded by onsite readings.

The digitization can be achieved by replacing analogue instrument with an advanced technologies, such as Internet of Things (IoT), wireless smart sensors, distributed control system (DCS), edge computing, Supervisory Control and Data Acquisition (SCADA), etc.

1.2.2 Digitalization

Digitalization is the next step in a process improvement sequence after digitization. First, we digitize the analogue data into digital data, then we involve data-driven applications, data integration, analytics, and metrics with the purpose of making processes more automated using digital processes.

Digitalization is the act of increasing the level of automation in processes through the use of digital technologies. It is about the improvement of workflows and processes and the application of knowledge and information rather than 'just data'. For example:

- To digitalize the production process, a company can implement a smart supply chain with Artificial Intelligence (AI) driven analytics and a transparent shipment-tracking platform.
- To understand an asset behaviour and using it for optimization, a company can digitally replicate its physical assets with help of a digital twin (see Section 1.2.4)

1.2.3 Digital Transformation

Digital transformation goes beyond digitalization. Digital transformation uses digital technology to change how an organization works from top to bottom. The changes can affect all departments, this includes changing how employees work, how customers are served, and how the company is run.

"We digitize information, so that we may digitalize a process (such as creating a digital twin), so that the organization can undergo digital transformation."

1.2.4 Digital Twin

As defined in section 1.2.2, a Digital Twin can be a product of digitalization. Various organizations and researchers have defined Digital Twin with the following definitions [10]:

- Digital Twin is the digital representation of a physical entity with possible data and models. The term "data" refers to the data from all the processes obtained during the run time and the system's development phase. [11]
- Digital Twin should always be synchronized with its related physical entities. [12]
- It is a simulation model for the working of the related physical entity or process. [13]

A six-layer Digital Twin architecture is proposed by [9], as shown in Figure 5. The architecture includes various physical devices, sensors, and data acquisition systems in the physical domain during the data transfer, processing, collection, computation, and communication in the virtual environment.

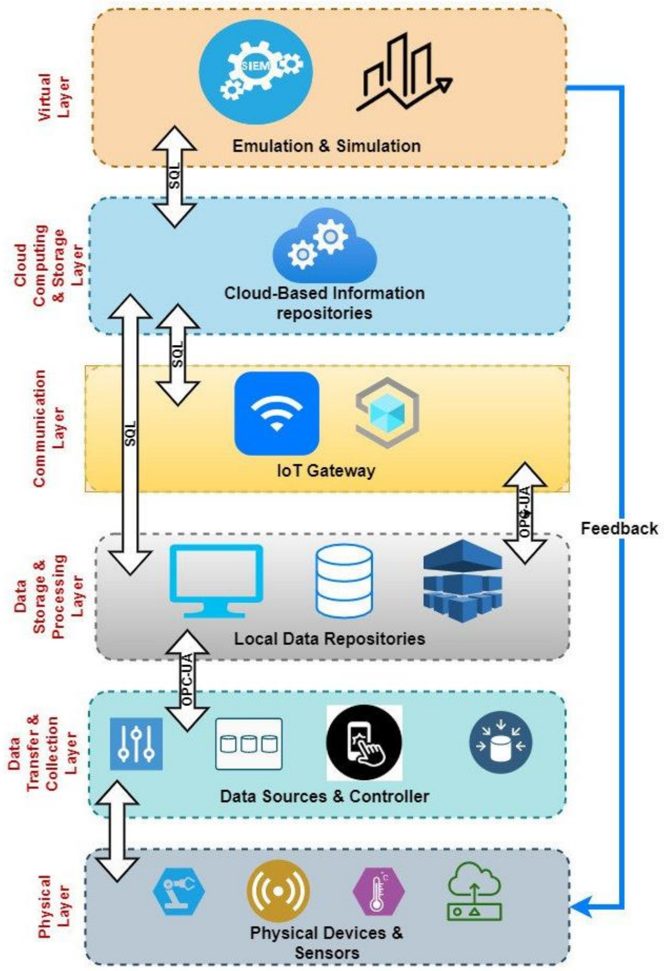

Figure 5. Six-layer architecture of digital twin

In the architecture, Layers 1 and 2 constitute the physical entity or devices. Layer 1 comprises actuators, sensors, and other physical devices, while the data source of the physical entity is specified by Layer 2. Layer 3 contains a local data storage, which acquires the controller values from Layer 2. Layer 4 links Layer 3 with Layer 5 by converting data from Layer 2 into the information sent to Layer 5. Layers 5 and 6 involve repositories of cloud and emulation and simulation tools, respectively. Layer 5 stores the historical information obtained from the previous layer. Layer 5 enhances the availability, ease of access, and precision of the digital twin. Layer 6 is the cognition layer of the architecture, which enables real-time monitoring of the asset condition and status, and contains historical information of the physical twin. This layer facilitates user integration with a virtual replica of the physical twin, which helps in decision-making, optimization, and predictions of the various tasks and processes.

1.3 Scope Definition

The definition of various digital words has been presented in the previous section. In this section the definitions are applied on a gas network. The scope of this work package is about digitalization of 100% hydrogen grids.

Also the definition regarding digitalization from Dutch DSO have been gathered. For example, Stedin defines the digitalization of the gas grid as the transformation of huge amounts of data in useful information about the gas grid. The objective is to create insights in the physical behaviour of the gas grid and develop grid modelling models to be used for (short term) safe and secure operational processes and (long term) grid design processes.

Digitalization of the gas grid can be distinguished into three systems:

1. Grid Modelling: using model(s) to calculate the capacity of the grid at any time and at any place.
2. Grid Monitoring: getting data out the gas grid (flow, pressure, and gas quality), from end-users, suppliers, and external databases.
3. Grid Control: control the gas grid balance (by pressure, flow, and gas quality).

These three systems are integrated into a workflow becoming a Digital Twin of a gas grid presented in Figure 6 as a product of digitalization.

The gas grid consists of pipes with different pressure regime (e.g. 100 mbar, 3 bar or 8 bar), gas pressure regulation stations, gas delivery stations, gas booster stations, valves and local gas feeders.

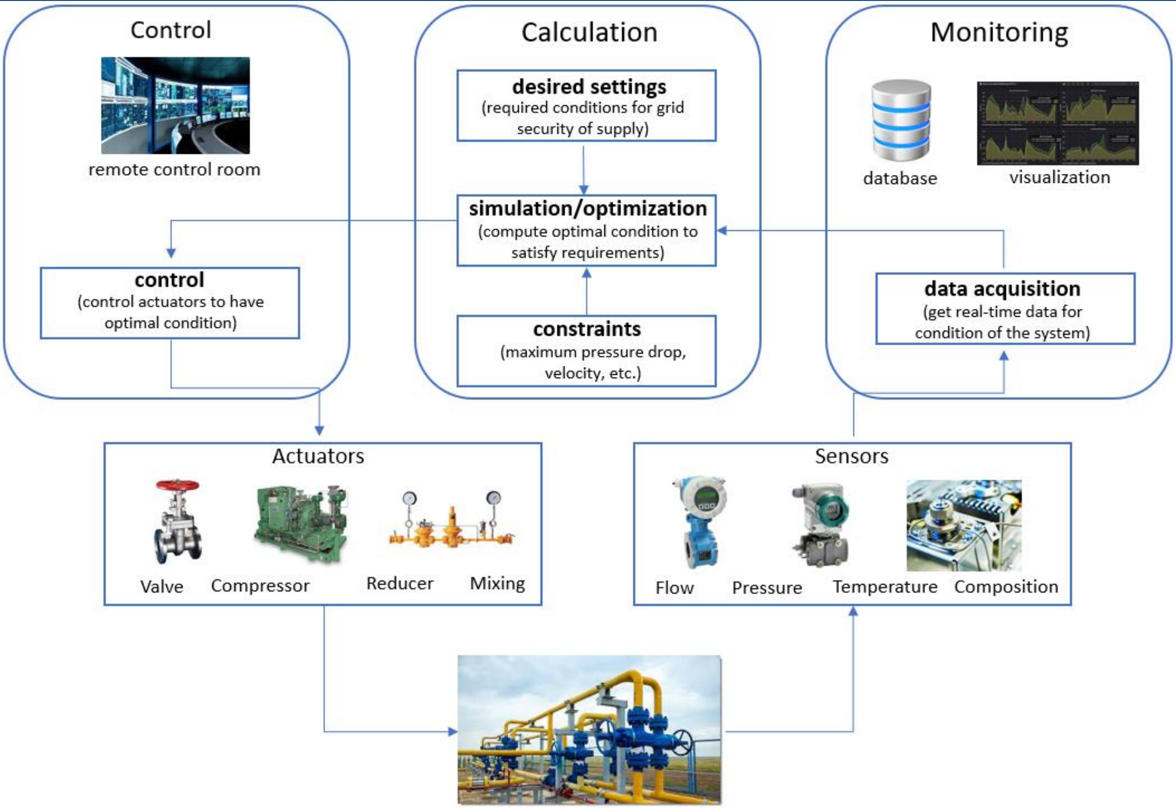

Figure 6 Closed loop gas grid monitoring, simulation and control.

