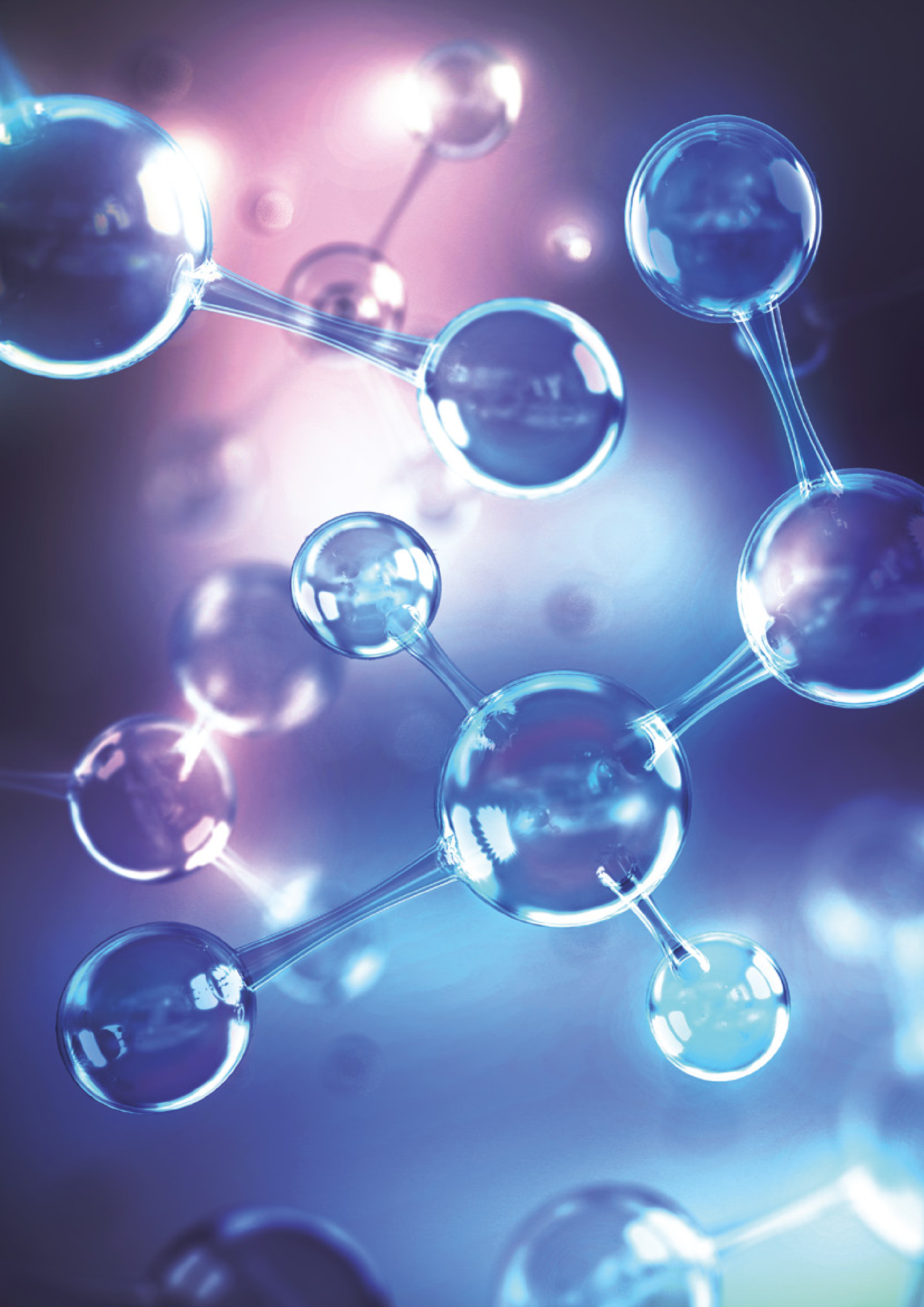
WHITEPAPER

BOOSTING THE ENERGY TRANSITION

THE IMPORTANCE OF RELIABLE ENERGY TRANSPORT IN THE FUTURE

TNO innovation for life

WHITEPAPER
OKTOBER 2019



INTRODUCTION

The energy transition will profoundly change the energy infrastructure. The target is to decarbonize applications and processes currently supplied with fossil fuels: industry, power generation, households, agriculture and mobility. This must be done as quickly as possible, attaining full decarbonization by 2050. The speed of the energy transition depends on public and industrial acceptance of the energy system infrastructure, which are mainly driven by affordability and reliability. Though sometimes perceived as competing goals, experience shows that reliable designs are also the most cost-effective in the long term. To keep costs low in the short term, new, lean infrastructure needs to be developed, or re-purposing existing infrastructure must be enabled.

