

Exploring the Mechanical Challenges of an Offshore Hydrogen Pipeline System

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Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Date.....**16/05/2025**.....

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Abstract

Offshore Hydrogen production powered by renewable energy such as offshore wind, is an emerging concept with the potential to contribute to net zero goals. However, the successful deployment of this technology depends on the ability to safely and efficiently transport Hydrogen. With one method of transportation being the use of dedicated offshore Hydrogen pipeline systems.

This dissertation explores the mechanical challenges associated with offshore Hydrogen pipelines. Unique Hydrogen chemical properties such as a wide flammability range, low ignition energy, small molecular size and susceptibility to embrittlement are reviewed. A base case is developed, which has been inspired by real world initiatives in the North Sea beginning to explore key parameters.

A review of current standards and codes highlights the absence of dedicated offshore Hydrogen pipeline standards. Installation methods such as S-Lay and J-Lay are assessed for suitability considering whether they could be feasible options. This dissertation concludes by identifying knowledge gaps and proposing areas of future research.

Table of Contents

Declaration.....	ii
Acknowledgements.....	iii
Abstract.....	iv
Glossary.....	vii
List of Figures	ix
List of Tables	x
1 Introduction.....	1
1.1 Project Contextualisation	1
1.2 Low-carbon Hydrogen	1
1.3 Offshore Green Hydrogen Production.....	2
1.3.1 Offshore Hydrogen Infrastructure.....	3
1.4 Aim and Objectives.....	4
1.4.1 Aim	4
1.4.2 Objectives.....	4
1.5 Dissertation Organisation	5
1.6 Research Methodology.....	5
2 Offshore Hydrogen Pipeline Materials and Challenges	6
2.1 Hydrogen Chemical Properties	6
2.1.1 Flammability Range	6
2.1.2 Auto-ignition Temperature	7
2.1.3 Minimum Ignition Energy	7
2.1.4 Molecular Size	9
2.2 Hydrogen Embrittlement.....	9
2.3 Material Selection for Offshore Hydrogen Pipelines.....	11
3 Base Case: Offshore Hydrogen Pipeline System	13
3.1 Geographical Location.....	13
3.2 Offshore Hydrogen Production.....	14
3.3 Technical Design Parameters	15
3.3.1 Pipeline Configuration.....	15
3.3.2 Pipeline Design Pressure.....	16
3.3.3 Export Pipeline Length.....	17
3.3.4 Transport Capacity.....	18
3.4 Export Pipeline Functional Requirements	18
3.4.1 General Functional Requirements	19
4 Codes and Standards for Offshore Hydrogen Pipelines	21
4.1 Offshore Hydrogen Pipeline Generic Bowtie	21

4.1.1	Preventive Barrier Category - Structure	23
4.1.2	Preventive Barrier Category – Containment.....	24
4.1.3	Preventive Barrier Category – Instrumented Safety Systems.....	24
4.1.4	Preventive Barrier Category – Ignition Control	25
4.1.5	Mitigative Barrier Category – Protection Systems	26
4.1.6	Mitigative Barrier Category – Power & Communication.....	27
4.1.7	Mitigative Barrier Category – Life Saving	27
4.2	Summary of Review.....	27
5	Offshore Hydrogen Pipeline Installation & Deployment	28
5.1	S-Lay Installation	29
5.2	J-Lay Installation.....	29
5.3	Reel-Lay Installation	30
5.4	Towed Lay Installation	31
6	Conclusions of the Dissertation and Proposed Future Work.....	31
6.1	Conclusions of the Dissertation	31
6.2	Proposed Future Work.....	33
	References	35
	Appendices	40
	Appendix A: ASME B31.12 Piping and Pipe Components.....	40
	Appendix B: ASME B31.12 Pipelines	42

Glossary

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BSH	Federal Maritim and Hydrographic Agency of Germany
CO ₂	Carbon Dioxide
COMAH	Control of Major Accidents
DNV	Det Norske Veritas
EU	European Union
EIGA	European Industrial Gases Association
EV	Emergency Valve
GHG	Greenhouse Gas
Gt	Gigatonnes
H ₂	Hydrogen
HAZOP	Hazard and Operability Study
IEC	International Electrotechnical Commission
IGC	Industrial Gases Council
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standardisation
JIP	Joint Industry Project
kWh	Kilowatt Hour
LCOH	Levelised Cost of Hydrogen
LFL	Lower Flammability Limit
MAH	Major Accident Hazard
MIE	Minimum Ignition Energy
MJ	Megajoule
MOP	Maximum Operating Pressure
MW	Megawatt
NFPA	National Fire Protection Association
NZIP	Net Zero Innovation Portfolio
O&G	Oil and Gas
OSHA	Occupation Safety and Health Administration

PEM	Proton Exchange Membrane
P&ID	Piping and Instrumentation Diagram
Psig	Pounds per Square Inch Guage
SEN 1	Specific Offshore Zone in the German North Sea
SSIV	Subsea Isolation Valve
STP	Standard Temperature and Pressure
UFL	Upper Flammability Limit
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

List of Figures

Figure 1: DNV Hydrogen Value Chains (DNV , 2023).....	2
Figure 2: Project LCOH Breakdown of Offshore Wind to Hydrogen (DNV , 2023).	3
Figure 3: Comparison of Gases - LFL and UFL.....	6
Figure 4: Comparison of Gases - Auto-Ignition Temperature.	7
Figure 5: Comparison of Gases - Minimum Ignition Energy.....	7
Figure 6: Image showing the aftermath of the Hydrogen explosion (OSHA , 2025).	8
Figure 7: Comparison of Gases - Molecular Size.	9
Figure 8: Hydrogen diffusion process (Laadel, et al., 2022).....	10
Figure 9: Stress-strain curves for Hydrogen embrittlement cases (Wu & Zirky, 2015).	10
Figure 10: Offshore Energy Areas in German Exclusive Economic Zone (BSH , 2024).	13
Figure 11: Simplistic Illustration of a Decentralised Concept Approach.....	14
Figure 12: Simplistic Illustration of a Centralised Concept Approach.	14
Figure 13: Simplistic Illustration of a Semi-Centralised Concept Approach.....	15
Figure 14: High Level System Overview P&ID.	16
Figure 15: AquaDuctus Artist Impression of Backbone Pipeline (AquaDuctus , 2024).	17
Figure 16: Generic bowtie model for offshore Hydrogen pipelines.....	22
Figure 17: Basic components of a Hydrogen pipeline system (EIGA, 2014).	26
Figure 18: Schematic representation of S-Lay Method (da Silva, et al., 2008).....	29
Figure 19: Schematic representation of J-Lay Method (Mawat, 2012).....	30
Figure 20: Schematic representation of Reel-Lay Method (Xianwei, 2012).	30
Figure 21: Schematic representation of Towed Lay Method (IndonesiaRe, 2020).	31

List of Tables

Table 1: Hydrogen Colour Classification System.	2
Table 2: High Level System Breakdown.	16
Table 3: Functional Requirements for Hydrogen and Natural Gas Export Pipelines	20
Table 4: Relevant Standards and Codes for "Structure" Category.	23
Table 5: Relevant Standards and Codes for "Containment" Category.....	24
Table 6: Relevant Standards and Codes for "Instrumented Safety Systems" Category.	25
Table 7: Relevant Standards and Codes for "Ignition Control" Category.....	25
Table 8: Relevant Standards and Codes for "Ignition Control" Category.....	26
Table 9: Relevant Standards and Codes for "Power & Communication" Category.....	27

1 Introduction

Hydrogen has emerged as a pivotal element in achieving net-zero emissions. With demand for low-emission Hydrogen increasing by 10% in 2023 and with demand projected to increase by 600% by 2030 to 6Mt (International Energy Agency, 2024). With these projections the production of low-emission Hydrogen and more specifically “Green” Hydrogen projects have gained traction. The global project pipeline has grown from 228 projects in 2021 to an estimated 1,572 projects in 2024 with 1125 having commercial operations date through 2030 (McKinsey & Company, 2024).

One emerging concept is the production of green Hydrogen offshore utilising an abundance of offshore wind as a renewable energy source. However, for successful realisation of commercial scale production of offshore green Hydrogen a reliable transportation system will be required. With one solution being the development and deployment of offshore Hydrogen pipeline systems transporting green Hydrogen to shore.

1.1 Project Contextualisation

In December 2015, the Paris Agreement was adopted under the United Nations Framework Convention on Climate Change (UNFCCC) by 196 parties. The agreement in short established aims for greenhouse gas emissions to peak by 2025, to be reduced by 43% by 2030 and to limit global warming to 1.5°C (United Nations Climate Change , 2024). This has led to new and enhanced net zero plans being adopted globally focussing on what is commonly referred to as the “Energy Transition”. A term frequently used to refer to the shift in the energy sector from fossil-based systems to renewable energy sources.

However, despite the mass adoption of the Paris Agreement a technical report published by the United Nations in 2023 stated that “global emissions are not in line with modelled global mitigation pathways consistent with the temperature goal of the Paris Agreement” (United Nations , 2023). Estimating that commitments are falling short by 20.3 to 23.9 Gt of CO₂ to achieve the target of limiting warming to 1.5°C by 2030. It was also recognised within this first global stocktake report that to achieve net zero CO₂ that the use of clean fuels would be required including the use of low-carbon Hydrogen.

1.2 Low-carbon Hydrogen

Hydrogen which is produced with significantly reduced greenhouse gas (GHG) emissions is often referred to as low-carbon Hydrogen. The classification of low-carbon Hydrogen is dependent on country specific regulatory frameworks where these exist. With the majority of the regulations and certification systems focussing on the method of production and emissions (International Energy Agency , 2023). Within the UK the GHG emission intensity

limit is set by the Department for Energy Security and Net Zero, with the limit currently set at $\leq 20.0 \text{ gCO}_2\text{e/MJ}$ for the Hydrogen produced to be compliant (Department for Energy Security & Net Zero, 2023). A more commonly used method to differentiated between different “types” of Hydrogen is through the allocation of different colours depending on the production method or technology as can be seen in Table 1. With low-carbon Hydrogen often capturing production methods using renewable energy sources or with carbon capture systems.

Colour of H ₂	Feedstock	Technology	Direct GHG Emissions (Kg CO ₂ e/kg H ₂)
Green	Renewable Electricity	Electrolysis	-
Yellow	Grid Electricity	Electrolysis	-
Pink	Nuclear Electricity	Electrolysis	-
Blue	Natural Gas or Coal	Methane reforming with carbon capture	0.5 - 4
Turquoise	Natural Gas	Pyrolysis	Solid Carbon
Grey	Natural Gas	Methane Reforming	9 - 11
Brown	Lignite	Gasification	18 - 20
Black	Black Coal	Gasification	18 - 20

Table 1: Hydrogen Colour Classification System.

1.3 Offshore Green Hydrogen Production

The production of green Hydrogen offshore is an emerging concept. A study performed by DNV in 2023, highlighted five Hydrogen value chains. The value chains as seen in Figure 1 highlight the means of renewable energy generation, transportation of the renewable energy and the eventual conversion into Hydrogen. Value chains A - D follow well understood generation and renewable energy transportation methods. The keys different with them being the conversion to Hydrogen rather than the usual integration renewable energy to the grid.

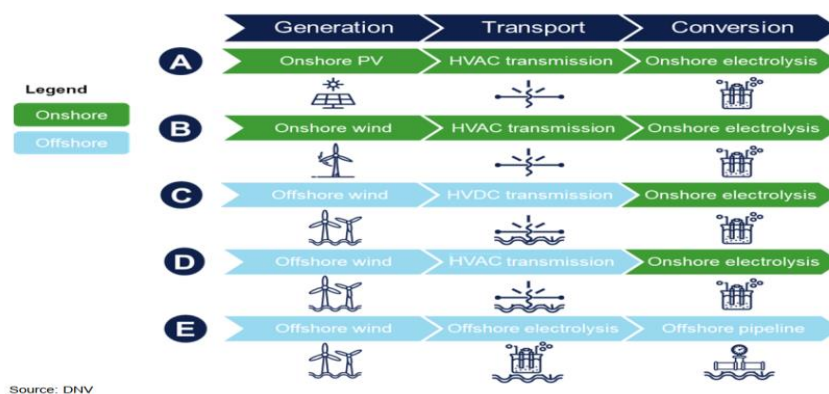


Figure 1: DNV Hydrogen Value Chains (DNV , 2023).

These 4 value chains (A - D) arguably offer the most simplistic options to integrate increased Hydrogen production into the energy transition. However, unlike these 4 value chains identified value chain E opts for the conversion of Hydrogen to be performed offshore and for this then to be transported onshore. This could be seen currently as a more complex method, involving both the development of offshore electrolysis production and also the development of pipeline.