An example of a workflow is balancing the gas grid flow and pressure in the system. First, the flow and pressure data is being collected from various locations (reducer station, consumer, local supplier, etc.). Then, the data is transferred to a central database in real-time. Engineers can monitor all sensor data directly from a control room via a monitoring dashboard. The sensor data also can be used as an input of an application to run simulations and assets optimization using real conditions. Either for balancing the network in giving priority for suppliers to feed-in, or for balancing the network if there is any leakage or maintenance of piping/stations in the system. The optimal setting of control actions, for example valve opening position, is then remotely sent to the actuators. While the system is being controlled, the closed loop feedback from the sensors are compared until the system realizes the desired situation.

1.4 Methodology

As a research methodology to execute work, the following approach is chosen:

1. Get insight in the state of the art of the current DSO gas grids. Interviews of DSO representatives were conducted based on a prepared list of questions. Follow-up questions (or unstructured interviews) were asked with the aim to gather in-depth information
2. Get insight in the needed digitalization of the future hydrogen grid. This was done by:
    a. Literature study. Gain information from scientific papers, research report or latest information from the website.
    b. A workshop with Dutch DSO representatives. The objective is to get common understanding from all participants and direct involvement in formulating general conclusion of the discussion.

3. Both the literature study and the outcome of the workshop with the DSO's has provided an indication of the desired situation of digitalization of the (future) hydrogen grid. The concrete topics from the workshop can be compared with the current situation regarding Modelling, Monitoring and Control. Within in the scope of the current investigation, we will give a qualitatively description on the technology gap, and a (preliminary) prioritization of the gaps.

2 State of the art technologies in the current gas grid

2.1 Approach

In order to understand what is the status of digitalization implemented in the Dutch DSO's, we gather information regarding the state of the art technologies based on three categories: Modelling, Monitoring and Control of the gas grid. This information will be summarized to get general conclusions how the Dutch DSO's are using digital technology for their operational gas network.

Representatives of DSO Liander, Stedin, Enexis and Rendo were interviewed. A questionnaire was also sent to the Transmission System Operator (TSO) Gasunie for benchmarking the current state of the art technologies between TSO and DSO. The list of questions are presented in appendix 7.1.

The results have been composed based on information that we got during the interview. It gives a sufficient base to derive global conclusions regarding the current state of the art of the Dutch DSO gas grid, and to investigate the gap analysis and prioritizing of the gaps regarding the future hydrogen grid.

2.2 Results

In this section, the summary of the current state of the art of technologies at Dutch DSO's is presented. This is completed with a comparison benchmark with similar technologies at Dutch TSO Gasunie.

2.2.1 Modelling

From the grid modelling tool survey, three out of four DSOs are using the same commercial tool called IRENE Pro from KIWA and one company is using Synergi Gas from DNV. This tool is used for capacity calculation for designing gas network. It is also used performing network calculations and determining the level of risk or delivery reliability.

In order to design network capacity, none of the DSOs are using dynamic hourly demand profiles from the customer from measurement data. Their networks are designed using the maximum demand flowrate based on connection capacity at certain winter condition when the ambient temperature is at -12°C or -13°C and then compare the grid pressure to their own pressure criteria.

Most of the tools are also able to calculate risk and reliability analysis of the network. The DSOs are using a similar approach called N-1 analysis. This approach is done by removing an asset like a station or a pipe to see the effect on the grid. If the grid pressure is still within the criteria and not too many customers are impacted. However this analysis is rarely done beforehand to get insight of reliability of the network. In general, they only do the analysis when there maintenance is planned.

The tool can also work with other gas compositions than natural gas, e.g. hydrogen gas modelling. However, at the moment it is not being used for analysis gas network with admixing of gas with a certain hydrogen concentration.

The calculation tool is validated based on pressure measurement data at some stations and also validated based on total flowrate at GOS. When the calculation model and measurement giving different results, then the model inputs and parameters are adjusted.

The data from measurement is not yet directly integrated to the simulation tool, the way currently being handled during analysis is by using it as a manual input of the tool or by manually comparing the value in Excel table.

Some grid operators develop their in-house tool to support additional functionalities that is not covered by current tool. For example, maintenance planning tool, green gas feeder, transition tool from natural gas to hydrogen, etc.

Benchmarking with Gasunie

Gasunie is using in-house tools for network calculation. Since the network is high pressure, a transient solver tool is also being used. They are also using the same approach for demand input data in dimensioning the network capacity. Currently, no dynamic hourly profile input is used. For risk and reliability analysis, Gasunie also use the same N-1 approach. However they also use probability failure functions to evaluate the gas network robustness/reliability. The tool is not only being used for natural gas, but also for admixing gas from low/high calorific gas and also hydrogen gas up to 10% admixing percentage is possible with the tool.

There is also no direct integration from sensor data to the simulation tool. The MCA tool has been validated by DNV and has been used more than 10 years for operational application. The comparison of the results is done also implicitly during operation each year.

There is additional capability of the tool for scenario optimization. Finding maximum transport capacity with the lowest transport cost.

2.2.2 Monitoring

Pressure (most times in combination with temperature) is the most common parameter being measured in the network. Need for flow data has been observed and most DSO's are working on that topic. The number of flow sensors are very limited in general. There is no sensor placed in the pipeline, only a limited number of stations are being measured. However flow data from GOS and green gas supplier is available.

Most of the data is manually accessed by the DSO by sending people to onsite location or a manual download from the website. Some station data of some DSO can be retrieved automatically via Remote Terminal Unit (RTU) unit.

The use of anonymized smart meter data at small consumers is limited (only Liander). Individual demand of small consumers is predicted by 'Standaard JaarVerbruik' (SJV) or by contract values for large consumer.

Benchmarking with Gasunie

Gasunie has more sensors and measurement locations compared to DSO. They measure data almost at all locations: entries, exit (GOS), station (compressor, reducer, mixing) and complex installation. There is also no sensor in the pipeline, but the insight regarding the pipe line (e.g. flow, pressure, wobbe, etc.) is calculated dynamically every 2 minutes. For consumer, only large consumers are being monitored (flow & sometime gas quality).

All data acquisition is done automatically via RTU every 5 minutes or via messages.

2.2.3 Control

The grid control at DSO is autonomous on pressure. The pressure setting is changed manually (there is no remote control). The grid is robust with respect to capacity; they recognize no huge need for advanced control of the grid capacity in normal operation. More advanced control might be needed in some cases of green gas supply in the grid, e.g. boosters and dynamic pressure management.

Most activities regarding Control are on green gas feed-in. Control is done by closing the valve in case of deviating gas quality. Manual control of the GOS pressure is done by request, to allow green gas feed-in in low demand period.

Benchmarking with Gasunie

Gasunie has an active control regulation (pressure, flow, quality) of the network at installations (e.g. compressor, mixing, and reducer stations). The other location is manual control setting. The setpoint control value can be sent remotely from the central control room. The network has already been fully digitized for control purposes.

3 Technologies for future hydrogen grid

In this section we will discuss the technology needed for digitalization of hydrogen in the future. There are two research methodologies applied within this section. The first method is to get input from Dutch DSOs via a workshop and the second method is by conducting a literature survey.