The energy transition requires more flexibility in the energy system to accommodate the intermittent nature of renewable sources and guarantee security of supply. This is achieved by long-term energy storage enabled by novel energy carriers. Natural gas, as one of the most important fossil energy carriers in our system, will be replaced by renewable gas, such as biogas, synthetic gas and hydrogen. Key molecules such as hydrogen and carbon dioxide are to be handled at scales and operating conditions for which there is no precedent, posing unknowns and challenges to operators and engineering contractors. Luckily, neither these substances alone nor the scales alone are alien to industry. However the application range is now expanding. This is the time to make the most of the knowledge developed for over a century in the production, storage and transport of traditional fuels as well as in the chemical industry.

In this paper, an inventory of points of attention with regards to reliability of energy infrastructure is offered, contributing to the affordability and reliability of the energy system of the future. A basis from which we can boost the energy transition.

BOOSTING THE ENERGY TRANSITION

THE IMPORTANCE OF RELIABLE ENERGY TRANSPORT IN THE FUTURE

The current world energy system is undergoing a profound transformation. The energy transition is a cornerstone to fulfill the societal commitments made in the 2016 Paris Agreements and the Dutch Klimaatakkoord[1]. More than 70% of global greenhouse emissions can be attributed to energetic purposes . These emissions are mostly caused by the combustion of fossil fuels. According to the Klimaatakkoord, greenhouse gas emissions in the Netherlands need to be reduced by 49% in 2030 compared to the 1990 levels and up to 95% in 2050.

In regions largely dependent on the use of fossil fuels, the infrastructure to produce, trade, transport and dispatch the fuel is developed and optimized for its current purpose. However, the energy transition will not lead to an energy system based on a single, dominating, molecule-based primary source of energy, in the same fashion as fossil fuels currently do. It is expected that electricity will play a more significant role in the energy system, while the molecules will have to be carbon free. As a result, hydrogen and CO_2 will play a more dominant role in energy transport and decarbonization. Each geographical region is expected to exploit its natural potential (or existing man-made infrastructure) for a particular renewable energy source to make the transition more cost-effective and reduce its import dependencies. In the Netherlands, domestic production of fossil fuels is certain to decline, and domestic (offshore) wind, solar and geothermal energy will significantly grow. The import-export balance of natural gas, but also other energy carriers has and will continue to change: the Netherlands has already become a net importer of gas in 2018. While it is unclear how decentralized an energy system based on renewable power will be[3], and what shape the future infrastructure will take, the final energy demand will certainly need to be satisfied both with electrons as well as molecules.

In contrast to other publications dealing with the economic or social aspects of the energy transition, this paper is focused on the importance of reliable transport of molecules that are to play a relevant role in the energy transition. In the context of this paper, reliable means that the risks of bringing molecules from one location to another is done with limited and manageable risks to the integrity of the infrastructure. Therefore, external safety aspects are outside the scope of this paper. There is no explicit differentiation made on whether transport is done over long distances (upstream and transport) or within specific facilities (downstream or distribution), as long as it is realized through pipes. The topics covered are related to oil & gas in the energy transition, a large scale roll-out of hydrogen as a synthetic fuel or feedstock, and Carbon Capture and Storage.

As mentioned, the future energy infrastructure will necessarily be more flexible, and can thus benefit enormously from real-time monitoring and optimization – not only from an operational perspective, but also for condition and maintenance optimization. This will be enabled by improved digitalization technologies and digital twins of the physical equipment and hardware, which are also discussed in this paper.

---

[1] Government of the Netherlands. Klimaatakkoord, June 2019.

[2] J.G.J. Olivier, K.M. Schure and J.A.H.W. Peters. Trends in global CO_2 and total greenhouse gas emissions: 2017 Report. PBL Netherlands Environmental Assessment Agency.

[3] Tennet-Gasunie. Infrastructure Outlook 2050. February 2019.