Value chain E is being considered as an option due to projected reductions in the Levelised Cost of Hydrogen (LCOH), measured in €/kg H₂. According to the DNV study conducted in 2023 on the Specification of a European Offshore Hydrogen Backbone, the LCOH for value chain E is projected to decline from 4.59 €/kg H₂ in 2030 to 3.79 €/kg H₂ in 2040, eventually reaching 3.24 €/kg H₂ by 2050, as illustrated in Figure 2 showing the value chains using offshore energy generation (DNV , 2023).

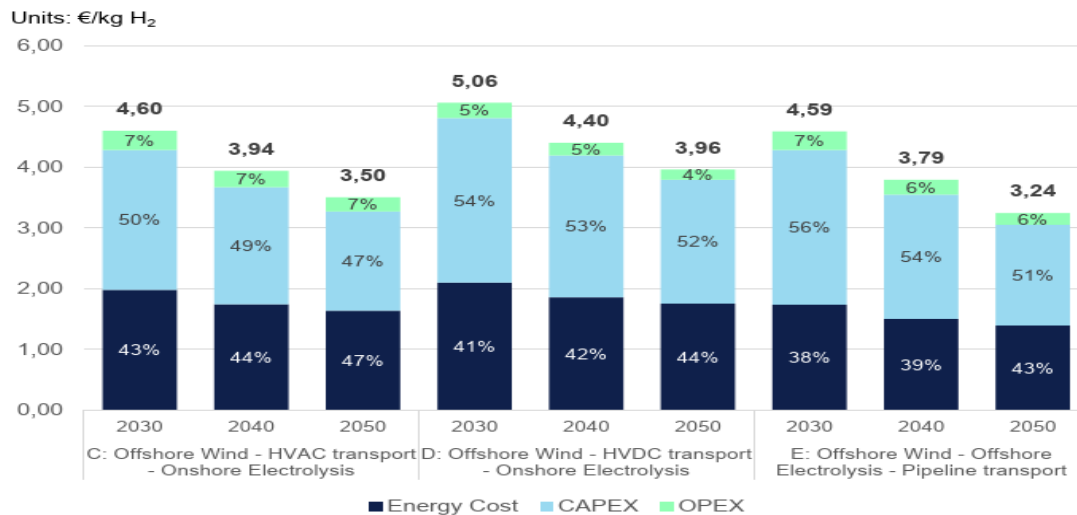


Figure 2: Project LCOH Breakdown of Offshore Wind to Hydrogen (DNV , 2023).

In comparison to the other 4 value chains, the predictions estimate that value chain E will have the lowest LCOH initially, mid-term and also in the long term.

AquaVentus is an initiative supported by more than 100 companies, organisations and research institutes and is one of many projects exploring the possibility of offshore Hydrogen generation. The project is focussed on the North Sea and the vision is for the transportation to be performed by pipeline. One part of the AquaVentus project is AquaDuctus a project specifically looking at a Hydrogen pipeline network in the North Sea with the ability to deliver GW scale offshore Hydrogen production (AquaDuctus , 2024).

1.3.1 Offshore Hydrogen Infrastructure

The establishment of offshore Hydrogen infrastructure is still in its infancy. Current production of Hydrogen offshore is being performed at demonstration scale and with no

dedicated transportation methods. A notable project is the Dolphyn Project which successfully launched the UK's first offshore Hydrogen production trials in 2024. The project has been developed by ERM a sustainability consultant, benefitting from over £8 million of funding awarded through the Net Zero Innovation Portfolio (NZIP) (Habibic, 2024).

One other notable offshore Hydrogen project is the PosHydon project located in the Dutch North Sea. The project involved introducing the production of green Hydrogen on an operational gas platform operated by Neptune Energy. The pilot was launched in the second half of 2024, with the pilot being supported by the Dutch state and seen as essential for the development of larger scale production of green Hydrogen (PosHYdon, 2023). Similar to the Dolphyn project the transportation methods will not include dedicated Hydrogen pipelines. The green Hydrogen will instead be blended into existing gas production at the platform, with blending specifications being increased from 0.02% to 0.5% Hydrogen by the Ministry of Economic Affairs and Climate Policy (Offshore Energy, 2023).

These early stages pilot projects have yet required dedicated Hydrogen transport, with both of these projects being small scale <1MW electrolyser production capacity. However, as the industry progresses the need to transport large volumes of Hydrogen is a foreseeable challenge. A challenge which is currently being explored by academics, existing offshore O&G companies and companies wishing to diversify energy portfolios.

1.4 Aim and Objectives

1.4.1 Aim

To explore the mechanical challenges associated with offshore Hydrogen pipelines for green Hydrogen transportation. It is not intended for this work to perform the "design" of a pipeline system but instead the intent is for this work to provide the premises for further design and installation discussions.

1.4.2 Objectives

The research in this dissertation has the following objectives:

- 1) Analyse chemical properties of Hydrogen and potential impact on pipeline materials.
- 2) Develop a base use case, defining the required general functions of the pipeline system and Hydrogen specific functions.
- 3) Review existing codes and standards reviewing applicability including those for carriers for established natural gas pipelines
- 4) Explore installation methods and propose best practices for offshore Hydrogen pipeline deployment.

1.5 Dissertation Organisation

This dissertation is structure in the following way;

Section 2 outlines the key Hydrogen material and challenges associated with transporting Hydrogen through offshore pipelines. First by exploring Hydrogen's chemical properties and then relating these to pipeline design considerations. This section also focuses on Hydrogen embrittlement, explaining the mechanism and potential impact. Finally, addressing material selection for offshore Hydrogen pipelines.

Section 3 outlines a base case for an offshore Hydrogen pipeline system, based on the Aqua Ventus project in Germany's North Sea. This section compares Hydrogen vs Natural Gas pipeline, comparing fundamental requirements and emphasising the need for Hydrogen specific requirements.

Section 4 looks into the current landscape of standards and codes potentially relevant to offshore Hydrogen pipelines, noting that dedicated offshore Hydrogen standards do not yet exist. A use of a generic bowtie model is used to map existing standards to key preventive and mitigative safety barriers.

Section 5 explores the existing offshore pipeline installation methods, reviewing the feasibility of using existing methods for an assumed offshore Hydrogen pipeline base case.

Section 6 contains the conclusion and the future work suggested as a result of this research.

1.6 Research Methodology

The research adopts a qualitative approach combining a review of secondary data and standards evaluation. Literature is referenced throughout the research which has assisted in arriving at the conclusions.

2 Offshore Hydrogen Pipeline Materials and Challenges

2.1 Hydrogen Chemical Properties

Hydrogen is the simplest and most abundant element in the universe, accounting for approximately 73% to 75% of the universe's mass. Despite its abundance, free molecular Hydrogen (H_2) is relatively rare and is more commonly found in compounds bound to other elements such as hydrocarbons, water and other organic molecules (Momirlan & Veziroglu, 2005). Under standard temperature and pressure (STP) exists as a diatomic molecule, where it is colourless, odourless and tasteless gas composed of diatomic modules, represented by the chemical formula H_2 . Hydrogen's unique chemical properties pose several challenges when transported through pipelines, a process traditionally performed onshore but now being considered for offshore and subsea applications.

2.1.1 Flammability Range

Hydrogen has a significantly wider flammability range compared to other common fuels as illustrated in Figure 3, with a range between 4 to 75% in air (Tretsiakova-McNally & Makarov, 2023).

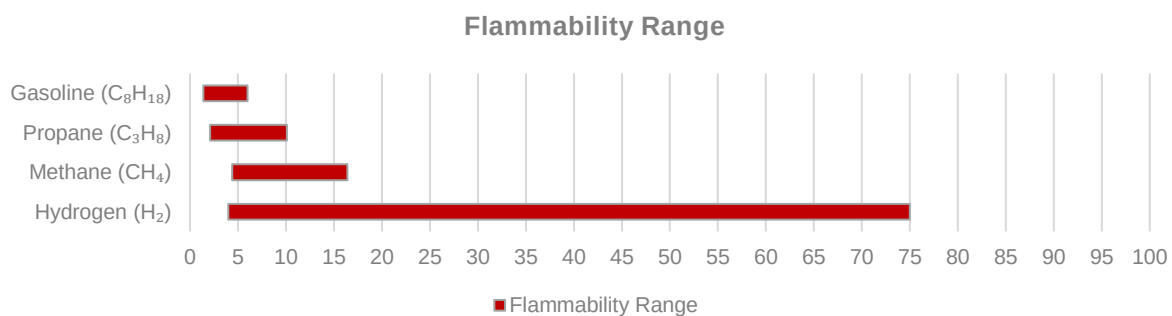


Figure 3: Comparison of Gases - LFL and UFL.

The lower flammability limit (LFL) of 4% represents the minimum concentration of Hydrogen (H_2) in air required to support combustion. The upper flammability limit (UFL) of 75% indicates the maximum concentration of Hydrogen in air that can still support combustion. This range is an important consideration when designing pipeline systems transporting H_2 , with a conservative approach in the design to assume that any Hydrogen leakage will exceed the LFL but remain below the UFL due to the significant range (Kotchourko & Jordan, 2022). Therefore, the design assumption which can be made without further modelling is that Hydrogen leakages from pipeline systems will occur at concentration levels capable of supporting combustion.

2.1.2 Auto-ignition Temperature

The lowest temperature at which a gas will spontaneously ignite is referred to as the auto-ignition temperature. At this temperature there is no need for an external ignition source and instead the temperature alone supplies the energy needed for combustion. As illustrated in Figure 4, this temperature for H_2 is 585 °C (Dagdougui, et al., 2018).

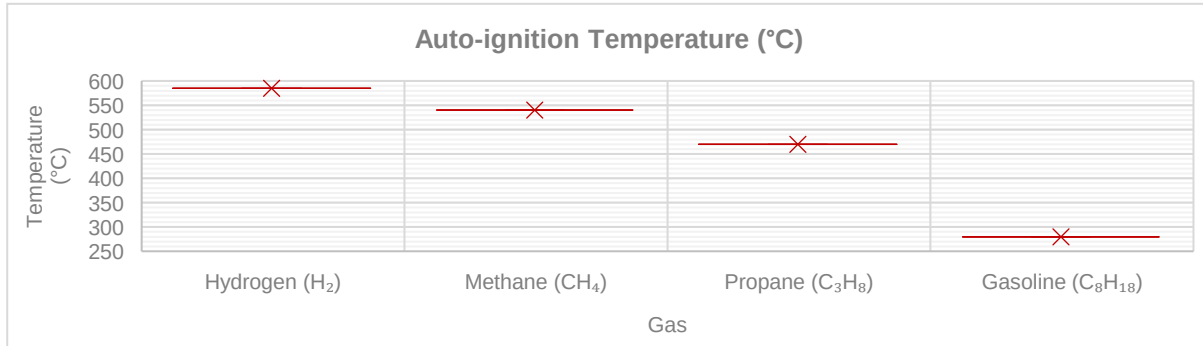


Figure 4: Comparison of Gases - Auto-Ignition Temperature.

Therefore, it can be assumed in the design that Hydrogen leakages from pipeline systems will usually occur at temperature below the auto-ignition temperature. This means that spontaneous ignition due to thermal energy alone is unlikely and an external ignition source would be required to ignite any Hydrogen leak from a pipeline system.

2.1.3 Minimum Ignition Energy

In addition to its wide flammability range, Hydrogen also has a low minimum ignition energy (MIE) for a Hydrogen an air mixture. The MIE is 0.019 mJ which is significantly lower than the minimum ignition energy for other flammable (Ono, et al., 2007). As illustrated in Figure 5, the MIE for Hydrogen is significantly lower which makes it more susceptible to a variety of ignition sources. These include but not limited to:

- Thermal – Heated surfaces, exhausts from vessels, open flames, heating systems.
- Electrical – Static electricity, electrical sparks.
- Mechanical – Friction, structural fractures, impacts.

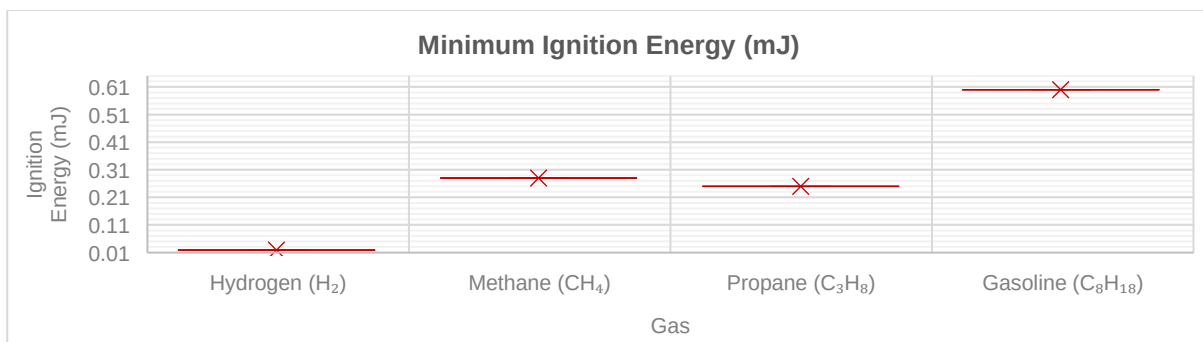


Figure 5: Comparison of Gases - Minimum Ignition Energy.