We start collecting ideas without constraints regarding the ideal future conditions for digitalization of hydrogen grid. When the list of digitalization technologies are gathered, then it will be categorized into three segments: modelling, monitoring and control and three phases: before transition, during transition and after transition. Transition here is defined as a process of converting a natural gas grid into a hydrogen grid.

3.1 Workshop results

There are 12 workshop participants in total. 8 people from Dutch DSOs (2 people per DSO), 1 person from Netbeheer Nederland, and 3 people from TNO. During discussion it is difficult to classify the ideas into original categories. Then, it is democratically decided by all participants to have the new working categories below:

a. Balancing and Storage
b. Gas Quality
c. Security and Supply
d. Data and Tooling
e. Transition
f. Collaboration
g. Other
h. Priority List

The digitalization ideas then are classified into new category as presented in Figure 7. The raw results of list of digitalization ideas are presented in Table 1.

Figure 7 Digitalization ideas from the workshop participants

Table 1 List of digitalization ideas from workshop participants

Category	Digitalization ideas
Balancing and Storage	• Working with multiple internal/external flexible storage • Centralized / decentralized storage in the grid • Working with profiles: demand, storage, production • Beside capacity also quantity in modelling : buffer, flattening • Support multiple injection points in the model. • Priority order of switching of customer • Insight in line pack • Balancing in real-time supply and demand • Given demand, so which producer is allowed to feed • Smart pressure & flow sensor positioning • RT consumer monitoring and connection with calculation model IRENE • RT balancing vs costly overdesign
Gas Quality	• Quality monitoring at buffers and boosters • Quality measurement in the grid • Monitoring H2 quality at producer • Good distinguish in controlling H2 / CH4
Security of Supply	• Guarantee accepted Security of Supply • Gas station maintenance • Balancing backbone and decentralized gas supply • Demand/Production control • Support remote control of valve and more • Maintenance planning using RT data and simulation tool • Automatic balancing pressure control at station
Data and Tooling	• Open database (with security margin) of information of the net (demand, supply, storage) • Support open data (temperature, wind, solar) • Use AI self-learning • Support compare design vs real-time • Display real-time measurement (pressure, Temp, Flow, Quality, smell) • RT insight consumer and producer • Distributed net, how do you control demand/supply of the net • Control of producer (not with pressure) but digital “the right” to feed in • All loads online : consumer data, producer data • Actual flow-model MPC • Flow monitoring on DS and OS station • RT stations flow meter • We can RT see what is flowing in the grid thus we are in control and can do root cause analysis • RT insight in demand / capacity trends • Support alarm & threshold • Insight status current network • Better demand forecast for grid planning to reduce CAPEX • Monitoring pressure at essential location in H2 grid • Support VR glass

	• "Beheerkaart bedrijfsvoering…?"
Transition	• Support segmentation to enable transition from CH4 to H2 • Model for transition planning • Tooling for construction CH4 / H2 • Support multiple alternative computational models • How to deal with uncertainty : less gas demand, production • Get the user profiles Small and Large consumer • Together get insight in demand development • Fast simulation tool • Coupling with scenario development
Collaboration	• Monitoring of the gras grid cross-border of DSO • Model integration with E-infra for P2G application • Support coupling with E-net, green gas, heat grid • Modelling including Gasunie • Read the flow of all H2 supply including the H2 backbone • Support control electrolyser for variable production • Monitoring / alignment with electrolyser and e-grid • What is the interaction between e-net and g-net • H2 net compensate the fast dynamic of the e-net
Other	• What is the leading role of DSO? • Allow for future extension of sensors, equipment in the grid and the model • Modular (smart station) sensing and control, communication, bidirectional • Trends and development 'bestemmingsplannen'

At the end of the workshop all participants are asked for their highest priority in digitalization of the future hydrogen grid, resulting in the following topics:

- Insight into the consumer profile, use of smart meter data.
- Learn how to balance the network (Gasunie), including gas storage on short/long term.
- Collaboration between DSOs, including TSO. Interaction between the grids.
- Learn from digitalization of the electricity network
- Deal with dynamics in the grid , e.g. overcapacity and use of line pack.

Two approaches have been taken to generate general conclusions from the workshop: 1) visualizing in a word cloud and 2) inductive research reasoning.

Word clouds or tag clouds are graphical representations of word frequency that give greater prominence to words that appear more frequently in a source text. The larger the word in the visual the more common the word was in the document.

The word cloud result of the digitalization ideas from the workshop is shown in the Figure 8. Control, Grid, Support, Monitoring, Demand and Model are the most common words appearing in the digitalization needs.

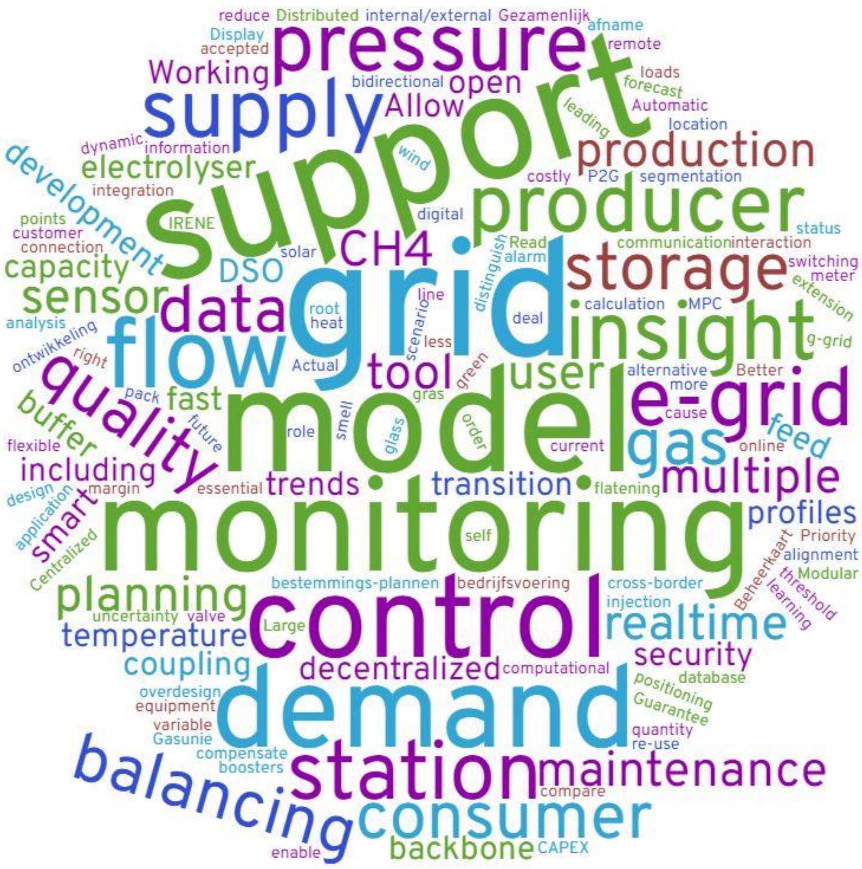

Figure 8 The most common words appear during workshop discussion

The second approach is by using inductive research reasoning. Inductive reasoning is a method of drawing conclusions by going from the specific observation to the general conclusion. It starts from specific observation (in our case is list of digitalization ideas), find the pattern (for example by grouping into What and How, by grouping into similar topic), then create a general conclusion. (Figure 9)

Figure 9 Inductive reasoning process

WHAT

Based on the approach above, we found that the main challenges of operating a hydrogen grid (disregarding the source of hydrogen: green, blue or grey) is about balancing the hydrogen grid. There are several factors that contribute to this challenge:

1. **Increasing dynamics in supply and demand:**
- Changing user profiles
  The hydrogen gas consumption in the future is really dynamic over the year. There are several scenarios of hydrogen demand from industry (feedstock, energetic), electricity & Combined

Heat & Power (CHP), transport, built environment, and export. For built environment, the hydrogen demand is driven by the use for heating.

- Local supply
  In the hydrogen grid, there will be also local supply in the grid at some point, similar to current green gas feeders in then natural gas grid. There are possibly distributed suppliers who produce hydrogen locally via an electrolyzer coupled with wind turbines or solar panels on a small scale. Intermittent hydrogen production also makes the supply profile becoming dynamic (Figure 10). The operational scenario of an electrolyzer will depend on electricity pricing, net congestion, load balancing, etc.