OIL & GAS IN TRANSITION

Oil & Gas production in the Netherlands is declining. While in general this simply follows the depletion of the existing reserves, governmental decisions around the production of the Groningen field results in an acceleration of this process. This means that the scale of natural gas imports to the Netherlands will increase, which requires more nitrogen blending to harmonize gas qualities required for the built environment. Offshore, life extension projects are necessary to continue production at economic conditions, and are especially common in the southern region of the North Sea. In addition, re-purposing and re-use of existing facilities is possible , which can delay the removal of the assets. Discovery of new fields and justification of developing new projects in the current context becomes more difficult; operating the current ones, more expensive. Consequently, production at lower pressures with the same aging facilities will happen in more assets, and operational costs are under pressure – meaning less offshore personnel, more remotely operated unmanned platforms, and minimization of maintenance.

If production declines, lower flow rates and lower pressures are expected, which poses a lower risk to the integrity of the installations. However, if investment in additional compression is made to keep production levels at lower pressures, the flow velocities will be higher than currently attained. Facilities were not necessarily originally designed for these new, late-life operational conditions. Higher flow velocities lead to an increased level of kinetic energy in the fluid, potentially creating more integrity challenges. Also, more start and stop cycles are likely, which are challenging from a multiphase flow perspective.

Fortunately, understanding and prediction capabilities for these challenges has improved significantly over the last decades. It is now possible to challenge rules-of-thumb and extract more value from the existing assets, while guaranteeing the integrity of the asset.

In the future, it is expected that digital twins of assets will replace offline engineering analysis and deliver real-time information of the status and remaining condition of the asset. More detailed information is provided in Highlight 1 regarding digitalization.

HYDROGEN

There is an unprecedented level of worldwide attention given to how hydrogen can contribute to a successful energy transition. This is because hydrogen can be obtained from renewable power via water electrolysis (among other processes), with no associated greenhouse gas emissions. This effectively means that hydrogen can act as a versatile and flexible transport and energy storage medium, bridging the gap between supply and demand of energy in time and space. Hydrogen can then be used as an energy carrier with multiple energetic end-uses, but also as a feedstock for industry[6]. Even though estimates of the global demand for hydrogen in the long term can differ significantly from different studies, there seems to be consensus that a place in the energy mix is reserved for hydrogen. In the Netherlands, the hydrogen demand in 2050 is estimated[3] at around 20-40 billion Nm³, which is in the same order of magnitude as the volumes of natural gas indigenously produced in 2018. Long-distance transport of large volumes of hydrogen can be best done by pipeline. This becomes especially

---

4 Van Geuns, L.; Juez-Larré, J.; de Jong, S.; Van Exporteur naar Importeur. TNO. August 2017.
5 Energie Beheer Nederland. Focus. Energie in Beweging 2018. August 2018.
6 TNO. Blue hydrogen as accelerator and pioneer for energy transition in the industry. July 2019.

attractive if the existing gas infrastructure can be used and reliably operated.

Multiple projects have investigated the suitability of the existing infrastructure for the transport of hydrogen. Hydrogen is more prone to leakage and, especially when it is trapped, can form explosive mixtures with air more easily than natural gas. A number of concerns exist in regard to material compatibility and the need to adjust safety equipment and procedures. However, no study to date has clearly flagged showstoppers to re-use existing infrastructure[7].

But what are the risks of flowing hydrogen instead of natural gas in the existing infrastructure? The answer to this question can be given by building on decades of industry experience with natural gas and many other industrial gases such as H_2, N_2 and CO_2. To transport the same amount of energy in the form of hydrogen as with natural gas, the gas needs to flow about three times faster. Existing guidelines[8] can be used to explore whether this increase in flow velocities can mean an increased risk of vibration induced fatigue failure in process pipework. A more detailed discussion of this is offered in Highlight 2, and a summary of the findings follows.

The maximum allowable flow velocity for hydrogen to attain similar risk scores for flow induced vibrations (FIV) as with natural gas is significantly larger (see Figure 1). Flow-induced pulsations (FIP) generated in current natural gas systems at e.g. T-joints, static mixers or temperature probes are also expected to be present with hydrogen. It is not expected that the dynamic loading exerted by the pressure pulsation will be larger than in the case with natural gas. The density is approximately 9 times lower than with natural gas, so even when the flow speed is 3 times larger to keep the same energy flux, there is a beneficial cancellation effect.

However, the caveat is that all of this occurs at higher frequencies (3x higher), and mechanically arresting vibrations at high frequencies is more difficult. Therefore a screening analysis and re-evaluation for existing facilities is still necessary, especially those that already implemented measures against FIP and FIV. Due to the higher speed of sound of hydrogen, higher amplitude noise will be generated when flowing at high speeds and at pressure reducing stations. This may increase the risk of high-frequency acoustic fatigue. Finally, instruments penetrating the bore of the pipe, such as thermowells, will need to be screened for re-use acceptability or replaced, as potential coincidence between vortex shedding and mechanical natural frequency is expected (excluding other non-compliance reasons such as material compatibility).