Due to Hydrogen's low MIE, safety standards such as IEC 60079-10-1 (Classification of Areas – Explosive Gas Atmospheres) highlight the necessity of stringent safety measures in environments where Hydrogen is present, even in areas classified as potential explosive hazardous zones (IEC , 2015). The standard states the importances of assuming the potential for ignition in all situations involving Hydrogen due to its extremely low MIE. This is further back up as numerous incidents have occurred where the determination of an ignition source has been difficult due to the low MIE and in some cases remained undetermined (Lewis, 2013).

An example of an incident where the ignition source could not be conclusively determined is the Muskingham River Power Plant Hydrogen explosion in Ohio on the 8th January , 2007. The explosion occurred after approximately 17.7 kg of Hydrogen was released into an internal space due to a rupture in the venting pipe after a bursting disc had prematurely released Hydrogen into the vent system (WHA International INC. , 2022). The resulting explosion tragically led to one fatality, injuries to ten others and significant damage to several buildings as shown in Figure 6.



Figure 6: Image showing the aftermath of the Hydrogen explosion (OSHA , 2025).

Despite a thorough investigation, the ignition source could not definitively identified as there were multiple potential sources of ignition in the area. The potential sources identified included electrical lights in the awning, electrical panels and even the possibility of an electrostatic discharge (OSHA , 2025). This incident is one example demonstrating the challenges faced due to the low MIE of Hydrogen combined with the wide flammability range, highlighting the importance of assuming potential ignition in all situations involving Hydrogen.

2.1.4 Molecular Size

The molecular size of Hydrogen molecule is relatively small compared to other gases, measuring approximately 0.289 nanometres (nm) (Mazloomi & Gomes, 2012). This small molecular size in comparison to other gases contribute to Hydrogen's ability to easily permeate materials and its high diffusivity, resulting in Hydrogen being prone to leakage but also rapid dispersion in the environment. As illustrated in Figure 7, the Hydrogen molecule is significantly smaller than other comparable gases.

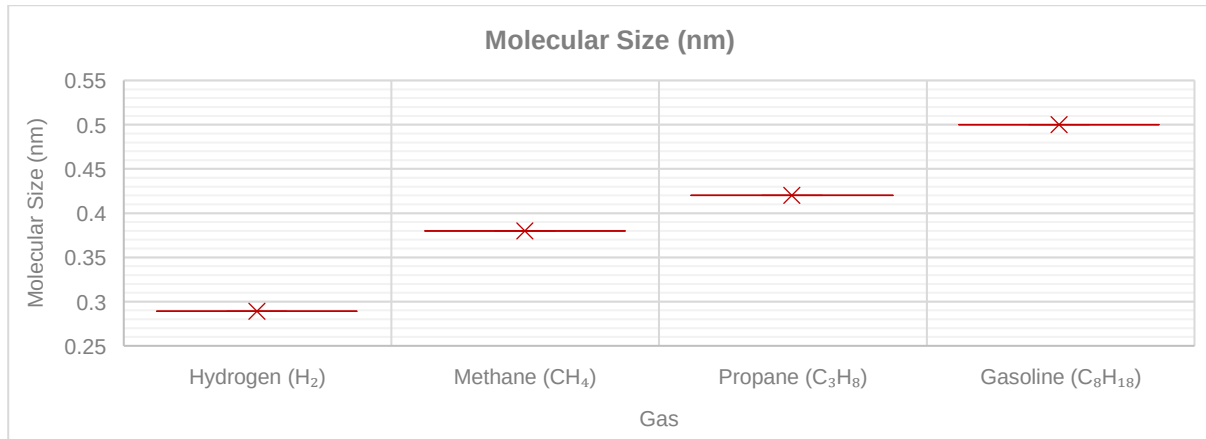


Figure 7: Comparison of Gases - Molecular Size.

Due to the small molecular size, Hydrogen pipeline designs should assume a high potential for permeability and diffusion through selected materials. This means that Hydrogen can easily migrate through materials, which increase the likelihood of leakage from the pipeline.

2.2 Hydrogen Embrittlement

Hydrogen can lead to the deterioration of the mechanical properties of metallic materials that are in constant and direct contact with Hydrogen. This phenomenon, often referred to as “Hydrogen Embrittlement” causes materials to become brittle (Nagumo, 2023). The process involves the diffusion of Hydrogen atoms into the metallic structure of the material, where they accumulate at dislocations, defects or grain boundaries. This accumulation disrupts the metal's mechanical integrity, reducing its ductility and toughness (Gabetta , et al., 2018).

ASTM F2078-22 - Standard Terminology Relating to Hydrogen Embrittlement Testing defines Hydrogen embrittlement as “the permanent loss of ductility in a metal or alloy caused by Hydrogen in combination with stress, either externally applied or internal residual stress” (ASTM International , 2022). Figure 8 illustrates a Hydrogen diffusion process, showing how Hydrogen is absorbed into the microstructure and how cracks propagate at the grain boundaries.

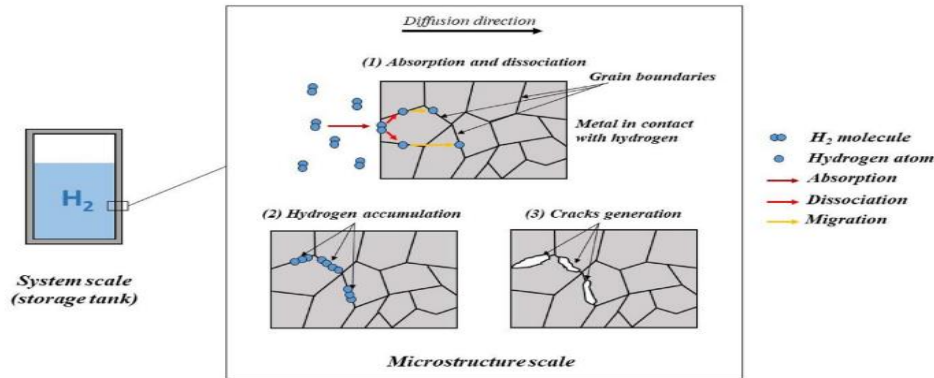


Figure 8: Hydrogen diffusion process (Laadel, et al., 2022).

The molecular size of Hydrogen at 0.289 nm, allows Hydrogen to diffuse through the microstructure of metals. In many failure cases, Hydrogen has contributed to crack propagation, especially when fatigue or stress corrosion cracking is already present (Moore & Shulman, 2017). The following three parameters are typically required to cause failure:

1. Tensile Stress e.g. stress corrosion cracking, corrosion fatigue, external stress.
2. Material Susceptibility.
3. Presence of Hydrogen.

Hydrogen embrittlement can significantly alter the mechanical properties of many materials including high-strength steels resulting in premature failure. A study published in the Journal of the Mechanics and Physics of Solids in 2015, attempted to predict diffusion assisted Hydrogen embrittlement failure in high strength steels (Wu & Zirky, 2015). The study found that prior to embrittlement, the material follows a conventional ductile stress strain with elastic deformation and gradual necking prior to fracture, as illustrated in Figure 9.

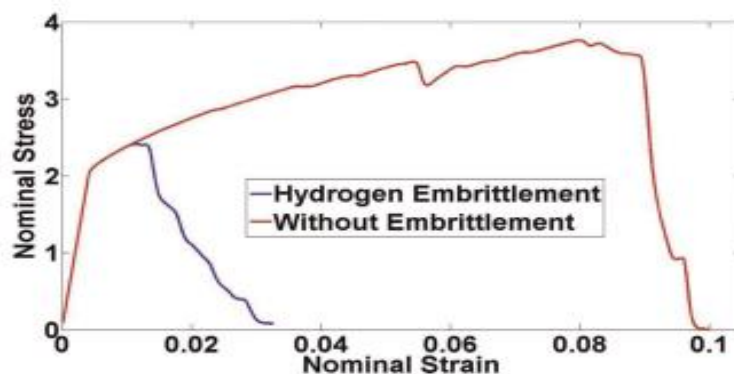


Figure 9: Stress-strain curves for Hydrogen embrittlement cases (Wu & Zirky, 2015).

After Hydrogen diffusion, the steel becomes brittle exhibiting reduced ductility and a lower ultimate tensile strength. As shown in Figure 9, a sudden failure in the steel was witnessed with minimal deformation. The study did not specify a standardised steel grade in

accordance with ASTM, ISO or EN standards but described material as low carbon martensitic steel. This type of steel is known to be highly susceptible to Hydrogen embrittlement, unlike pipeline steels which are specifically designed to resist Hydrogen induced cracking and embrittlement (Wu & Zirky, 2015).

One of the most critical factors influencing Hydrogen embrittlement is the material's Hydrogen permeability, which is the materials ability to allow Hydrogen atoms to diffuse through its structure. Hydrogen permeability between differing materials can vary significantly and can have a major impact on the susceptibility of a material to embrittlement. Materials with high Hydrogen permeability allow Hydrogen atoms to diffuse more easily into their structure, which increase the likelihood of embrittlement under conditions where Hydrogen is present (Laadel, et al., 2022). Low Hydrogen permeability materials, means that Hydrogen may be unable to diffuse as deep into the material. Therefore, reducing the risk of Hydrogen diffusion but even low Hydrogen permeability materials can still suffer Hydrogen embrittlement if Hydrogen is present at high pressure or if the material is under significant tensile stress (Feund, 2016).

2.3 Material Selection for Offshore Hydrogen Pipelines

The fundamental chemical properties of Hydrogen such as the flammability range, auto-ignition temperature, minimum ignition energy and diffusion rate are not expected to significantly change in an offshore environment. However, various external factors associated with offshore subsea Hydrogen pipeline can influence how these properties behave in practical applications (Yuan & Chen, 2014).

International codes for the transportation of Hydrogen in pipelines are still in development, existing industry standards such as those of AMSE B31.12 Hydrogen Piping & Pipelines and ISO 13623:2017 Petroleum and Natural Gas Industries – Pipeline Transportation Systems are shaping the regulatory landscape for offshore Hydrogen pipelines. A key challenge in the development of offshore Hydrogen pipelines is the risk of Hydrogen embrittlement, which significantly influences material requirements. The following material requirements are critical for ensuring safe and efficient offshore Hydrogen pipelines:

1. Resistance to Hydrogen Embrittlement

Materials must have resistance to Hydrogen embrittlement, either through the material properties or through the suitability of the material for coatings and linings to be applied (Nagumo, 2023).

2. Corrosion Resistance

Materials must be capable of being exposed to highly corrosive environments, including saltwater and other environmental factors. The materials must offer resistance to both general and localised corrosion (Sierszecki, et al., 2018).

3. Durability and Strength

An offshore environment can have extreme external conditions, including temperature variations and high pressure especially when considering subsea applications. The material must offer high strength and durability to be capable of operating under long term stress (Moore & Shulman, 2017).

4. Low Permeability to Hydrogen

Small molecular size and high diffusivity means that materials must be selected which have low permeability to minimum the risk of leaks and material degradation (Mazloomi & Gomes, 2012).

5. Fatigue and Impact Resistance

Material must be resistant to fatigue and impact, the fatigue will likely come from cyclic loading of pressure in the line and impact could be from several different sources including accidental impacts (Feund, 2016).

Existing codes such as ASME B31.12, outline approved materials for onshore Hydrogen piping and pipelines. Appendix A includes Table GR-2.1.1-1 which details the material specifications for piping and pipe components. Additionally, Table GR-2.1.1-2 provided in Appendix B specifies the material requirements for onshore Hydrogen pipelines (ASME, 2019).

In addition to ASME B31.12, the European Industrial Gas Association (EIGA) IGC Doc 121/14 Hydrogen Pipeline Systems provides comprehensive guidance on the selection of materials for Hydrogen pipelines (EIGA, 2014). This document is widely used within the industrial gas sector, where Hydrogen production is a well established process and offers specific recommendations for Hydrogen pipeline distribution systems transport pure gaseous Hydrogen at pressures ranging from 150 psig to 3000 psig (EIGA, 2014). The document states that the common carbon steel piping grades which have been widely used in Hydrogen gas service with minimal reported problems are API 5L X52 and ASTM A 106 Grade B. Attributing to the minimal issues to the relatively low strength of the alloys which provides resistance to Hydrogen embrittlement. The use of these steel is further confirmed with both stated in Table IX-1B Steel Pipe Commonly Used in Pipeline Systems published in ASME B31.12 (ASME, 2019).