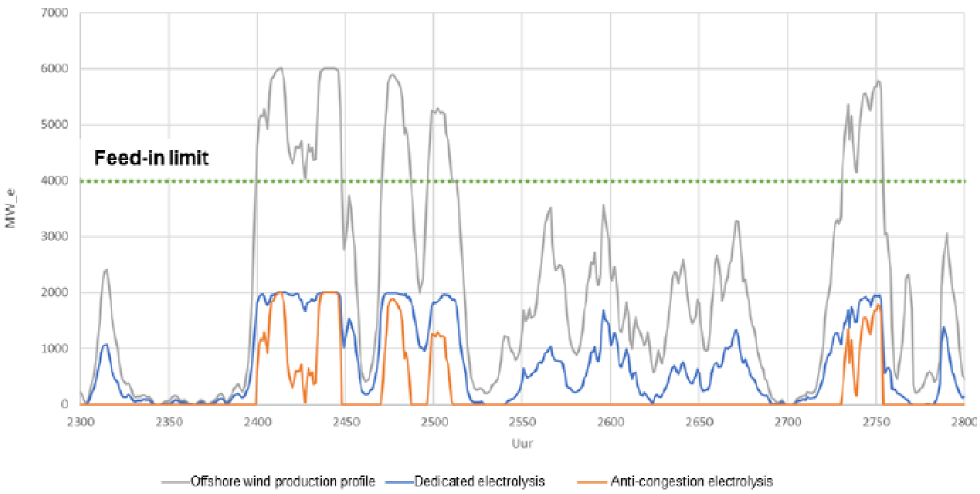

Figure 10 Example of intermittent hydrogen production based on different operating scenarios [13].

- Storage and line-pack
  The intermittent electricity production (wind or solar) for generating hydrogen creates additional reasons to introduce storage facility in the grid. It will store the hydrogen during over-supply periods and use hydrogen from the storage when there is peak demand.

2. From a stand-alone gas grid to a multi-connection grid:

- Connection to other DSO's
  The grid will be interconnected not only receiving hydrogen from GOS, but also possibly receiving gas from neighboring DSO's or exporting gas to another DSO's network.

- Gasunie backbone
  Similar to the current situation, Gasunie will play a role delivering hydrogen from high pressure pipelines to DSO's network. Possibly there are additional entry points in the future. As we see already in the current situation in the natural gas grid, transport of hydrogen from the DSO network to the backbone may be needed.

- Connection to E-grid (bi-directional)
  The electrolyzer creates an additional operational dimension of the hydrogen network. It not only interacts with the hydrogen network, but since it is coupled with the electricity network, the dynamics of the E-grid needs to be included in the calculations, e.g. in the event of a bottleneck in the electricity network

HOW

The workshop delivered many ideas in **how** to address the main challenges. There are several actions to address the problems. They will be qualitative described in detail in the next chapter. The list of actions is categorized as follows, based on the standing out topics of the wordcloud which corresponded well with the earlier defined systems:

1. Monitoring
    - Real-time data of Supply, Demand and Storage
    - Measurements in the grid (stations, pipes): Flow, Pressure, Quality
2. Modelling
    - Real-time capacity models with coupling to externals: E-grid, TSO, other DSO's
    - Tooling for short term transition planning from natural gas to hydrogen
3. Control,
    - Controlling the priority of suppliers which can feed into the network.

3.2 Literature study results

Smart energy, data and digitalisation are playing an important role in enabling gas networks to support the roll out of the green technologies that we need to accelerate progress towards our Net Zero emissions goal. The digitalization is not only taking place in the Netherlands but also abroad. Below, the outcome of a literature study regarding digitalization strategies for smart gas grid networks outside the Netherlands will be presented. The actions are divided into the three subcategories defined earlier: Modelling, Monitoring and Control. The focus will be on digitalization topics for design/operational technology of gas networks (technology for improving customer satisfaction, etc. is out of scope). Also the results presented below focuses only on the list of already implemented technologies and/or the activities that are already mentioned in their action plan. Note, not all the foreign DSO's have plans for each category modelling, monitoring, control in their digitalization plan.

The following DSO's have been investigated:

- GRDF, France
- Cadent, UK
- Scotia Gas Network, UK

3.2.1 GRDF France

Smart Grid definition of GRDF: A smart Gas Grid is a digitized gas network supporting new features by integrating innovative, low cost and smart sensors based on nanotechnologies. It is also an innovative way of collecting data and processing it (data analytics, Artificial Intelligence). These solutions allow a more dynamic monitoring of the distribution network, including local balancing. [5]

Figure 11 Smart gas grid vision of GRDF.

There are several plan for digitalisation within GRDF. The list below summarizes what they are currently working on for smart grid development.

Monitoring

- In order to monitor gas consumption of each consumer more reliable, a Smart Gas Meter is deployed large scale. GRDF is aiming to install around 11 million smart meters. 6 million meters have been installed by 2020 with a 150.000 meters/month installation rate. The main objective is to realize monthly billing based on actual use. According to GRDF's definition, the smart meter consists of flow and pressure measurement device and communication module that transfer consumer data via radio frequency of 169 MHz to data concentrator. The meter can keep 3 days of hourly data in its memory. [15]
- Remote sensing helps improving flow reconstruction by combining data from the various meters and sensors at key points in the network. Added benefits include improved response in emergency situations, optimized investments and optimized stocks.

Control

- The reverse flow unit is a facility that allows gas transfer from the distribution system to the transmission system using gas compression. When there is a surplus injection at distribution grid, it can supply neighbouring regions via a higher pressure level gas pipe.
- Adjusting pressure setpoints at a transmission/distribution interface point allows transmission network operators to finely adapt the volume of conventional gas delivered to the distribution network, complementing local gas injection delivery.
- Remote control of certain installations – already in place for biomethane injection stations – will help maximize the injection of renewable gases and allow better balancing between supply and demand.

3.2.2 Cadent UK)

The digital ambitions of Cadent are split over two time horizons, within RIIO-2 (RIIO means ‘Revenue = Incentives + Innovation + Outputs’) and after year 2026. RIIO-2 is an investment programme to transform the energy networks and the electricity system operator to deliver emissions-free green energy in GB.

Cadent defines digitalization to optimize their network operations as:

“Delivering Operational Efficiency. Improving our operational performance and driving efficiencies across our network, assets, communities and customer touchpoints. Supporting business decisions by applying insights and predictive analytics to take the next best action.” [16]

The progress will be measured by:

- Increase the data collection through asset and process digitalisation.
- Develop predictive analytics and scenario modelling.
- Enhance Health and Safety using technology and data to support our safety focussed culture.

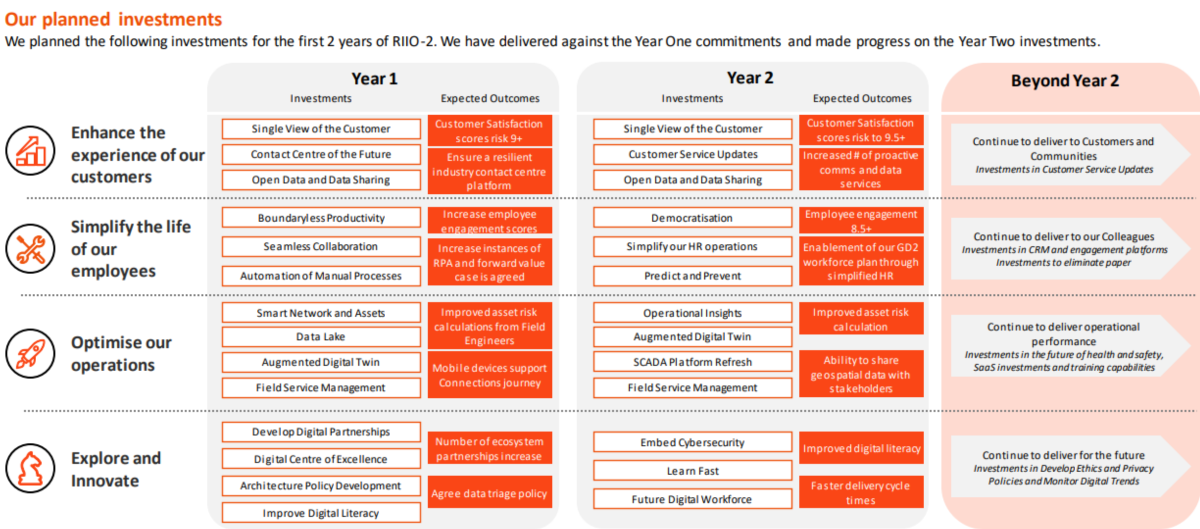

Figure 12 Digitalization investment plan of Cadent within RIIO-2

<u>Modelling</u>

- Digital Twin Network Pressure and Control Management. The creation of a virtual representation to simulate improved network pressure and control using big data. It will enable better planning for potential future connections and network constraints and provide insight to assist optimising of the network.
- Operational Insights: Implementation of an advanced analytics platform to deliver improved operational data and insights through natural language querying (NLQ).