In general it can be stated that transporting the same amount of energy with hydrogen instead of natural gas results in a different behavior that must be assessed, but it is manageable. Because potential vibration frequencies will be increased, robust mechanical designs of the systems may be more challenging to implement. It is also

---

[7] van der Noort, A., Sloterdijk, W., Vos, M.; Verkenning waterstofinfrastructuur, DNV-GL. November 2017.

[8] Energy Institute; Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework, 2008.

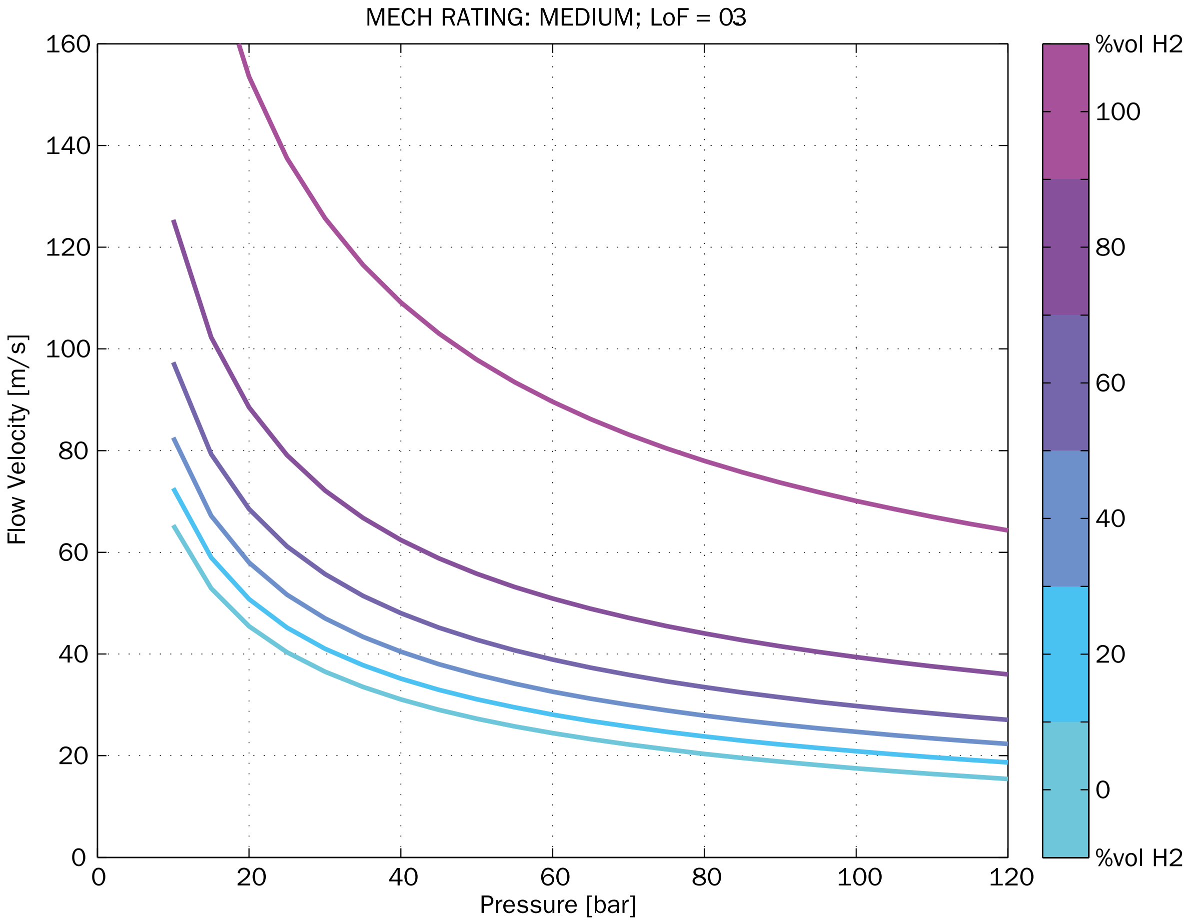


FIGURE 1. MAXIMUM ALLOWABLE FLOW VELOCITY TO REMAIN UNDER A LIKELIHOOD OF FAILURE SCORE OF 0.3, AS A FUNCTION OF PRESSURE, AND FOR DIFFERENT MOLAR CONCENTRATIONS OF H2 IN STANDARD G-GAS. THIS ASSUMES FLOW AT 0°C AND A 36” (DN900) HEADER WITH SCHEDULE XS, WITH A MECHANICAL SUPPORTING LAYOUT DEEMED AS MEDIUM.

expected that flows of hydrogen at very high speed will create more environmental noise. It is recommended to better understand how these issues can be best tackled, especially for existing infrastructure, which essentially means that an intensification of the research in the area of high-frequency dynamics is required.