3 Base Case: Offshore Hydrogen Pipeline System

Developing a base case use is crucial for understanding the mechanical challenges associated with an offshore Hydrogen pipeline. The base case provides an opportunity to explore and define the essential function of an offshore Hydrogen pipeline system, addressing both the general requirements for pipeline transport and the specific functions related to Hydrogen. This base case has been developed using publicly available information from the AquaVentus project in the German North Sea, selected due to the availability of information and ongoing development activities of the project consortium.

Utilising a real proposed location as a base case helps to develop a more realistic base case and address challenges of offshore Hydrogen pipelines.

3.1 Geographical Location

The German government has designated a geographical area known as “SEN-1”, as shown in Figure 10 for the development of green Hydrogen. Located in the German North Sea, this area has an estimated wind power capacity of 1 GW, with an initial tendering round expected to be in the region of 255 MW (Havibic, 2024).

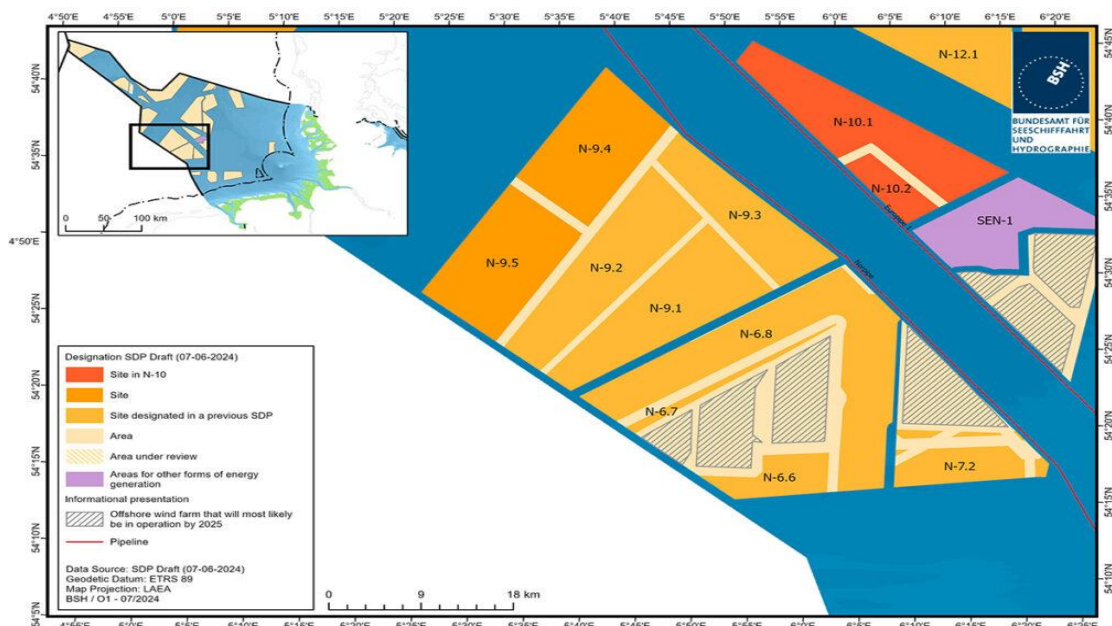


Figure 10: Offshore Energy Areas in German Exclusive Economic Zone (BSH, 2024).

The SEN-1 area is approximately 150 km offshore from Germany and is considered the initial site for offshore Hydrogen development. Future expansions are expected to extend up to 300 km offshore, supporting Germany's pursuit of commercial scale offshore Hydrogen production. It is assumed that the SEN-1 is similar to the adjacent N-10.1 lease area which has an average depth of 42 m (Spinergie, 2025), suitable for fixed bottom turbines.

3.2 Offshore Hydrogen Production

Offshore Hydrogen production concepts can be classified into three main categories:

- **Decentralised Concept** – Each wind turbine is equipped with an electrolyser and required balance of plant. The generated Hydrogen is then transported from each turbine to a central collection platform, where it undergoes treatment and compression before being transported to shore via a dedicated pipeline. This concept is illustrated in Figure 11, with the “green” line representing Hydrogen.

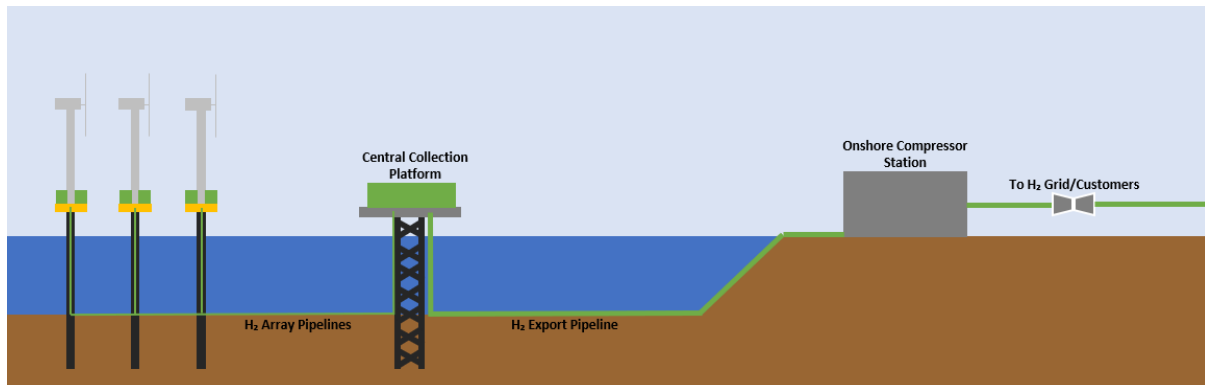


Figure 11: Simplistic Illustration of a Decentralised Concept Approach.

- **Centralised Concept** – Generated electricity of each wind turbine is transmitted to a centralised off shore platform that hosts all the Hydrogen production equipment and balance of plant. Treatment and compression performed on the platform prior to it being sent directly to shore via a dedicated pipeline. This concept is illustrated in Figure 12, with the “yellow” line illustrating electricity and “green” Hydrogen.

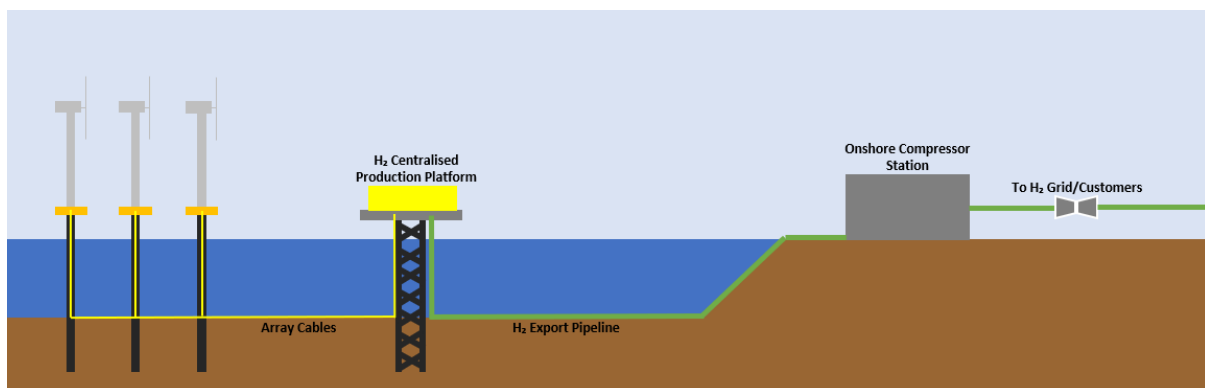


Figure 12: Simplistic Illustration of a Centralised Concept Approach.

- **Semi-Centralised Concept** - Hydrogen produced on several smaller scale dedicated Hydrogen platforms, each powered by a proportion of the wind farm. Generated Hydrogen gathered at a common platform for treatment and compression, then transported to shore via a dedicated pipeline. This concept is illustrated in Figure 13.

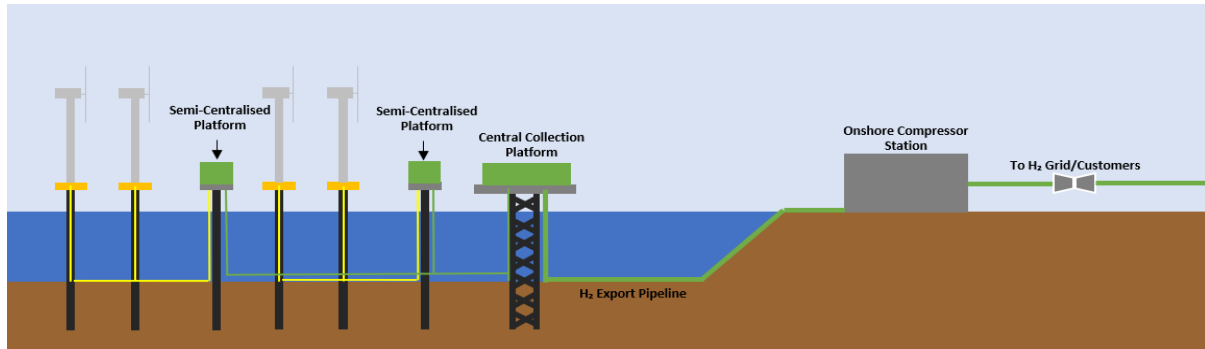


Figure 13: Simplistic Illustration of a Semi-Centralised Concept Approach.

As demonstrated in all three concepts, the variation on the H_2 export line is minimal. As the variations between the concepts occur upstream of the compression stage, which is required to transport Hydrogen to shore. The decentralised concept has been selected due to its more complex configuration upstream of the compression stage with the use of inter array H_2 pipework. This complexity may present additional mechanical challenges to the H_2 export line, making it a more demanding scenario to use in the base case.

3.3 Technical Design Parameters

3.3.1 Pipeline Configuration

Regardless of whether H_2 is produced using a centralised, decentralised or semi-centralised electrolysis approach further compression upstream of the H_2 export pipeline will be required. The necessity arises from the characteristics of proton exchange membrane (PEM) electrolyzers, which are currently the most advanced and commercially viable electrolysis technology. PEM electrolyzers available in the market currently will generate pressurised Hydrogen at approximately 30-40 bar (Hancke, et al., 2024), which is insufficient for long transport via pipeline.

The base case has been developed based on current knowledge and anticipated requirements, drawing insights from the AquaSector project in the German North Sea. It is expected that projects within this region will have access to a “backbone” pipeline, serving as a high capacity Hydrogen export route to shore. The backbone pipeline would allow multiple projects to connect to a share infrastructure, enabling large scale Hydrogen transport with a projected capacity of up to 10 GW (Gascade, 2023).

Based on this projection, the backbone pipeline is expected to be a large scale export pipeline with this base case assuming a diameter of approximately 40 inches. Designed to accommodate multiple Hydrogen producers, the backbone pipeline must ensure seamless integration for various projects. The focus of this dissertation is the export pipeline downstream of the compressor which will tie in to the backbone pipeline, which must be

engineered to withstand the required pressure for an effective tie in. However, the local pressure at the SEN-1 tie in point is an unknown. Figure 14 presents a high level overview of the main components assuming a de-centralised setup, while Table 2 provides a further detail on each stage of the system.

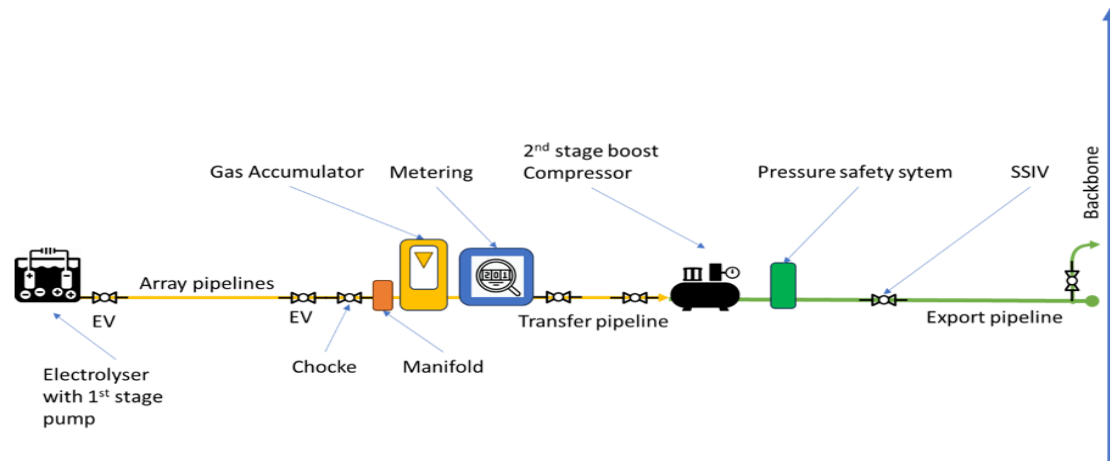


Figure 14: High Level System Overview P&ID.