<u>Monitoring</u>

- Smart Network and Assets: Lay the foundations for enhanced visibility, control and management of the Cadent network and assets through the use of smart Internet of Things (IoT) sensors and

empowered edge technologies. Installation of Street Level pressure sensors across selected areas of the network. installation of 600 smart District governor sensors across the network. [17]
- Bringing together scattered data sources to provide insights enabling data driven decisions which are subjective to the degree of risk identified. The objective is reduction in reactive maintenance of asset failures, optimised asset maintenance programmes and reduced frequency of cyclic maintenance intervals, etc.
- Data Warehouse and Data Lake: Create a central, structured and governed store for all of Cadent data, that can drive their ambitions to make their data open. This will provide a basis for data science and advanced analytics.
- SCADA Platform Refresh: Ensure the reliance of the Cadent SCADA platform and ensure it is fit for purpose as we increase the scale and granularity of network monitoring.

<u>Control</u>

- Gas injection smart control by developing capability to optimise pressure management and compressor operation as we see increasing levels of local gas producer connecting to the network, alongside the installation of new compressors to manage flows.

<u>Others</u>

- Streamline processes and transform field operations Field Service Management (FSM). Enable new capabilities such as customer appointment booking and streamlined field data. Allow back office Operational teams to allocate any type of job, to any field operative anywhere, thus optimising how operatives' working time is used.

3.2.3 Scotia Gas Network UK

SGN digital strategy has 4 new digitalization projects emerge around Digital Twins for Green Hydrogen and Gas Distribution Network [18]. An Intelligent Gas Grid project to expand the use of AI and Analytics to predict and prevent safety incidents. The SGN digitalization action map is presented in Figure 13.

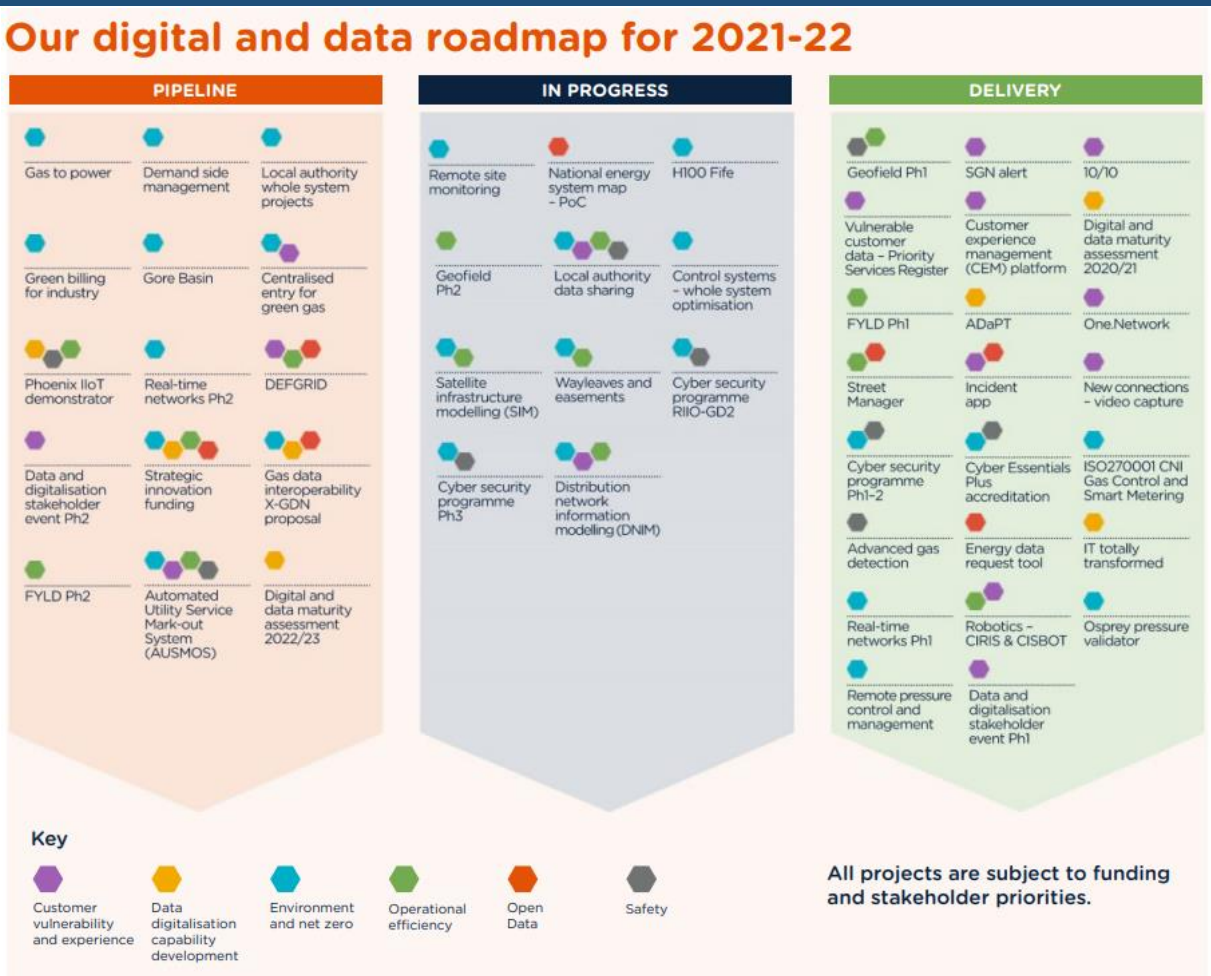

Figure 13 SGN Digitalisation Strategy Action Plan 2022

<u>Monitoring</u>

- SGN has created a public cloud centric design to host their Gas Control systems. This design, validated by NCSC, is now being implement on Amazon Web Services (AWS). This will migrate our Gas Control applications to a highly secure, resilient and scalable platform. This is an essential move for SGN to digitalise some of our more traditional platforms, such as SCADA systems, to be utilised in digitalization through concepts such as Digital Twins.

<u>Modelling</u>

- SGN is in the process of deploying a technology application that provides significantly improved data management capabilities. The selected tools 'Talend' provides technology features such a scanning system to create metadata models, data lineage and data quality flags

<u>Control</u>

- Digital Twins in running the Cadent Distribution Network. In addition, they have also secured SIF funding to develop AI capabilities in predictive safety interventions, and, development of an intelligent gas grid to autonomously and intelligently monitor and control network using data.

3.2.4 Northern Gas Network UK

NGN defines its digitalization strategy as to build a digital platform for NGN that meets the needs of the present without precluding the needs of the future. There are four main pillars in this vision [19]:

- Collect data at source, store it securely and use it wisely.
- Build applications and processes that are easy to use by colleagues, partners and customers.
- Deliver world-leading technology that keeps them at the frontier of efficiency, safety, customer and integrity
- Never lose sight of the fact that it is colleagues who will make this technology work

Data is the essential factor of NGN, thus it needs to be integrated in the bases of Integrated Information Management as shown in Figure 14.