Where pipes represent the arteries of the energy system, compressors represent its heart. While turbo compressors are the natural choice for boosting large volumes of natural gas, a system based on hydrogen will be best based on reciprocating piston compressors. This is mature, widely used technology used in the refining sector for decades (see Highlight 3). However, scalability for national gas transmission does not come free of hurdles[9], and a system with multiple machines will be necessary. This adds to the complexity of the design and operation of the units, such that interactions between them from pulsation and vibration point of view must be carefully considered.

[9] Albers, N.; van Lier, L.; van der Biezen, M.; Engineering approach for world’s largest hydrogen compression system. Proceedings of the 11th EFRC conference, Madrid, 2018.

CARBON CAPTURE AND STORAGE (CCS)

The urgency of reducing emissions makes the CCS technology crucial to achieve the emission reductions targets for 2030 and beyond. In between the capture location and the offshore storage site, the CO_2 has to be transported. CO_2 is a molecule with a molecular weight significantly larger than those encountered for a typical natural gas composition, and its critical point is well within the operational range. In the journey to the reservoir throughout the years, CO_2 will go through a number of different conditions: low and high pressures; low and high temperatures; gas, liquid, and supercritical state, but also there will be locations and conditions in which the CO_2 is transported as a two-phase mixture.

Projects in the Netherlands consider storage at offshore depleted reservoirs, and therefore low pressures are expected at an early development stage. As more CO_2 is stored underground, the pressure increases over time. Depending on the reservoir pressure, different transport conditions are required, and some combinations present a number of challenges for the reliability of the system. In particular, these are:

- Multiphase flow conditions are expected in the topside piping, downstream of the flow control valves (chokes). This can induce severe flow-induced vibration as a combination of high flow velocity and high liquid hold-up is expected. Occasionally, multiphase flow is also expected in the transport pipeline after a long cool-down, or on top of the well at medium reservoir pressures.
- Because of the large pressure drop induced in the chokes, elevated noise levels are expected. Besides the HSE risk for the people of the injection platform, this can also pose an acoustic fatigue risk for small bore connections downstream of the chokes. At the chokes themselves, the temperature can also drop to very low values.
- The thermal management of the well can be challenging during certain transient operations, such as well shut-in and the restart afterwards. Hydrate formation can also occur under some circumstances.
- Supercritical fluid effects are expected to affect the reliability of centrifugal compressor impellers, due to coupling of acoustic and mechanical natural frequencies. Understanding and prediction models are currently being developed.

In the Dutch Klimaatakkoord[3], it is acknowledged that more research regarding CO_2 transport is necessary. Given the short timelines of the CCS developments currently envisaged in the Netherlands, projects will have to be designed with existing knowledge and make use of safety factors wherever uncertainties remain. To lower the costs of future projects in a relatively short timeframe, it is recommended to intensify experimental research by constructing research infrastructure where the primary issues mentioned before are addressed, such as: flow across chokes (flashing, noise); piping vibrations in two phase flow conditions; and transient conditions such as slugs expected during start-up. This experimental research would also provide information on the applicability of pressure drop models in two-phase CO_2 flow.

CLOSING

The energy transition will change the infrastructure to an extent not yet fully known. However, it is known that storage of renewable power in molecular energy carriers such as hydrogen will be needed. Gas and oil assets will still be in use for years to come. Thus, a reliable infrastructure to produce, transport and deliver these molecules will remain of critical importance. Capture and disposal of CO_2 will follow the opposite route of natural gas. Reliability of these systems is key to safely achieve the climate objectives at a reasonable cost and with societal support. The associated risks are manageable, when designed, monitored and controlled to the high standards that we have today. Additionally, it is not a start from scratch: the existing knowledge base of decades of oil and gas production, transport and use in different industries is still available. So is the infrastructure. New technologies offered by the digital industry can deliver great benefits.