Item	Description
Electrolyser	The electrolyser will be capable to pressurise the Hydrogen gas to between 30 – 40 bar.
Emergency Valve (EV)	Within the de-centralised concepts a minimum of one EV is located at each turbine.
Array Pipeline	Pipeline from each turbine to a central platform.
Emergency Valve (EV)	Located at the opposite end of each array pipeline.
Manifold	Connecting the array pipeline into a single pipeline.
Gas Accumulator	Required to reduce pressure variations in the array pipeline system. Accumulator will reduce the choking of pressure or flow at each electrolyser.
Metering	Metering can be performed at a central metering platform (as represented in this configuration) or at each turbine.
Transfer Pipeline	Pipeline from manifold to the 2 nd stage compressor.
2 nd Stage Boost Compressor	Boosting the pressure to meet actual pressure in the backbone pipeline.
Pressure Safety System	Protection of the array pipeline system, metering platform and electrolyser from over pressure in the backbone pipeline.
Emergency Valve (EV)	Entrance to export pipeline.
Export Pipeline (Dissertation Focus)	Length and size relates to the location of any 2 nd stage boost compressor and the routing of the backbone pipeline.
Subsea Isolation Valve (SSIV)	Minimisation of consequences of a failure in the array system.
In-line Tee at Backbone	Connection to backbone pipeline with valve and pigging.
Backbone	Common transport pipeline to shore.

Table 2: High Level System Breakdown.

3.3.2 Pipeline Design Pressure

The operating pressure for AquaDuctus, the Hydrogen backbone project highlighted in Figure 15, has not yet been publicly disclosed. Therefore, to establish a base case pressure

for this backbone pipeline, similar projects and concepts can be used to estimate the maximum required pressure for the export pipeline from the production site. One relevant reference project is BarMar, a conceptual offshore Hydrogen pipeline designed to connect Barcelona with the industrial hub in Fos-sur-Mer, Marseille. The estimating operating pressure for this pipeline is 210 bar over a distance of 450 km, using either a 28 inch or 42 inch diameter pipeline (H2med, 2025). Given the similarities in the purpose and scale, this estimated pressure provides a suitable estimate for this base case.



Figure 15: AquaDuctus Artist Impression of Backbone Pipeline (AquaDuctus , 2024).

Based on the information provided, the export pipeline downstream of the compressor must be designed to match the estimated 210 bar pressure of the backbone pipeline. According to ASM B31,12 a design pressure safety factor must be applied to the maximum operating pressure (MOP) to ensure the integrity and safety of the pipeline. Section 841.5 of ASME B31.12 recommends a safety factor of 1.5 to be applied to the MOP. This results in a design pressure of 315 bar for the export pipeline (ASME, 2019).

In addition to the standard safety factor, ASME B31.12 also suggests the user of a higher safety factor of 2 in situations where there are significant design uncertainties, due to high risk environments or extreme pressure conditions. However, for the purpose of the base case the design pressure will be assumed to be 315 bar based on the recommended safety factor of 1.5 times the MOP.

3.3.3 Export Pipeline Length

The length of the export pipeline downstream of the compressor is directly influenced by the distance at which the compression platform is located from the backbone pipeline. Currently, the exact coordinates of the backbone pipeline are not publicly available and the SEN 1 covers a large area. As a result, the potential positioning of a centralised compression platform within the region could vary significantly. Due to these uncertainties a 20 km export pipeline length has been assumed as the base case.

3.3.4 Transport Capacity

The export pipeline must be designed to handle peak Hydrogen production volumes, ensuring adequate capacity for efficient Hydrogen flow. The pipeline diameter will be determined based on the total flow downstream of the compressor, corresponding to the full production output. Additionally, the pipeline must be optimised to minimise frictional losses and prevent excessive pressure drops during the transportation to the backbone pipeline.

Based on the assumption that the SEN 1 tendering will involve approximately 255 MW of installed Hydrogen production capacity, the Hydrogen production rate can be determined using Equation (1).

$$\text{Hydrogen Production Rate} = \frac{P \times \eta}{E_{H_2}} \quad (\text{Eq. 1})$$

Where:

P : Electrolyser Power Input (MW).

η : Efficiency of the electrolyser (Fraction).

E_{H_2} : Energy required to produce 1 kg of hydrogen (kWh/kg).

Electrolyser efficiency typically ranges between 60-80%, depending on the electrolyser technology used (Kumar & Himabindu, 2019). For this base case, a Proton Exchange Membrane (PEM) electrolyser is assumed, which generally operates at 65-75% efficiency (IRENA, 2020). To provide an optimistic estimate, the maximum efficiency of 75% is applied.

Additionally, based on reviewed literature PEM technology is assumed to consume 45.44 kWh per kg of Hydrogen produced (Aghakhani, et al., 2023). Using these parameters, the Hydrogen production rate is calculated as follows:

$$\text{Hydrogen Production Rate} = \frac{255 \times 0.75}{45.44}$$

$$\text{Hydrogen Production Rate} = 4208.8 \text{ kg/h}$$

The resulting Hydrogen production rate is 4,208.8 kg per hour under optimal efficiency conditions. This value is crucial for determining the required pipeline capacity and ensuring reliable transport of Hydrogen without excessive pressure drops.

3.4 Export Pipeline Functional Requirements

The functional requirements for the offshore Hydrogen export pipeline to ensure the efficient, safe and cost effective transportation of Hydrogen from production to the back bone. These

requirements can be categorised into general functional requirements, which are essential for any offshore gas transportation system and specific functional requirement related to Hydrogen transportation.

3.4.1 General Functional Requirements

The primary objectives for any offshore pipeline system, including those transporting natural gas and Hydrogen include the following:

- **Safety and Risk Management:** The ability to safely operate through the correct material selection, pressure containment, corrosion resistance and adequate leak detection.
- **Accessibility and Availability:** The pipeline must be designed to allow continuous and flexible transportation, minimising downtime and ensuring redundancy in the system design.
- **Operational Flexibility:** The ability to operate at varying productions rates and ensuring compatibility with downstream pressure fluctuations.
- **Environmental Protection:** The design and operation of the pipeline should minimise environmental impact, considering aspects such as leakage prevention, materials selection and carbon footprint reduction.

Table 3 outlines the general functional requirements for Hydrogen outlines the general functional requirements associated with both Hydrogen export pipelines and natural gas pipelines. These function requirements have been derived from industry standards and guidelines, including ISO 13623 Petroleum and Natural Gas Industries – Pipeline Transportation Systems for general pipeline design (ISO, 2017). DNV-ST-F101 Submarine Pipeline Systems for offshore pipeline considerations (DNV, 2021). ASME B31.12 Hydrogen Piping and Pipelines has been considered to cover specific Hydrogen pipeline requirements (ASME, 2019).

Functional Requirements	Hydrogen Export Pipeline	Natural Gas Pipeline
Material Selection	Carbon steel with grading X52 or lower. External coating three layer PolyEthylene/Propylene to prevent corrosion and damages during handling and installation. Coating to also reduce possibility of Hydrogen embrittlement.	Carbon steel and corrosion resistant alloys, potential use of a coating to mitigate corrosion in offshore environments.
Corrosion and Integrity Control	Embrittlement concerns due to Hydrogen diffusion. Corrosion prevention using coatings, use of cathodic protection.	Corrosion prevention using coatings, cathodic protection. Regular inspection and maintenance necessary to prevent corrosion from internal gases.

Pressure and Overpressure Control	Overpressure protection with pressure relief valves, rupture discs and automatic shutoff valves. Hydrogen has a lower density and requires specific pressure management technique.	Overpressure protection with pressure relief valves, rupture discs and automatic shutoff valves.
Leak Detection Systems	Pressure drop sensors to detect early leaks, Hydrogen high diffusivity leads to susceptibility of leakage.	Leak detection systems like acoustic sensors, infrared sensors, and pressure drop monitoring. Gas pipelines require robust systems to detect leaks of methane, which is also flammable.
Ignition and Fire Hazard Mitigation	Flame arrestors, spark arrestors, and ignition-proof equipment to handle Hydrogen's low ignition energy. Increased attention to explosive risks.	Flame arrestors, spark arrestors, and explosion-proof equipment. Focus on preventing ignition due to the flammability of natural gas, with attention to safe venting.
Compression and Pumping Systems	Hydrogen compressors designed for lower energy consumption, optimised for Hydrogen's low density. Specialized compressors are required due to Hydrogen's low molecular weight.	Natural gas requires larger compressors to maintain pressure and flow over long distances.
Emergency Response Systems	Automated emergency shutdown systems (ESD) that can isolate sections in case of leaks or pressure problems. Rapid shutdown necessary to prevent escalation of leaks.	Similar ESD systems that isolate sections of the pipeline in case of emergencies such as high-pressure drops, leaks, or equipment failure.
Risk Management	Comprehensive risk assessments (HAZOP, fault tree analysis) to address Hydrogen-specific hazards (embrittlement, diffusion, explosion).	Risk management strategies focus on explosion hazards, corrosion, overpressure, and leak detection. Methane's explosive range requires close attention to safety protocols.
Design Codes and Standards	No current standards address offshore Hydrogen. Currently onshore Hydrogen standards are being utilised and similarities between natural gas transportation considered.	ISO 13623, API 1104 (Welding of Pipelines), ASME B31.8 (Gas Transmission and Distribution), DNV-ST-F101 (Offshore Pipelines).

Table 3: Functional Requirements for Hydrogen and Natural Gas Export Pipelines

The comparison between the functional requirements of an offshore Hydrogen pipeline and a natural gas pipeline reveals several similarities, with key differences arising from the unique chemical properties of Hydrogen as discussed in the base case. Both types of pipelines would typically use carbon steel with protective coatings to prevent corrosion and apply corrosion control methods such as cathodic protection. However, the functional requirements for Hydrogen pipelines must also account for Hydrogen embrittlement, a phenomenon caused by the diffusion of Hydrogen into metals which requires additional protective measures.

Both pipeline systems must address the need to minimise leakage and incorporate leak detection systems, such as pressure drop sensors. However, Hydrogen's high diffusivity makes Hydrogen pipelines more susceptible to leakage necessitating enhanced monitoring and more sensitive detection methods. Both types of pipelines implement emergency

shutdown systems to isolate affected sections in case of leaks or pressure issues but Hydrogen pipelines require particular emphasis on rapid shutdowns to prevent escalation due to the higher risk of explosion and combustion. Risk management strategies for Hydrogen pipelines focus on the specific challenges posed by embrittlement, Hydrogen diffusion and the risk of explosions. Natural gas pipelines are more concerned with the flammability of methane and explosion hazards associated with natural gas.

While the design of natural gas pipelines follows well established standards such as ISO 13623 and API 1104, the design of Hydrogen pipelines is currently based on onshore Hydrogen standards and natural gas transportation codes. These standards are still evolving, with necessary adjustments being made to address Hydrogen's specific challenges. In the context of the base case, this comparison highlights that while the general functional requirements for Hydrogen and natural gas pipelines align well, the design of Hydrogen export pipelines demands specialised considerations. These adjustments are critical to ensuring the safe, efficient and reliable transport of Hydrogen as emphasised by the assumptions made in the base case.

4 Codes and Standards for Offshore Hydrogen Pipelines

The transportation of Hydrogen through offshore pipelines is an emerging concept that currently lacks dedicated codes and standards specific to this application. However, there is growing consensus within the industry that existing standards for onshore Hydrogen transportation are likely to be reviewed and adapted for offshore use. Industry bodies such as DNV are committing to Joint Industry Projects (JIP) on offshore Hydrogen, are actively working on the development and adaptation of relevant standards to support safe and efficient offshore Hydrogen infrastructure (DNV, 2023).

The mechanical challenges associated with onshore Hydrogen pipeline are well documented and it is anticipated offshore Hydrogen pipelines will present a comparable risk profile. To contextualise and assess to which existing standards address key risks, a bowtie model has been developed with relevant standards mapped onto it.