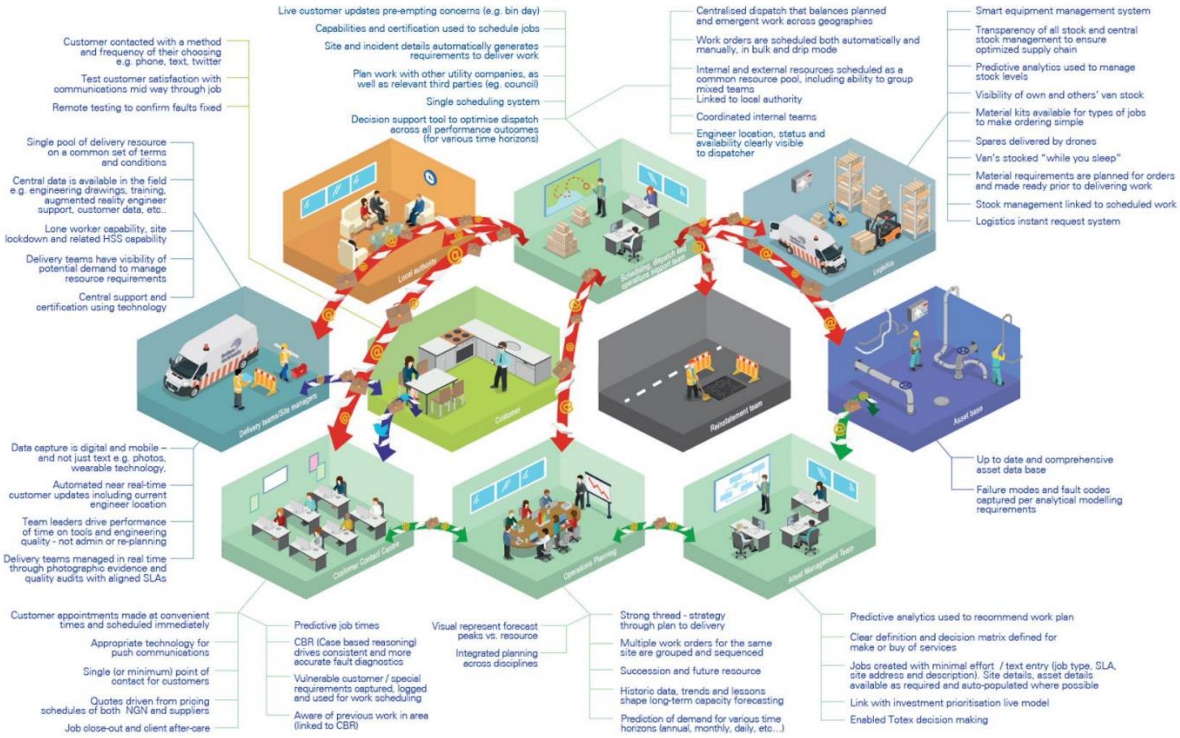

Figure 14 A vision of the NGN Digital Enterprise enabled by integrated information management

Here will be presented the digitalization at NWN focus only on operational of their gas network.

<u>Monitoring</u>

- Internet of Things – Pressure Sensors. By implementing pressure sensors in their assets, then integrated with S4 and SAP Analytics Cloud.
- A new GIS system to monitor the gas network
- Use of SCADA in public cloud

<u>Modelling</u>

- Complimenting Realtime information with AI to make better decisions

3.2.5 Summary

It is observed that foreign DSOs also agree that digitalization is needed to improve the operations of the gas network. Not only for current grids but also for future grids where hydrogen is admixed with natural gas or fully hydrogen gas will be transported.

In the UK currently there is a performance based model RIIO (Revenue = Incentives + Innovation + Outputs) to set price controls to ensure consumers pay a fair price for investment in digitalization. This program accelerates the digitalization program for each DSO. They are focussing on how to make energy networks smarter.

All DSOs are in the process of digitization of sensor data. Some of them just started and some of them already cover the majority of their targets. This involves next to placing a smart device IoT for measuring data, also preparing how they collect the data remotely through IT cloud infrastructure solutions. Getting data from the customer are top priority, not only for understanding the demand profile, but also to be used later for network and operational optimization to reduce energy consumption.

Most of DSOs have been operating their network for several years. Common programs now also invest in a new monitoring system (replacing/upgrading their old SCADA system). Also they invest in other IT technology (e.g. customer support, maintenance planning, education, etc.)

Regarding controlling the network, they are also focussing on building remote control technology for pressure management of the network. Thus being able to balance their network. Also creating a digital twin of the asset for optimizing its operating range or detect when the asset performance deteriorates and allow for predictive maintenance.

One DSO is investing in the collaboration between TSO and DSO by implementing reverse flow installations and data exchange between transmission and distribution service operators.

Currently, it is not seen that foreign DSO's building a tool for short term planning of the transition of natural gas to hydrogen in a specific street or neighbourhood. This could be due to different national strategies. In the UK, there is a plan to have admixing of hydrogen with natural gas in the grid up to 20% from 2023.

4 Technology gap analysis

Both the literature study and the outcome of the workshop with the DSO's give an indication of the desired situation of digitalization of the (future) hydrogen grid. Especially, the 'HOW' topics from the workshop can be compared with the current situation as described in Chapter 2. Based on these inputs, the (qualitative) technology gap analysis is presented in this report.

4.1 Monitoring

In the frame of monitoring, there is a need on real-time data of boundary connections of the grid, i.e. data on Supply, Demand and Storage. Furthermore there should be more measurements in grid assets such as stations and pipes of Flow, Pressure and Quality of the hydrogen gas.

Supply data from the GOS and local green gas supply is available at this moment. In most cases, the data is not real time. The (small) consumer demand data is scaled with the 'Standaard JaarVerbruik'. No real-time data is available, except in rare cases where smart meter data can be used. The technology of getting real time consumer data is already available. But legislation/privacy issues and practical exposing to DSO's hinder at this moment that the data is available for the DSO's on large scale. Storage of gas is not performed at this moment at DSO level, so getting real-time storage data is a completely new field to be developed. Although storage data on Gasunie level is already available [21].

Regarding measurements in the assets (mainly stations), at this moment only a limited number of pressure sensors has been installed. Flow and Quality measurement in the assets are not performed at this moment. Both flow and quality, are performed by the suppliers (GOS and local green gas supply). The data is available to the DSO's, in most cases not real-time.

Comparing the needs for monitoring for the current situation we get the gap analysis as described in the table below.

Table 2 List of technology gaps in terms of Monitoring area

Tech	Topic	Gap
Monitoring	Realtime supply data	
	Realtime consumer data	
	Realtime storage data	
	Flow measurements in assets	
	Pressure measurements in assets	
	Quality measurements in the assets (stations, pipes)	

Red: Not available
Orange: Rarely available
Blue: Available, but should be extended

4.2 Modelling

As presented in the Chapter **Error! Reference source not found.**, all DSO's have a modeling tool that is capable to simulate the gas network for capacity design of the network or for planning maintenance. However, there are additional needs to have a modeling tool that is capable to simulate more complex networks (connected to other DSO or connected to TSO's network) and that also can interact with electricity or thermal heat networks.

For a network which is connected to another DSO's network, the simulation tool that is using a quasi-steady state flow solver might be sufficient to analyze the network. However, when DSO wants to do line pack analysis, then there is a need to have a transient solver to calculate the dynamic pressure effect in system.

Hydrogen will be produced by sustainable electricity such as wind turbines or solar panels. When the gas grid and electricity grid are physically coupled, there is a need of a modeling tool that is capable to run multi-commodity simulations in order to understand the interaction between the gas and electricity network (especially in the case of intermittent electricity production as the source of an electrolyzer generating hydrogen). The modeling tool should be able to prioritize the sources based on the boundary conditions at the gas and electricity grid. For example, when the electricity price is low due to peak production of wind turbine / solar panel an electrolyzer may produce more hydrogen and store it in a surface or subsurface storage.

The current method for dimensioning of the network is not optimal. The modeling tools are only using the maximum connection capacity (worst case scenario) as input demand and extrapolate the flow rate value for a condition when the outside temperature is -12 or -13 C. It would be more beneficial if there is real-time flow data used as an input of the modeling tool, thus the capacity design of the network is more cost optimal, avoiding unnecessary oversizing the network.

Real-time sensor data coupling has benefits for operational or planning maintenance of the network. Thus, the engineer can quantify the effect of actions in the network using a real-time modeling tool.