These are the high-priority R&D items and actions that can be taken to guarantee the integrity of our future energy infrastructure:

- Assets can benefit enormously from digitalization technologies focused on condition monitoring and optimized maintenance, enabled by the development of digital twins of the physical hardware.
- Infrastructure operating with pure hydrogen will experience similar levels of risk for their mechanical integrity as current natural gas systems do. However, potential vibrational issues will happen at higher frequencies. Careful and robust design of the mechanical layout of new piping, compressors and intrusive equipment is necessary. If a facility is repurposed, a full re-evaluation of this subject must be carried out. In either case, more radiated noise from the facility is expected.
- Compressors are the hearts of the energy infrastructure. Large scale hydrogen boosting can be best done with piston compressors, and multiple units will be required in each site, potentially creating complex interactions. Carbon dioxide compressors are also special: though the more smooth centrifugal compressor type can be used, special effects caused by the density of the gas must be addressed by the vendors.
- Transport of carbon dioxide in pipes present many challenges from a thermal and vibrational management perspective.
  A better understanding supported by the parallel development of better physical models and experimental research will accelerate future developments. Construction of an infrastructure to carry out this research is endorsed.

An intensification of R&D for the points above will help filling the existing experience gaps and move industry forward, boosting with it the energy transition.

HIGHLIGHT 1. DIGITALIZATION FOR CONDITION MONITORING

In the energy transition, the infrastructure will require more flexibility, challenging the bounds of the operational envelopes of the assets. From an operational reliability point of view, this enlarged envelope can be demanding for operators and engineering contractors, as it will be required to accurately assess the integrity of the system under changing operational modes and act accordingly. In order to make correct decisions, the operators need properly designed decision-support (condition monitoring) tools.

In a monitoring system, data captured from adequately placed sensors is processed to discern anomalies/diagnose any faults and to indicate the condition of the system or even propose remedial actions. This 3-step approach follows an Observe-Understand-Act philosophy. In the context of condition monitoring against fatigue failure:

(1) Quality of sensor placement is defined as the ability to produce data that describe relevant dynamic behavior. As the operational envelopes become larger, the response of the system gets more complicated; sensors placed to describe the response under a given condition may be “blind” to relevant behavior in other conditions. When a wide range of vibration modes have to be captured, higher spatial resolutions could be required for sensor placement, making the monitoring system design costly or even unfeasible. Numerical modelling is needed to determine the bare minimum number of sensors and their optimal locations for all expected operational conditions.

(2) As system behaviors get more complex, the sense of “normal” changes continuously. There will be an increasing need for decision-support tools that helps the user to find anomalies. Abundance of affordable computational power coupled with complementary advances in numerical tools (e.g. big data analytics), have already been penetrating the market need for automated anomaly and fault detection.

(3) State-of-the-art condition monitoring systems generally offer a traffic light representation to indicate the system condition. The sensor data is continuously screened against manually defined thresholds, that represent different color (or alarm) levels. Replacing this approach with established numerical predictive models is expected to revolutionize this field. The condition of the system will, then, be screened against the output of an objective degradation model and time indications will be given for impending failures so that maintenance or replacement can be planned on time. Although using numerical models of real life systems (digital twins) is gaining momentum, it is still not widely applied.

When applying digitalization technologies to maintain reliable operations, trade-offs may occur that in the current situation are solved by the system operator. For instance, system efficiency can be in opposition to system reliability. System-wide modelling can be used to determine the optimal balance between these two while achieving the asset operational goals.

HIGHLIGHT 2. HOW $3^2/9 = 1$ HELPS THE ENERGY TRANSITION: FIP AND FIV FOR HYDROGEN SYSTEMS

Mechanical vibrations can be induced by internal flow due to a number of excitation mechanisms such as turbulence, pulsation sources in e.g. T-joints or highly turbulent jets at restrictions such as chokes and valves. In this box, hydrogen and natural gas transport are compared to each other in the assumption of a similar energy transport flux. At a given transport pressure, this means an increased velocity for hydrogen (factor 3 to 1) but a reduced density (factor 1 to 9)

Flow Induced Pulsations: flow induced pulsations can arise as a result of a flow-acoustic interaction, typically in closed side-branches. The interaction occurs if the frequency of the acoustic source (shear layer instability) is similar to acoustic resonance frequencies of the piping, in a similar fashion as a flute works. The source frequency depends on the flow velocity, whereas the acoustic resonance frequencies depends of the speed of sound of the medium. Therefore, resonant conditions occur in the vicinity of particular Mach numbers M^res (ratio between actual flow velocity and speed of sound):

$$M^{res} = \left(\frac{1}{4}\right)\left(\frac{D_{sb}}{L_{sb}}\right)\left(\frac{1}{Sr}\right)$$

Where Dsb is the diameter of the side-branch, Lsb the length of the side-branch, and Sr is the Strouhal number – a number that proportionally connects the acoustic source frequency and flow velocity. The speed of sound of pure hydrogen at similar pressure and temperature is 3 times that of standard Groningen gas (G-gas). As the desired flow speed is also 3 times larger, these two effects will compensate each other. Resonance risks already present with natural gas will remain similar when flowing the amount of hydrogen needed to transport the same energy flux. However, these will occur at 3 times higher frequency.