4.1 Offshore Hydrogen Pipeline Generic Bowtie

One of the key concerns related to the mechanical challenges of offshore Hydrogen pipelines is the potential for Major Accident Hazards (MAHs), particularly due to the properties of Hydrogen and potential high pipeline pressures involved. The bowtie model method is a well established risk management methodology that effectively visualises the potential pathways from causes to consequences in major accident scenarios (Fiorentini, 2021). A feature of the bowtie approach is the identification of "barriers", which both prevent

measures that reduce the likelihood of a hazardous event and mitigative measures that minimise consequence. By mapping existing codes and standards to these specific barriers, it allows for identification of where existing standards and codes exist currently.

For the purpose of this activity, a generic bowtie model for offshore Hydrogen pipelines has been developed. The focus was not placed on detailing specific causes, hazardous events or consequences. These have been intentionally left undefined, as their specifics are not critical to this analysis. Instead the exercise focussed on identifying the barriers that would generally be expected to prevent or mitigate any major accident associated with offshore Hydrogen pipelines. A major accident hazard (MAH) in this context refers to an event such as fire, explosion or the release of dangerous substances arising from uncontrolled developments in the course of operation, which could pose to serious danger to human or the environment (Health and Safety Executive (HSE), 2015).

Figure 16 presents a generic bowtie model developed for offshore Hydrogen pipelines using a simplified approach. It is acknowledged that not all barriers are positioned with complete accuracy and some may not be applicable to every initiating cause or hazardous event. The model is intended to serve as a high level representation to support the identification and alignment of safety barriers with relevant standards.

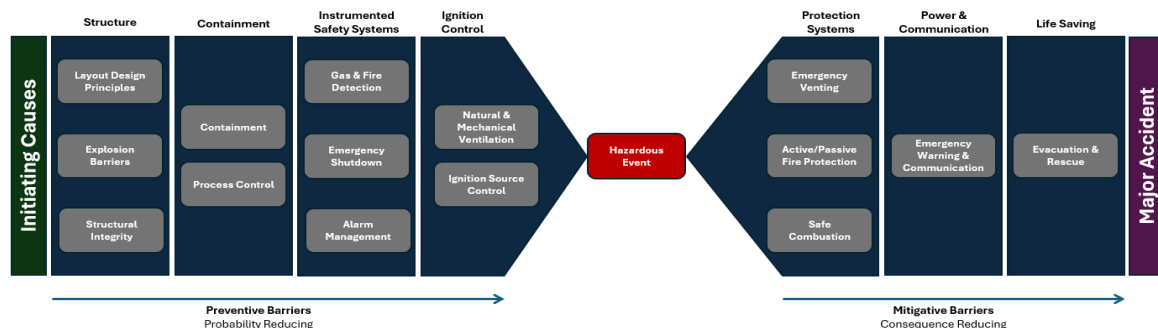


Figure 16: Generic bowtie model for offshore Hydrogen pipelines.

The bowtie model identifies a central “hazardous event” which for the purpose of this exercise could be an event such as a catastrophic pipeline rupture. The bowtie comprises of several safety barriers which have been categorised into:

- Structure
- Containment
- Instrumented safety systems
- Ignition control
- Protection systems
- Power and communication

- Life saving

These categories address both preventive measures aimed at reducing the likelihood of a hazardous event and mitigative measures intended to minimise its consequences. This research includes a review of international, regional and industry specific standards and codes relevant to Hydrogen pipeline safety. These standards have been mapped against the defined bowtie categories. While there is currently a lack of standards developed specifically for offshore Hydrogen, much of the current guidance has been adapted from existing onshore Hydrogen standards and offshore oil and gas standards.

4.1.1 Preventive Barrier Category - Structure

The category of “Structure” comprises three key barriers, layout design principles, explosion barriers and structural integrity. These barriers play a crucial role in preventing hazardous events that may arise from mechanical challenges such as high pressures, potential collisions, corrosion and other similar factors. Due to these risks it is essential that offshore Hydrogen pipeline address these structural challenges. While Hydrogen specific offshore standards are still in development, there are existing standards and codes which can be used for reference. These offer valuable guidance evolving from both the existing oil and gas industry and also onshore Hydrogen pipeline transportation.

The standards and codes identified as relevant to the “structure” category, specifically in the context of offshore or Hydrogen pipelines during the review are listed in Table 4.

Standard/Code Identification	Title
EN ISO 13623	Petroleum and natural gas industries – Pipeline transportation systems
DNV-ST-F101	Submarine pipeline systems
ASME B31.12	Hydrogen Piping and Pipelines

Table 4: Relevant Standards and Codes for "Structure" Category.

EN ISO 13623 provides a comprehensive framework which covers the full lifecycle of pipeline transportation systems in the petroleum and natural gas industries. The standard provides guidance on the integrity management and addresses mechanical challenges such as overpressure, corrosion, fatigue and more (ISO, 2017). DNV-ST-F101 is a technical guidance standard produced by DNV on the topic of submarine pipelines, including guidance on structural design, material selection, installation and more (DNV, 2021). These two standards have traditionally been used solely for offshore natural gas pipelines. However, it is recognised that the standards offer valuable guidance for offshore Hydrogen pipelines. ASM B31.12 differs as this has been developed primarily for onshore Hydrogen pipelines, covering mechanical design principles and offers the ability for industry to adapt these principles into offshore Hydrogen pipeline designs (ASME, 2019).

4.1.2 Preventive Barrier Category – Containment

The category of “Containment” comprises two key barriers, process control and containment. This category focusses on the ability for the offshore pipeline system to adequately retain both the capacity and pressure of Hydrogen under varying operational conditions. This category addresses not only the physical integrity of the pipeline but also incorporates process control measures to manage pressure and maintain overall system integrity.

The standards and codes identified as relevant to the “Containment” category, specifically in the context of offshore or Hydrogen pipelines during the review are listed in Table 5.

Standard/Code Identification	Title
PED 2014/68/EU	Pressure Equipment Directive

Table 5: Relevant Standards and Codes for "Containment" Category.

The preventive barrier “containment” overlaps significantly with barriers in the “structure” category. As a result, the standards and codes listed in Table 5 are limited to those not already covered in previous sections to avoid duplication.

PED 2014/68/EU is not specific to offshore pipeline systems, instead it provides direction on where pipelines interface with pressure rated components such as valves, compressors. The standard also provides details specific to Hydrogen pipeline applications, with components involved required to meet increased standards of pressure containment due to Hydrogen’s high diffusivity, molecular size and susceptibility to embrittlement (EU, 2014). ASME B31.12 also offers material compatibility requirements for associated equipment in Hydrogen service which is aimed at reducing the risk of loss of containment from the system.

4.1.3 Preventive Barrier Category – Instrumented Safety Systems

The category of “Instrumented Safety Systems” is made of several individual barriers, including emergency shutdown, alarm management, gas and fire detection. Instrumented safety systems are a critical layer of protection by enabling early detection, automated response and also real time operator awareness. The offshore Hydrogen pipeline system as previously discussed with by exposed to a range of mechanical challenges. These conditions can increase the likelihood of leaks or mechanical failures, which make the need for these systems even more essential.

It is critical that robust instrumented safety systems are incorporated, offshore Hydrogen pipeline specific standards and codes are under development. However, the standards and codes listed in Table 6 were identified as relevant to the “Instrumented Safety Systems” category.

Standard/Code Identification	Title
IEC 61511	Functional Safety – Safety instrumented systems for the process industry
NFPA 2	Hydrogen Technologies Code
ISO 26142	Hydrogen detection apparatus – Performance requirements
API RP 554	Process Control Systems: Instrumentation, Control and Alarm Systems

Table 6: Relevant Standards and Codes for "Instrumented Safety Systems" Category.

IEC 61511 provides a comprehensive framework for lifecycle management of Safety Instrument Systems (SIS) within the process industry. The standard is widely used and is used across a range of industries including within onshore Hydrogen and offshore gas industries. The standard includes guidance on the design, verification, validation and also functional safety assessment of instrumented systems (IEC, 2016). NFPA 2 is a Hydrogen specific code that defines detection thresholds, system response requirements and also recommended alarm parameters (NFPA, 2023). ISO 26142 further supports NFPA 2 outlining performance requirements for Hydrogen detection apparatus, with the aim to ensure fast and accurate detection of potential leaks. API RP 554 provides guidance on instrumentation and alarm management systems, with the aim to improve response times in the event of hazardous events (API, 2021). While all of these have been developed not specifically for an offshore Hydrogen pipeline system, these could all potentially be used as essential guidance on the safe applications of instrumented safety systems.

4.1.4 Preventive Barrier Category – Ignition Control

The category of "Ignition Control" consists of two individual barriers, with the first being ignition source control and the second ventilation both natural and mechanical. Due to Hydrogen's low ignition energy and broad flammability range the category ignition control is a critical barrier. As discussed in prior sections, even minor ignition energy can result in ignition of gaseous Hydrogen. Therefore, strict control over potential ignition sources is essential particularly at connection points above sea level.

The standards and codes identified as relevant to the "Ignition Control" category during the review are listed in Table 7.

Standard/Code Identification	Title
IEC 60079	Explosive atmospheres (Equipment for hazardous areas)

Table 7: Relevant Standards and Codes for "Ignition Control" Category.

IEC 60079 provides methodologies for the classification of areas where explosive atmosphere may occur, offering detailed guidance on hazardous area zoning and also ventilation requirements (IEC, 2017). The application of this standard is relevant for offshore Hydrogen pipelines, with the standard specifically stating Hydrogen use. The zoning

methodologies are transferrable to pipeline application and is a standard used across a wide range of industries.

4.1.5 Mitigative Barrier Category – Protection Systems

The category of “Protection Systems” consists of three individual barriers which aim to minimise the severity of the consequence after the hazardous event. The barriers include emergency venting, safe combustion and active/passive fire protection. Hydrogen fires can present different challenges to other fuel fires. This includes the visibility of Hydrogen flames, high temperature combustion and also the pressure at which Hydrogen would be transported at. Emergency venting is an effective mitigative barrier when dealing with release of Hydrogen incidents, with the philosophy being to remove the fuel source rather than directly deal with the fire.

The standards and codes identified as relevant to the “Protection Systems” category during the review are listed in Table 8.

Standard/Code Identification	Title
API 521	Pressure-relieving and depressuring systems
EIGA Doc 121/14	Hydrogen Pipeline Systems

Table 8: Relevant Standards and Codes for "Ignition Control" Category.

API 521 is a commonly used guidance document for pressure relief systems and is applied in both onshore and offshore process industries. The document includes methodologies for emergency depressuring, flare designs and thermal relief which are all relevant to offshore Hydrogen pipeline systems (API, 2020). This standard could be used to ensure that rapid isolation and controlled venting of an Hydrogen pipeline system was designed accordingly to prevent further escalation during a leak or rupture cases. EIGA Doc 121/14 is a document produced by the European Industrial Gases Association (EIGA) specifically for Hydrogen pipeline systems. Within the document there is information on safe design, construction, operation and maintenance of Hydrogen pipelines (EIGA, 2014).

The EIGA document is primarily intended for onshore application, it includes information and recommendations that may also be relevant to offshore settings. An example of this is present in Figure 17, which outlines suggested basic components of a Hydrogen pipeline system including pressure relief and venting.

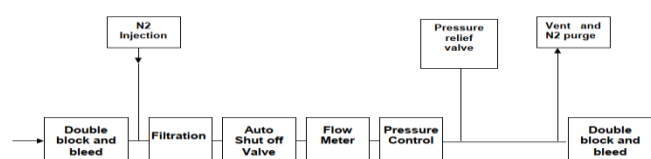


Figure 17: Basic components of a Hydrogen pipeline system (EIGA, 2014).

4.1.6 Mitigative Barrier Category – Power & Communication

The category of “Power & Communication” includes one single barrier which relates to emergency warning and communication. This barrier addresses both the ability to maintain control, coordination and response capabilities during emergency events. Although offshore Hydrogen specific requirement are still developing there are existing standards which could be used for guidance on this barrier. Table 9 provides the standards and codes which were identified during the reviewed that were relevant to the category “Power & Communication”.

Standard/Code Identification	Title
ISO 22320	Emergency Management – Guidelines for Incident Response
ISO 15544	Oil & Gas – Requirements and guidelines for emergency response
OGP Report 478	Guidelines on Emergency Preparedness

Table 9: Relevant Standards and Codes for “Power & Communication” Category.