Converting the grid from natural gas to hydrogen is a lengthy process. There should be an optimal schedule to help the engineer to convert all natural gas grids in their network. Thus a transition planning tool is needed to give recommendations about the neighborhoods that should be converted first and how this should be done, to minimize the risk that customers do not receive gas.

Comparing these needs for modelling with the current situation, the gap analysis described in the table below is obtained.

Table 3 List of technology gaps in terms of Modelling area

Tech	Topic	Gap
Modelling	Tool for modelling a large(complex) network	
	Tool for modelling multi-commodity interaction	
	Tool for modelling transient effects in the network for high pressure	
	Tool for modelling a storage	
	Direct integration with real-time sensor data	
	Modeling tool for transition from natural gas to hydrogen	
	Tool to enable simulation of dynamic profiles	

Red: Not available
Orange: Rarely available
Blue: Available, but should be extended

4.3 Control

The main challenge of operating a future hydrogen grid is how to balance the network. Especially if there are several local producers, storage facilities and different types of consumers (industrial users, domestic users). In order to minimize operational cost and to make sure the grid is stable, dynamic pressure control is needed. Thus, the DSO can prioritize which producer can supply the grid, when to use the storage, etc.

In order to achieve this control strategy, there are several requirements needed:

- Real-time pressure and flow data from all boundary conditions
- Virtual representation of the network via a modeling tool
- Optimization algorithm for source allocation (producer priority) and operational strategy to minimize network cost.
- Actuators that can be controlled remotely (e.g. valve opening)

Comparing these needs for control with the current situation we get the gap analysis as described in the table below, on top of the gaps already mentioned for Monitoring and Modelling.

Table 4 List of technology gaps in terms of Control area

Tech	Topic	Gap
Control	Optimization algorithm for producer priority allocation and network operational strategy	Red
	Actuators that can be controlled remotely	Orange

Red: Not available
Orange: Rarely available
Blue: Available, but should be extended

5 Conclusions and recommendations

5.1 Discussion on the gaps

An overview of the gap between current technology level of the DSO gas grids and future requirements for DSO hydrogen grids is given below.

Table 5 List of technology gaps combined

Tech	Topic	Gap
Monitoring	Realtime supply data	Blue
	Realtime consumer data	Orange
	Realtime storage data	Red
	Flow measurements in assets	Red
	Pressure measurements in assets	Blue
	Quality measurements in assets (stations, pipes)	Red
Modelling	Tool for modelling a large complex network	Blue
	Tool for modelling multi-commodity interaction	Red
	Tool for modelling transient effect in the network for high pressure	Orange
	Tool for modelling a storage	Red
	Direct integration with real-time sensor data	Red
	Modeling tool for transition from natural gas to hydrogen	Orange
	Tool to enable simulation of dynamic profiles	Orange
Control	Optimization algorithm for producer priority allocation or network operational strategy	Red
	Actuators that can be controlled remotely	Orange

Red: Not available
Orange: Rarely available
Blue: Available, but should be extended

From a technology readiness point of view the availability of real-time storage data, flow measurements in the assets and quality measurements in the assets represent the largest gap.

From these topics the gas quality could have the lowest priority; the purity of hydrogen should be better than 98% [19] because the hydrogen in the DSO grid will mainly be used for heating, where the requirements are less strict than e.g. in the case of Fuel Cell applications.

Monitoring of the storage depends strongly on the type of storage. In general, the topic is completely new in the DSO domain. This may have high priority in case of local injection of hydrogen, with a temporarily unbalance in supply and demand.

On flow measurements in the grid assets (mainly District Stations) already activities have been started, as discussed in the state-of-the-art interviews. We foresee that this can be implemented in the short term (2 to 5 years). An interesting research question would be what the added value of flow measurement, relative to pressure measurement is in the grid.

The availability of real-time consumer data is seen as a big need for digitalization of the grid. The technology is ready and should be implemented, as well as access to the smart meter data.

Regarding the technology gaps on modelling, the largest gaps are in the capability of the tool to include multi-commodity interaction (e.g. electricity or heat), modeling of the storage, and direct integration between measurement data with the simulation tool. Ability to simulate a dynamic profile, calculate dynamic pressure using transient solver and tool for planning transition to hydrogen are less larger gaps.

A tool for multi-commodity simulations couples hydrogen sources to electricity sources, such as an electrolyzer, or couples with hydrogen demand for heating. The renewable electricity source usually is intermittent and the demand profile for heating is like a 'bath tub' curve with a peak during winter and low demand during summer time. The simulation tool must have capabilities to realistically simulate these different operational conditions.

Storage is also becoming needed when there is big fluctuation at supply and demand. Thus, in order to balance the network a storage model is also needed in the tool. The storage can be a surface tank or subsurface underground (salt cavern). Both storage methods have different model dynamics and characteristics.

When simulating the future hydrogen network, the design is not stopping at network capacity calculation in a static way. The tool should be capable to run scenario's with an hourly time step to investigate the strategy how to balance the network including how to optimize the storage capacity. Also direct integration of the tool with measurement data (e.g. smart meter from consumer, hydrogen gas production supply) is needed to have an accurate simulation.

Regarding gaps in control technology, there is already technology available that can control the network remotely; like implemented by Gasunie. Then DSO may use similar technology implemented in their networks to have ability to control their network.

Currently pressure grid control is autonomous based on individual assets. When there are multiple hydrogen suppliers, multiple demands and multiple storage-facilities in the grid there might be an optimal algorithm needed to balance the network. Which supplier can feed the grid? When to use storage? These are typical questions that will arise in the future.

5.2 Prioritizing the gaps

Till now we discussed the gaps in digitalization from technology readiness point of view. Another aspect is the timing of technologies that should be developed. We assume three timing levels:

1. Short-term: within five years.
2. Mid-term: five to ten years.
3. Long term: after ten years.

Adding these timing levels will give an indication of the priorities in developing technology for digitalization. The timing priority regarding technology gaps in monitoring and control is presented in Figure 15, while the timing priority for modelling technology gaps is shown in Figure 16.

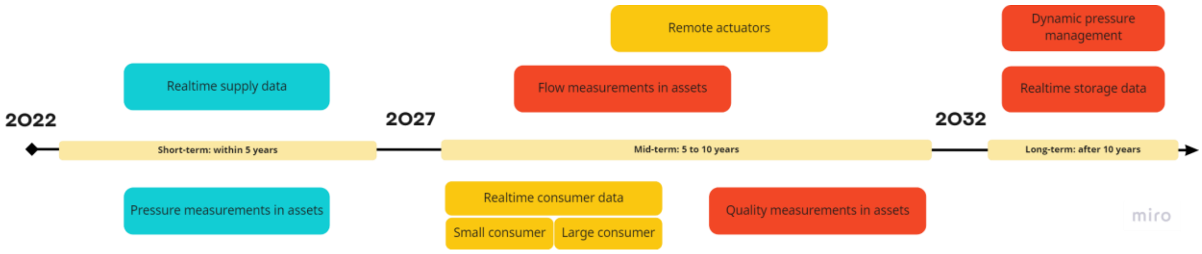

Figure 15 Timing priority of monitoring and control technology gaps

<u>Monitoring</u>

In the short-term, the DSO needs to have more pressure measurement in the assets and real-time supply data. These topics basically have been already started, for example regarding pressure sensors, but the DSO need to increase the number of pressure measurements in the stations and also possible assets, e.g. pipe, booster, etc. Furthermore work should be done in making data retrieval automatic, using remote data acquisition. The supply data from GOS and local feeders are also available, but they still need to change the process from manual gathering to automatic data acquisition.

In the mid-term, real-time flow data measurement from customers is needed for balancing the network to guarantee security of supply. DSO's have already data from large consumer, while for small consumers they are still not able to retrieve smart meter data due to privacy law. Since this issue is related to external parties (government), it could be the implementation is not straight forward. The next action is to implement flow sensor in the assets to get more insight about how the network being utilized. It can be started first on a critical assets (main delivery pipe, station, the most far customer clusters, etc.). In the case of 100% hydrogen pipeline, the quality sensor implementation is the last priority but it is still needed, if there will be several distributed local hydrogen producers or if the hydrogen will be used also for high quality demanding sectors, like mobility in the future.