Once a resonance is hit, its damaging potential will depend on the amplitude of the pulsation, which is a function of the acoustic damping in the branch and the pulsation source magnitude. The resulting pressure amplitude p’ can be calculated from:

$$p'_{ac} = pU_0^2\left(\frac{2F}{\alpha_0 \, L_{sb}}\right)$$

As the kinetic energy/dynamic pressure term $\rho U2$ [Pa] remains approximately constant at similar energy transport capacities, the ratio of dimensionless source strength F and acoustic damping $\alpha0$ is key. In case of hydrogen, the dimensionless source strength will be the same, but the damping is somewhat larger. Therefore, the final resulting amplitude and dynamic loading will be lower. However, the mechanical response of the system can be different at higher frequencies.

In summary: All current assets not experiencing flow-induced pulsation issues are not expected to develop them if their energy transport capacity is provided with hydrogen instead of G-gas, since

- Though the flow velocity increases by a factor 3,
- the gas density decreases by a factor 9,
- and the speed of sound increases by a factor 3.

The caveat is that the pulsation frequency is shifted upwards by a factor 3, for which it is more difficult to mechanically arrest the potential vibrations. It is recommended to screen any installations that took corrective actions in the past due to flow-induced pulsation when using natural gas, if they are to switch to hydrogen duty.

Flow Induced Turbulence: flow induced turbulence is typically not an issue for single phase gas systems. For a large diameter pipe, supported by a mechanical layout considered medium in stiffness rating, hydrogen is not expected to cause any issues up to a flow speed of 80 m/s (at 80 bar). For comparison: the same calculation for a pipe with G-gas duty results in a critical velocity of 20 m/s, which is four times lower. Since at those velocities hydrogen and G-gas transport the same energy flux, the risk level for both will be the same.

Noise: Flow induced turbulence is also responsible for the hissing noise heard when gas flows through pipes at high speeds. Though in terms of noise amplitude inside the pipe, the same levels are expected between hydrogen and G-gas, its spectrum will be shifted to higher frequencies. This may lead to different noise radiation patterns and more complaints with regards to noise emissions. This also holds for specific locations where strong pressure drops occur, such as control valves and restriction orifices.

Operational transients: Transient conditions due to the operation of control valves, especially when they occur fast and incidentally, can lead to failure conditions due to different mechanisms. Gas hammer occurs if a valve suddenly closes. Normally, for dry gas conditions as those expected in natural gas or hydrogen transmission systems, this is not an issue. Moreover, it is estimated that the severity of these events, if any, is exactly the same as with natural gas when flowing hydrogen three times as fast. The second mechanism is the opposite of the first: when a valve suddenly opens, a thrust force will arise creating a whiplash on the pipe system around the valve. Finally, in the case of a rapid flow discharge, for instance in relief lines or as a result or a quick depressurization due to exogenous reasons, high noise levels can be generated. Besides the noise, these can endanger the integrity of the small bore lines and instrument connectors. This should be judged in a case-by-case basis, but if similar conditions are assumed, hydrogen would show somewhat higher noise levels than a similar event happening with G-gas.

Intrusive elements: Intrusive equipment such as thermowells, certain probes and types of flow meters are subject to the unsteady forcing exerted by the flow. A serious threat exists when the frequency of the unsteady loads coincides with a mechanical natural frequency of the intrusive element. Because for the same energy transport capacity, hydrogen has to flow approximately three times as fast as natural gas, the load frequencies will be three times larger. Therefore, the chance to hit a mechanical natural frequency is multiplied. In case of re-use of facilities, all thermowells and other intrusive elements will need to be screened for suitability for hydrogen flows and intended operating conditions. In the case that the element fails the screening, a replacement with a more robust design (whether mechanical or equipped with devices such as vortex breakers) will be necessary.