ISO 22320 outlines the general principles of incident management and emergency response, with an emphasis on effective communication and coordination during emergency situations. Unlike previously mentioned technical standards and codes, ISO 22320 is designed to be broadly applicable and is not specific to any particular technology or industry. It is likely that this standard can be applied to offshore Hydrogen pipeline systems in its entirety with the need for significant adaptation (ISO, 2018). However, standards such as ISO 15544 offer industry specific guidance for emergency response planning primarily for the petroleum and natural gas sectors. The standard covers natural gas pipelines, providing response strategies in high risk environments (ISO, 2024). This standard could be used to ensure that appropriate considerations are made for emergency communication and response, in line with practices from other similarly hazardous industries.

4.1.7 Mitigative Barrier Category – Life Saving

There is significant overlap between the identified standards in Section 4.1.6 and this section. ISO 22320 and ISO 15544 have been previously mentioned and are also directly relevant to the “Life Saving” category, as they provide comprehensive guidance on emergency response in addition to guidance on communication. As these standards cover the key aspects of life saving measures, including evacuation and rescue procedures a separate review under this section was deemed unnecessary due to the potential for duplication.

4.2 Summary of Review

In summary, while there are currently no standards developed specifically for offshore Hydrogen pipeline systems, there is a broad range of existing relevant standard and codes. These have originated from both onshore Hydrogen and offshore oil and gas industries.

Notably, documents such as EIGA Doc 121/14 and ASME B31.12 are well established within the onshore Hydrogen sector and provide a reference point for future applications. The use of a generic bowtie model in this review has enabled the mapping of these standards to key barriers, supporting the identification of relevant existing guidance.

Ongoing industry initiations, including those led by DNV through JIPs are expected to drive the adaptation of standards specifically tailoring them to offshore Hydrogen infrastructure including pipeline systems. Overall, the findings of this review highlight a solid foundation of applicable standards that can be used for guidance, while also emphasising the need for targeted adaptation to address the unique mechanical and operational challenges associated with offshore Hydrogen pipeline systems.

5 Offshore Hydrogen Pipeline Installation & Deployment

The development of a scalable offshore Hydrogen industry is highly dependent on the ability to transport Hydrogen to shore safely and efficiently. This dissertation has focussed specifically on the Hydrogen export pipeline, operating under the assumption that new offshore subsea Hydrogen pipelines will be required for this purpose. While the exact role and configurations of these pipelines remain uncertain, whether they will connect into existing natural gas pipelines or operate as dedicated pipelines to shore. It is evident that offshore Hydrogen pipeline installation will be a critical requirement in either case.

For the purpose of this section, the previously defined base case will be applied. Therefore a 20 km export pipeline with a diameter of 40 inches, installed at a sea depth of 42 m. All installation consideration discussed will be based on the base case scenario.

Offshore pipeline installation is a mature industry, primarily developed for the transportation of oil and natural gas. The industry over the years have developed industry standards such as those produced by API and DNV, which have shaped the safe, reliable and cost effective methods for installing within a wide range of marine conditions.

Installation methods are selected depending on key factors, including the following:

- Pipeline diameter.
- Water depth.
- Environmental constraints.
- Topology.
- Project logistics and schedule.

The four existing offshore pipeline installation techniques are S-Lay, J-Lay, reel-lay and towed lay systems (Guo, et al., 2013). Each method has its own suitability based on technical, economic and environmental parameters.

5.1 S-Lay Installation

The S-Lay method is a commonly used offshore pipeline installation technique where the pipe sections are welded, inspected and coated onboard a lay vessel. The pipeline is then supported over a curved steel stinger before entering the water (Palmer & King, 2008). The method can be performed in shallow to medium water, up to approximately 500 meters and support high installation throughput (Guo, et al., 2013).

Figure 18 illustrates the S-Lay method, highlighting the key features of the S-Lay barge, overbend region, stinger, unsupported span of pipeline and also the seabed touchdown point.

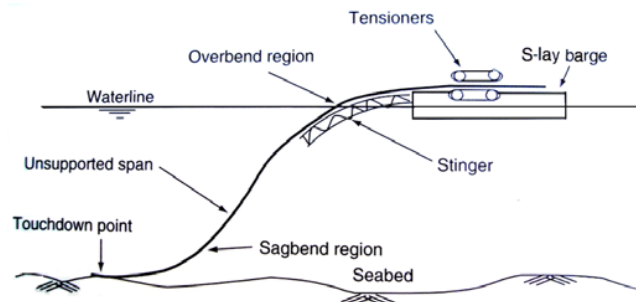


Figure 18: Schematic representation of S-Lay Method (da Silva, et al., 2008).

For the installation of the assumed base case the S-Lay method would be a suitable method. The shallow water depth of approximately 42m would mean that the S-Lay method could be used, benefitting from the continuous laying process allowing for more efficient installation times (Oladimeji, et al., 2016). Hydrogen pipelines pose unique challenges due to the risk of Hydrogen embrittlement and also the small molecular size, the S-Lay method can mitigate this by enabling controlled, high quality welding and inspection onboard.

5.2 J-Lay Installation

The J-Lay method is another widely employed offshore pipeline installation technique, which can be suitable for deep water installations. In this method the pipe sections are welded, inspected, then coated onboard a J-Lay vessel and then lowered vertically through a J-Lay tower. The vertical deployment minimises bending stresses in the pipeline during installation (Palmer & King, 2008).

Figure 19 illustrates the J-Lay installation method, showing the key components of the method including the vertical deployment and the sea bed touchdown point.

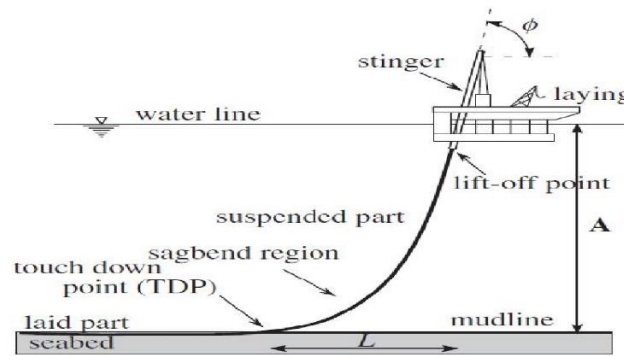


Figure 19: Schematic representation of J-Lay Method (Mawat, 2012).

For the installation of the assumed base case the J-Lay method is technically feasible but is often not used for shallow water. It is primarily design for deepwater pipeline installations, due to the steep departure angle of the pipeline this method become impractical and can lead to increase installation complexity (Guo, et al., 2013). However, the unique requirements of Hydrogen pipelines could make J-Lay an option due to the ability to have a highly controlled welding environment and less bending during installation (Oladimeji, et al., 2016). While S-Lay is a more efficient method in shallow waters, J-Lay could be considered an alternative especially where weld integrity is prioritised such as in Hydrogen pipelines.

5.3 Reel-Lay Installation

The Reel-Lay method is an efficient offshore pipeline installation technique, widely used for small to medium diameter pipelines and is particularly well suited for diameters ranging from 16 to 18 inches (OUCO, 2023). This method involves the pipeline being welded, inspected and tested onshore before being spooled onto a large reel. The pipeline is gradually unspooled and guided to the seabed.

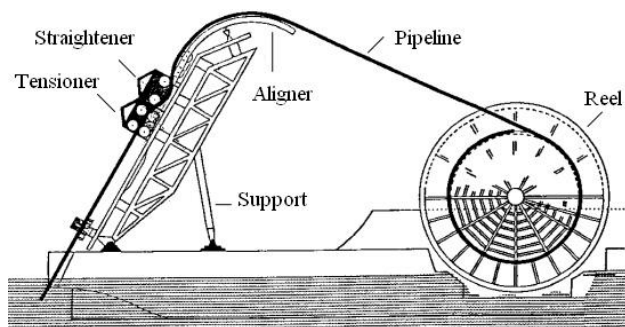


Figure 20: Schematic representation of Reel-Lay Method (Xianwei, 2012).

For the installation of the assumed base case the Reel-Lay method would be technically infeasible due to the large pipe diameter. Additionally, Hydrogen pipelines require excellent weld quality and material integrity to mitigate risks such as Hydrogen embrittlement. The

cold bending that occur during the Reel-Lay can increase the likelihood of structural damage.

5.4 Towed Lay Installation

The towed lay method involves the fabrication of the pipeline onshore and towing it to the installation site. Once at the installation site, the pipeline is then guided to the seabed using controlled ballasting or tension systems. For the assumed base case, the towed lay method could be feasible. However, the large diameter would present handling challenges and the towed lay method would offer less control over pipe stress and bending during the installation. This could be problematic when considering Hydrogen pipelines as the installation needs to provide minimal mechanical strain and minimise unpredictable stresses. Figure 21 illustrates a towed lay installation using a surface tow method.

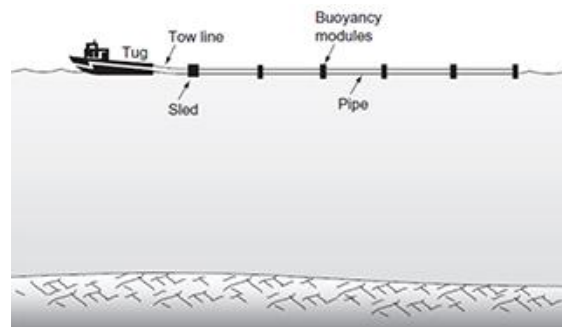


Figure 21: Schematic representation of Towed Lay Method (IndonesiaRe, 2020).

6 Conclusions of the Dissertation and Proposed Future Work

6.1 Conclusions of the Dissertation

As outlined in the project contextualisation, the urgency to achieve net-zero and realise future low carbon energy solutions has been emphasised through initiatives such as the Paris Agreement. The integration of green offshore Hydrogen as discussed throughout the research is a growing concept, with the potential to utilise an abundance of offshore wind. However, one of the significant challenges is the ability to develop a robust offshore hydrogen pipelines to ensure efficient and safe transportation. This dissertation has explored this, which can be seen as one of the technical challenges of realising the concept of offshore Hydrogen production.

At the centre of these challenges is Hydrogen's unique chemical behaviour, which differentiates significantly from other common fuels. Hydrogen's wide flammability range, low minimum ignition energy and small molecular size means it is far more prone to leakage and ignition. Additionally, the risk of Hydrogen embrittlement where Hydrogen atoms can infiltrate microstructures causing premature cracking and loss of ductility is a critical concern. This

research has shown that addressing these risks begins with an enhanced understanding of Hydrogen's physical properties and their implications on material performance. The research also highlighted that these challenges are fairly well understood due to the transportation of Hydrogen via pipelines being a well established process onshore. With existing publications covering the challenges that the properties of Hydrogen can bring to pipelines such as ASME B31.12.

A key contribution of the dissertation was the establishment of a realistic base case for an offshore Hydrogen pipeline system. The base case was modelled on the SEN-1 zone within the German North Sea and inspired by real word initiatives seen in both AquaVentus and Aqua Ductus. This allowed for the base case to be established using a plausible engineering scenario. This base case enabled the definition of technical design parameters, including pipeline diameter, design pressure, length and flow capacity. This resulted in a valuable framework for identifying mechanical challenges related to pressure containment, flow stability and structural integrity.

The calculation of the Hydrogen rate based on a 255 MW electrolyser capacity and accounting for realistic efficiency levels, determined an estimated output of over 4,200 kg of Hydrogen per hour. A design pressure of 315 bar was adopted based on ASME B31.12 guidance, applying an appropriate safety factor. The calculations demonstrate the scale and complexity of the infrastructure needed to support offshore Hydrogen systems which ultimately end up feeding in the pipeline system.

In reviewing the current landscape of applicable standards and codes, it became clear that the offshore Hydrogen sector does not have established specific standards. However, it does sit between two established sectors the O&G and onshore Hydrogen pipeline sector. With both sectors having well established standards. Standards such as ASM B31.12 and ISO 13623 were evaluated for their applicability to offshore. The standards in conclusion offer a valuable starting point but do not fully address Hydrogen in offshore environments. The integration of a bowtie risk model provided a structure approach to map the identified standards. This method identified that there is a wide range of standards and codes which could be considered relevant but none which are specific to offshore Hydrogen.

The dissertation also examined the offshore pipeline installation methods. These methods are well established in the O&G sector, their adaptation for hydrogen introduces new mechanical considerations. For example, the welding techniques must ensure Hydrogen compatible joint integrity. The findings from this led to the conclusion that offshore Hydrogen pipeline installation is technically feasible but further consideration would be required to ensure that the unique Hydrogen chemical properties were considered.

In conclusion, the dissertation has met its aims by identifying and evaluating mechanical challenges that offshore Hydrogen pipelines face. It has also demonstrated the value of combining theoretical analysis with a practical base case inspired by real word initiatives, show how such systems could be realised in the near future. While the technical feasibility of Offshore hydrogen pipelines has been supported, the findings reinforce the need for further research, regulatory development and installation best practices to be established.