In the long-term, for balancing the hydrogen network due to intermittent hydrogen production one can use storage tanks. Thus the real-time storage data will be important when DSO's are allowed to have control when to store/produce the hydrogen to/from tank storage to guarantee security of supply in their local network.

<u>Control</u>

Short-term activity from control technology gaps are not foreseen, due to limited monitoring data and modelling tools in this phase.

In the mid-term, DSO's can start to have actuator setpoint to be changed remotely by sending setpoint pressure or flow from their control centre, without sending people going to the field.

In the long-term, when the monitoring data is sufficient and the remote control actuator is available, they can regulate their network by utilizing dynamic pressure management. This control can lead to an improvement in balancing the network and guarantee security of supply.

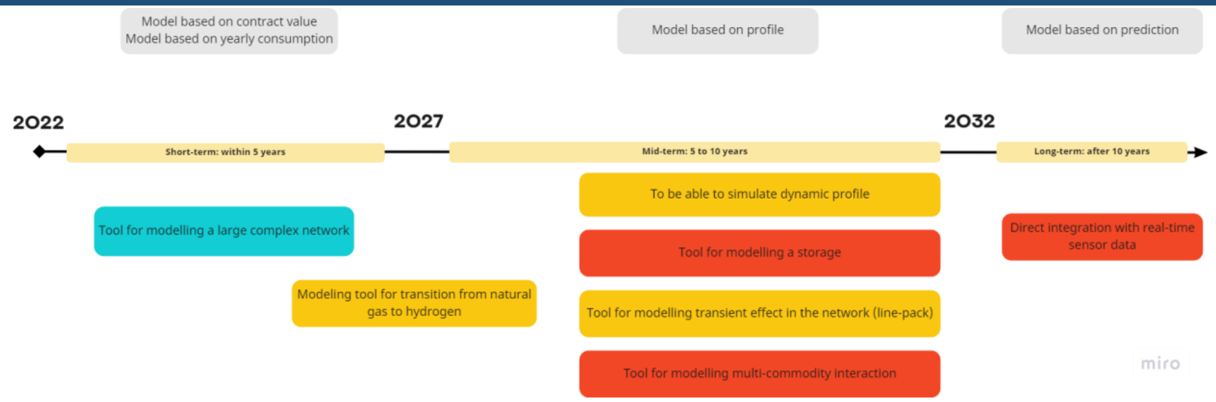

Figure 16 Timing priority of modelling technology gaps

<u>Modelling</u>
In the short-term, the DSO's can improve their current tools to be able to simulate a large complex grid which has more requirements: more suppliers, different gas composition, large network, coupling with other DSO networks. Then DSO's can focus on the development of modelling tools for day-to-day transition from natural gas to hydrogen in a specific region, e.g. transition planning schedule tool.
In the mid-term, when the real-time data is available DSO's should be able to design and operate the network using a tool that can handle dynamic profile data. And due to intermittent production, the tool is also needed to be able to simulate this transient behaviour to calculate the line-pack. In the future the tool that can do modelling of storage and other commodities (electricity and heat) is becoming important when there is a bottleneck and e.g. for peak shaving. For example converting electricity to hydrogen when there is bottleneck in the electricity network and store it in the tank.

For the long-term: assuming the real-time-data and the remote control is available and furthermore the modelling tool has several functionalities, this means that the DSO's can start to integrate the real-time data to the modelling tool for creating the digital twin of the network. That also can be used for automatic dynamic pressure management.

In the second part of the current HyDelta2 project we will investigate a selection of the gaps in use cases. To provide more quantitively information regarding the development of the main technologies for digitalization of the hydrogen grid.

5.3 Recommendations for further investigation

Possible investigations in the frame of balancing the hydrogen grid:

- Investigation on the number of flow sensors and pressure sensors needed in the grid. Investigate the added value of flow sensors?
- Investigation on the added value of using demand profiles and intermittent supply profiles for balancing the hydrogen grid using storage by utilizing producer priority and grid pressure regulation.

Based on maximal two use cases, containing a selection of the components below

- Several local hydrogen suppliers with varying supply profiles (wind parks, solar parks);
- Including storage;
- Realistic domestic demand profiles and industrial profiles;
- Bi-directional connection to a GOS.

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7 Appendix

7.1 Interview question list of state of the art technology

Table 6 Questions of interview distributed to the DSO

No.	Question	Answer
	In this section, we would like to know what is currently available in your company to do network planning and design.	
1	Do you use software for designing your gas network?	
2	If yes, what software do you use for designing the gas network? Vendor name?	
3	Question regarding software functionalities:	
3a	Can you use the software for determining gas network capacity? How do you that?	
3b	Can you use the software for dimensioning gas network? How do you do that?	
3c	Can you use the software for risk analysis? How do you do that?	
3d	Can you use the software for reliability analysis? How do you do that?	
3e	Is the current software supporting modelling the effect of diverging gas quality, biogas feeders and hydrogen?	
3f	Do you have other functionalities from the software? Please explain.	
4	When designing gas network, what is your input regarding demand? (hourly profile, SJV, peak demand, etc.)	
5	If you are using demand profile for each individual user, what data is being used? How is this profile being generated? (weather profile, NEDU profile, etc.)	
6	Are you using the software also for operational application? If yes, can you explain how do you use it? Can you describe your operational tasks using this software?	
7	Is the software integrated with a measurement sensor database? Which measurement data? How is this data coupled to software? What is the frequency of data? What is the data retention policy?	
8	Have you ever validated your software results with measurement in your network? If yes, what parameters (flow, pressure, temperature, composition, etc.) are being compared and what is the percentage error?	
9	Do have plans to use/invest in software tools with respect to the energy transition?	

10	Do you have any other information about software for network design that we are not covering yet?	
	In this section, we would like to know how you currently monitor your network.	
1	Where do you gather data of your network?	
	a. GOS	
	b. Other producers (delivery point)	
	c. Stations	
	d. Demand location (small & large consumers)	
	e. Pipelines	
2	If you get the data at **GOS**, - What parameters do you get? - Frequency of getting the data (hours, minutes, days, etc)? - How do you get the data? - Other relevant info regarding data from GOS	
3	If you get the data at **other delivery points** - What parameters are being measured? - Frequency of getting the data (hours, minutes, days, etc)? - How do you get the data? - Other relevant info regarding data from delivery	
4	If you get the data at a Station, please specify **per type of Station**: - Why do you monitor the Station (e.g. failure tracking, model validation, …)? - What parameters are being measured? - Frequency of getting the data? - How do you get the data? - How many percentage of the stations are being monitored? - Is there a criterium to select the number of stations to claim to have 100% insight in the grid? - Other relevant info regarding data from stations	
5	If you get the data at **Demand locations**, please specify for both large and small consumers: - What parameters are being measured? - Frequency of getting the data? - How do you get the data? - Other relevant info on data from consumers	
6	If you get the data from **Pipeline** locations: - What is the criterium to monitor specific pipelines? - How many percentage of the pipelines is being monitored? - What parameters are being measured? - Frequency of getting the data? - How do you get the data? - Other relevant info on data from pipelines	

7	Do you have any company strategy to place sensors in the network? If yes, can you explain?	
8	Do you have any other relevant information related to network monitoring?	
	In this section, we would like to know how you currently control the network	
1	Do you control your gas network? How do you do that, can you explain?	
2	If yes, what parameters are being controlled? (Capacity and flow, pressure, gas quality, etc.)	
3	What is your control actuator? And where is it located?	
4	Is it manual control on site, or automatic control, or remote control?	
5	Can you control your actuator online?	
6	Do you have any System in your BedrijfsVoeringCentrum, gathering data of DSO assets. E.g. a system for tracking consumption, flow, demand, etc.	
7	If yes, can you provide the vendor name and list of capabilities?	
8	What other IT/OT platform do you use for controlling your network? Can you describe?	
9	Do you have sensor for gas quality monitoring? How do you see the role of DSO's in checking the gas quality: only at delivery points, in the grid, others..?	
10	What is you strategy for controlling gas quality in the network?	
11	Do you have any other information related to network control?	
	General questions	
1	Do you have a pilot project (in past, currently running or planned in future) for digitalization of the gas grid? If yes, why?	
2	Any other info you want to share related to Digitalization of the gas grid?	