HIGHLIGHT 3. LARGE SCALE HYDROGEN COMPRESSORS

Pipe line compression for natural gas is done with turbo compressors (most favorable for large capacity). However, for compression of hydrogen, reciprocating compressors are traditionally used. In particular in the refining sector, large amounts of high-pressure hydrogen are needed for hydrocracking processes. Though reciprocating compressor design is in principle mature and well-known technology, the machine is an intrinsic source of unsteady pulsating flow.
The unsteady flow and pressure may be amplified by acoustic resonance effects in the piping system and lead to large pulsation-induced shaking forces on the piping. If mechanical structural resonances are triggered by the shaking forces, large vibrations and cyclic stress may be the consequence, ultimately leading to loss of containment and unscheduled shutdown. Detailed industry standards such as API 618 and modeling tools are available to control harmful effects of pulsations during the design stage. Comparing natural gas compression with hydrogen compression generally favors the latter, since the molecular weight is lower and the risk to excite acoustic resonances is lower. On the other hand, the beneficial effect of pulsation damper volume and other buffer vessels is typically smaller for hydrogen.

The main challenge for application of reciprocating compressors for hydrogen transport is the required capacity. Typically, the capacity required for a pipeline compressor station is an order of magnitude larger than the larger refinery hydrogen compressor systems. Note that in refinery business, a trend toward large-capacity systems is found. The large system introduce various ‘scaling’ challenges. The systems consist of many parallel compressors, many cylinders, large cylinder sizes and/or increased compressor speeds. All these aspects require a robust but cost-effective design with respect to pulsations and vibrations.

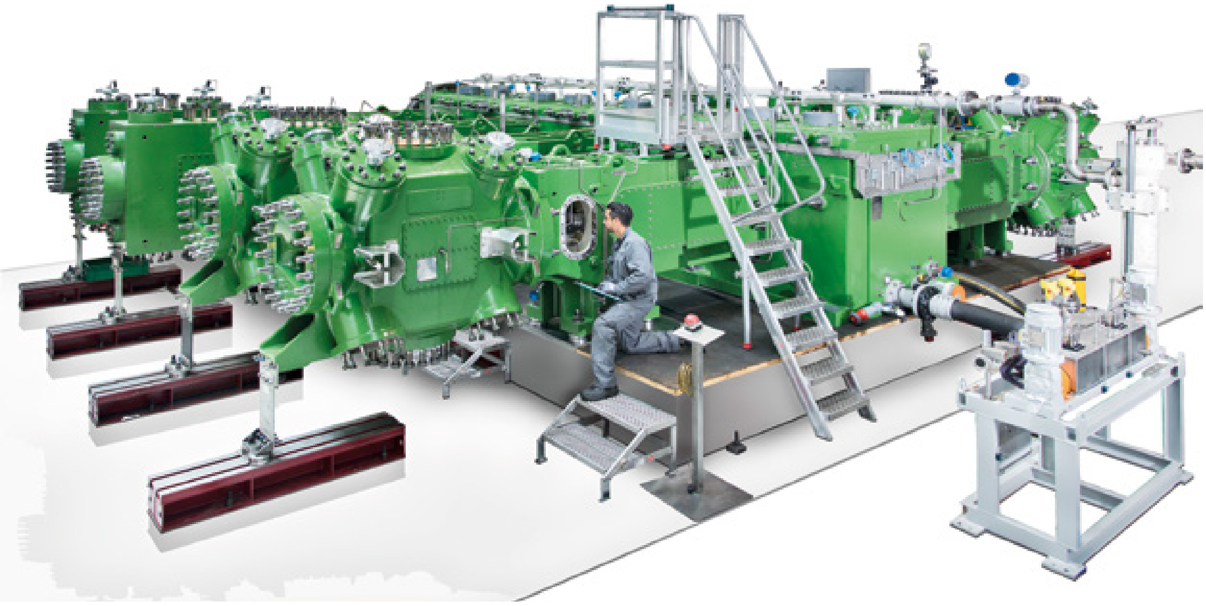


FIGURE 2: LARGE HYDROGEN RECIPROCATING COMPRESSOR UNIT. COURTESY OF HOWDEN GROUP LTD.

CONTACT
Néstor González Díez
PROGRAM MANAGER H2 FLUID DYNAMICS
UNIT ENERGY TRANSITION
✉ nestor.gonzalezdiez@tno.nl

Lennert Buijs
CLUSTER MANAGER SAFETY OF ENERGY INFRA
Unit Energy Transition
✉ lennert.buijs@tno.nl

innovation
for life

TNO.NL