At the time of writing this dissertation, the future of offshore Hydrogen remain uncertain largely due to global political and economic volatility. Rising interest rates and inflation in recent years have significantly increased the cost of capital, which has contributed to project delays and cancellation even in matured renewable energy sectors such as wind and solar (IEA, 2024). As a result, emerging technologies like offshore Hydrogen, which involve substantial upfront investment and are commercially unproven are facing heightened scrutiny and financial caution.

Despite these uncertainties, this dissertation has identified areas for proposed future work that are essential to advancing the safe and effective development of offshore Hydrogen pipeline systems.

6.2 Proposed Future Work

Offshore Hydrogen transport via pipelines is a new and emerging concept. Therefore, there are numerous aspects in this dissertation which would benefit from future work. The following could be addressed;

1. The referenced analysis in Section 2.2 and 2.3 highlights how hydrogen embrittlement and corrosion are critical risk for offshore Hydrogen pipelines. Although research concluded that materials such as API 5L X52 are commonly used, more testing is needed under real offshore conditions. This would include long term exposure to sea water and high pressure Hydrogen. This future work would aim to improve material specifications and validate performance.
2. The base case developed in Section 3 was based on public information from projects such as AquaVentus and AquaDuctus. This base case included several assumptions, future work could involve refining this base case. Using real environmental conditions, pipeline distances, bathymetric data from confirmed offshore Hydrogen development zones such as SEN-1.
3. As discussed in Section 4, there is currently no dedicated set of standards for offshore Hydrogen pipeline systems. Existing codes such as ASME B31.12 and ISO 13623 provide a reference point but do not address the full range of offshore specific factors. Future work should support the review and development of

specific standards related to offshore Hydrogen pipelines, which is currently being carried out through industry led initiatives like the Joint Industry Projects (JIPs) by DNV.

4. The use of bowtie risk models were used in Section 4.1 as a framework for mapping existing standards to safety barriers. However, more detailed quantitative risk assessments such as HAZOPs could offer a more enhanced framework to assess the availability of standards and codes.
5. In Section 5 pipeline installation methods were reviewed in the context of the base case of a 40 inch, 20 km pipeline at 42 m water depth. Future research could refine these methods to adapt them specifically for Hydrogen's mechanical requirements.

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Appendices

Appendix A: ASME B31.12 Piping and Pipe Components

ASME B31.12-2019

(19)

Table GR-2.1.1-1 Material Specification Index for Piping and Pipe Components

Spec. No.	Title
ASTM	
A36	Carbon Structural Steel [Note (1)]
A53	Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless [Note (2)]
A105	Carbon Steel Forgings for Piping Applications [Note (2)]
A106	Seamless Carbon Steel Pipe for High-Temperature Service [Note (2)]
A134	Pipe, Steel, Electric-Fusion (Arc)-Welded (Sizes NPS 16 and Over) [Note (1)]
A135	Electric-Resistance-Welded Steel Pipe [Note (2)]
A139	Electric-Fusion (Arc)-Welded Steel Pipe (NPS 4 and Over) [Note (2)]
A179	Seamless Cold-Drawn Low-Carbon Steel Heat-Exchanger and Condenser Tubes [Note (2)]
A181	Carbon Steel Forgings for General-Purpose Piping [Note (2)]
A182	Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service [Note (2)]
A204	Pressure Vessel Plates, Alloy Steel, Molybdenum [Note (2)]
A213	Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes
A216	Steel Castings, Carbon, Suitable for Fusion Welding, for High-Temperature Service
A234	Piping Fittings of Wrought Carbon Steel and Alloy Steel for Moderate and High Temperature Service [Note (2)]
A240	Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications [Note (3)]
A249	Welded Austenitic Steel Boiler, Superheater, Heat-Exchanger, and Condenser Tubes
A269	Seamless and Welded Austenitic Stainless Steel Tubing for General Service
A283	Low and Intermediate Tensile Strength Carbon Steel Plates [Note (1)]
A299	Pressure Vessel Plates, Carbon Steel, Manganese-Silicon [Note (2)]
A302	Pressure Vessel Plates, Alloy Steel, Manganese-Molybdenum and Manganese-Molybdenum-Nickel [Note (2)]
A312	Seamless, Welded, and Heavily Cold Worked Austenitic Stainless Steel Pipes [Note (2)]
A333	Seamless and Welded Steel Pipe for Low-Temperature Service [Notes (2) and (4)]
A334	Seamless and Welded Carbon and Alloy-Steel Tubes for Low-Temperature Service [Notes (2) and (4)]
A335	Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service [Note (2)]
A350	Carbon and Low-Alloy Steel Forgings Requiring Notch Toughness Testing for Piping Components [Note (2)]
A358	Electric-Fusion-Welded Austenitic Chromium-Nickel Stainless Steel Pipe for High-Temperature Service and General Applications
A369	Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High-Temperature Service
A376	Seamless Austenitic Steel Pipe for High-Temperature Central-Station Service
A381	Metal-Arc-Welded Steel Pipe for Use With High-Pressure Transmission Systems [Note (2)]
A387	Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum [Note (5)]
A403	Wrought Austenitic Stainless Steel Piping Fittings
A409	Welded Large Diameter Austenitic Steel Pipe for Corrosive or High-Temperature Service
A420	Piping Fittings of Wrought Carbon Steel and Alloy Steel for Low-Temperature Service [Note (2)]
A451	Centrifugally Cast Austenitic Steel Pipe for High-Temperature Service
A479	Stainless Steel Bars and Shapes for Use in Boilers and Other Pressure Vessels [Note (3)]
A516	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service [Note (5)]
A524	Seamless Carbon Steel Pipe for Atmospheric and Lower Temperatures [Note (2)]
A537	Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon Steel [Note (5)]
A587	Electric-Resistance-Welded Low-Carbon Steel Pipe for the Chemical Industry [Note (2)]
A671	Electric-Fusion-Welded Steel Pipe for Atmospheric and Lower Temperatures [Note (2)]
A672	Electric-Fusion-Welded Steel Pipe for High-Pressure Service at Moderate Temperatures [Note (2)]
A691	Carbon and Alloy Steel Pipe, Electric-Fusion-Welded for High-Pressure Service at High Temperatures [Note (2)]
B21	Naval Brass Rod, Bar, and Shapes
B26	Aluminum-Alloy Sand Castings
B42	Seamless Copper Pipe, Standard Sizes
B43	Seamless Red Brass Pipe, Standard Sizes
B61	Steam or Valve Bronze Castings [Note (6)]
B62	Composition Bronze or Ounce Metal Castings [Note (6)]
B68	Seamless Copper Tube, Bright Annealed

Table GR-2.1.1-1 Material Specification Index for Piping and Pipe Components (Cont'd)

Spec. No.	Title
ASTM (Cont'd)	
B75	Seamless Copper Tube
B88	Seamless Copper Water Tube
B96	Copper-Silicon Alloy Plate, Sheet, Strip, and Rolled Bar for General Purposes and Pressure Vessels
B98	Copper-Silicon Alloy Rod, Bar and Shapes
B127	Nickel-Copper Alloy (UNS N04400) Plate, Sheet, and Strip
B133	Copper Rod, Bar, and Shapes
B148	Aluminum-Bronze Sand Castings
B150	Aluminum Bronze Rod, Bar, and Shapes
B152	Copper Sheet, Strip, Plate, and Rolled Bar
B165	Nickel-Copper Alloy (UNS N04400) Seamless Pipe and Tube
B169	Aluminum Bronze Plate, Sheet, Strip, and Rolled Bar
B171	Copper-Alloy Condenser Tube Plates
B187	Copper Bar, Bus Bar, Rod, and Shapes
B209	Aluminum and Aluminum-Alloy Sheet and Plate
B210	Aluminum and Aluminum-Alloy Drawn Seamless Tubes
B211	Aluminum and Aluminum-Alloy Bar, Rod, and Wire
B221	Aluminum and Aluminum-Alloy Extruded Bars, Rods, Wire, Profiles, and Tubes
B241	Aluminum and Aluminum-Alloy Seamless Pipe and Seamless Extruded Tube
B247	Aluminum and Aluminum-Alloy Die Forgings, Hand Forgings, and Rolled Ring Forgings
B280	Seamless Copper Tube for Air Conditioning and Refrigeration Field Service
B283	Copper and Copper-Alloy Die Forgings (Hot-Pressed)
B345	Aluminum and Aluminum-Alloy Seamless Pipe and Seamless Extruded Tube for Gas and Oil Transmission and Distribution Piping Systems
B361	Factory-Made Wrought Aluminum and Aluminum-Alloy Welding Fittings
B466	Seamless Copper-Nickel Pipe and Tube
B467	Welded Copper-Nickel Pipe
B491	Aluminum and Aluminum-Alloy Extruded Round Tubes for General-Purpose Applications
B547	Aluminum and Aluminum-Alloy Formed and Arc-Welded Round Tube

API

5L Line Pipe [Note (2)]

GENERAL NOTES:

- (a) The design pressure shall not exceed 15,000 psi for all materials unless otherwise noted, provided the material suitability is demonstrated by tests in hydrogen, such as per ASME BPVC, Section VIII, Division 3, Article KD-10.
- (b) See [Mandatory Appendix II](#) for reference dates of specifications.

NOTES:

- (1) For nonpressure applications only.
- (2) The design pressure shall not exceed 6,000 psi unless the material suitability is demonstrated by tests in hydrogen, such as per ASME BPVC, Section VIII, Division 3, Article KD-10.
- (3) Austenitic grades only.
- (4) Grades containing Ni additions above 0.50 shall not be used.
- (5) The design pressure shall not exceed 4,500 psi unless the material suitability is demonstrated by tests in hydrogen, such as per ASME BPVC, Section VIII, Division 3, Article KD-10.
- (6) Brass and bronze castings that are polymer impregnated should not be used.

Appendix B: ASME B31.12 Pipelines

Table GR-2.1.1-2 Material Specification Index for Pipelines

Spec. No.	Grade	Description
ASTM		
A53	A	Electric resistance welded, seamless 30,000 psi
A53	B	Electric resistance welded, seamless 35,000 psi
A106	A	Seamless 30,000 psi
A106	B	Seamless 35,000 psi
A106	C	Seamless 40,000 psi
A135	A	Electric resistance welded 30,000 psi
A135	B	Electric resistance welded 35,000 psi
A139	A	Electric fusion welded 30,000 psi
A139	B	Electric fusion welded 35,000 psi
A139	C	Electric fusion welded 42,000 psi
A139	D	Electric fusion welded 46,000 psi
A139	E	Electric fusion welded 52,000 psi
A333	1	Seamless, electric resistance welded 30,000 psi
A333	6	Seamless, electric resistance welded 35,000 psi
A333	10	Seamless, electric resistance welded 65,000 psi
A381	...	Class Y-35 double submerged-arc welded 35,000 psi
A381	...	Class Y-42 double submerged-arc welded 42,000 psi
A381	...	Class Y-46 double submerged-arc welded 46,000 psi
A381	...	Class Y-48 double submerged-arc welded 48,000 psi
A381	...	Class Y-50 double submerged-arc welded 50,000 psi
A381	...	Class Y-52 double submerged-arc welded 52,000 psi
A381	...	Class Y-56 double submerged-arc welded 56,000 psi
A381	...	Class Y-60 double submerged-arc welded 60,000 psi
A381	...	Class Y-65 double submerged-arc welded 65,000 psi [Note (1)]
API		
5L	A	Electric resistance welded, double submerged-arc welded 30,000 psi
5L	B	Electric resistance welded, seamless, double submerged-arc welded 35,000 psi
5L	X42	Electric resistance welded, seamless, double submerged-arc welded 42,000 psi
5L	X52	Electric resistance welded, seamless, double submerged-arc welded 52,000 psi
5L	X56	Electric resistance welded, seamless, double submerged-arc welded 56,000 psi
5L	X60	Electric resistance welded, seamless, double submerged-arc welded 60,000 psi
5L	X65	Electric resistance welded, seamless, double submerged-arc welded 65,000 psi [Note (1)]
5L	X70	Electric resistance welded, seamless, double submerged-arc welded 70,000 psi [Note (1)]
5L	X80	Electric resistance welded, seamless, double submerged-arc welded 80,000 psi [Note (1)]

GENERAL NOTES:

- (a) The maximum operating pressure (MOP) shall not exceed 3,000 psi for all materials unless otherwise noted, provided the material suitably is demonstrated by tests in hydrogen, such as per ASME BPVC, Section VIII, Division 3, Article KD-10.
- (b) Grades containing Ni additions above 0.50 shall not be used.
- (c) See [Mandatory Appendix II](#) for reference dates of specifications.

NOTE: (1) MOP shall be less than 1,500 psi.