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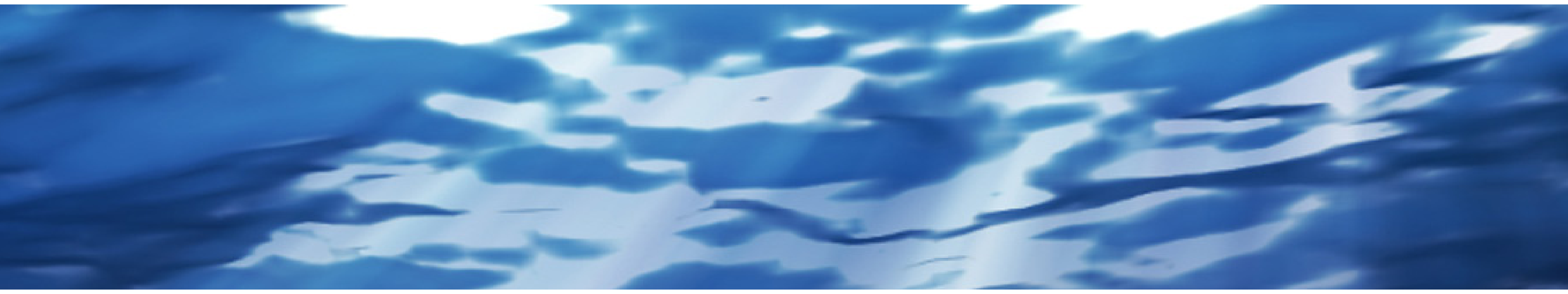

LIGHTHOUSE REPORTS

Hydrogen to port

How to transport hydrogen from product to port?

Ett förstudie initierad av Lighthouse. Publicerad januari 2024

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How to transport hydrogen from production to port?

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Summary

This feasibility study has been initiated and financed by Lighthouse and aims to increase knowledge about the use of hydrogen as a marine fuel, where it has good conditions to be a sustainable and efficient fuel in certain segments.

Hydrogen (H) is the most common element, about 75% of all mass in the universe is hydrogen. Hydrogen gas (H_2) is formed from two hydrogen atoms, the gas has a high energy content per unit weight, about 3.5 times higher than diesel, which is a very good property for a fuel. However, hydrogen gas does not exist naturally but must be produced by releasing hydrogen from other molecules. The most common way to produce it sustainably is by splitting water into hydrogen and oxygen in an electrolysis process. However, the use of hydrogen is difficult by the fact that it is very voluminous, at 200 bar pressure, one cubic meter weighs about 15 kg. Which means that transporting hydrogen can be very costly.

In this report we study how hydrogen can be transported from production to the quay. Port of Visby and the future hydrogen-powered Gotland ferries, Gotland Horizon and Horizon X, is used as a case study.

With an assumed regional production of hydrogen and the expected demand for hydrogen, the report shows that a solution where hydrogen is transported in a pipeline system is the most efficient solution. The report provides an overview of rules and regulations governing the establishment of a pipeline system for hydrogen. Finally, calculation methods are presented to design both pipelines and compressors for a given flow.

As part of the work, a seminar with the theme of hydrogen handling in ports has also been arranged in collaboration with Lighthouse, Ports of Stockholm, Swedish Marine Technology Forum, RISE and Uppsala University.

The feasibility study has been carried out by Björn Samuelsson, Uppsala University (project manager), Jim Allansson, Uppsala University and Ellinor Forsström, RISE. The work has been done in collaboration with Christer Bruzelius, Gotland Tech Development and Charlotta Solerud and Camilla Strümpel at Stockholms Hamnar

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Sammanfattning

Denna förstudie har initierats och finansierats av Lighthouse och har som syfte att öka kunskapen kring användning av vätgas som ett marint bränsle, där den har goda förutsättningar att inom vissa segment vara ett hållbart och effektivt bränsle.

Väte (H) är det vanligaste grundämnet, ca 75% av all massa i universum är väte. Vätgas bildas av två väteatomer, H_2, denna gas har ett högt energiinnehåll per viktenhet, ca 3.5 gånger högre än diesel, vilket är en god egenskap för ett bränsle. Dock finns inte vätgas naturligt utan måste skapas genom att frigöra väte från andra ämnen. Det vanligaste sättet att framställa vätgas på ett hållbart sätt är genom att dela upp vatten i vätgas och syre i en elektrolysprocess. Användningen av vätgas försvåras dock av att den är väldigt voluminös. Vid 200 bars tryck väger en kubikmeter ca 15 kg, vilket innebär att transport av vätgas kan bli mycket kostsam.

I denna rapport analyseras med utgångspunkt i vätgasens egenskaper hur denna bör transporteras till kaj. Som fallstudie används Visby hamn och de framtida vätgasdrivna Gotlandsfärjorna, Gotland Horizon och Horizon X.

Med en antagen regional produktion av vätgas och den förväntade efterfrågan av vätgas visar rapporten att en lösning där vätgas transporteras i ett pipeline-system är den effektivaste lösningen. I rapporten ges en översikt över de regler och förordningar som styr etableringen av ett pipeline-system för vätgas. Slutligen presenteras beräkningsmetoder för att dimensionera såväl pipelines som kompressorer för ett givet flöde.

Kopplat till förstudien har även ett seminarium med tema vätgashantering i hamn arrangerats i samarbete mellan Lighthouse, Stockholms Hamnar, Svenskt Marintekniskt Forum, RISE samt Uppsala universitet.

Arbetet med förstudien har gjorts av Björn Samuelsson, Uppsala universitet (projektledare), Jim Allansson, Uppsala universitet samt Ellinor Forsström, RISE. Arbetet har skett i samarbete med Christer Bruzelius, Gotland Tech Development samt Charlotta Solerud och Camilla Strümpel vid Stockholms Hamnar

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1 Introduction

Hydrogen has a good potential to become an important part of the necessary transition to a fossil free shipping. However, as well as there are good opportunities there are also certain challenges that must be addressed before a large-scale implementation can be undertaken. An absolute necessity for the implementation is a safe, cost-efficient, and reliable supply system. In this report we will analyse one important part in the supply system: the transport of hydrogen from production to quay.

1.1 Transport of hydrogen

Hydrogen has the benefit of a high energy value per weight unit, about 3,5 times higher than diesel. But, on the other hand hydrogen is very voluminous. One cubic meter of hydrogen pressurized to 200 bars has a weight of ca 15 kg, which can be compared to diesel which has a weight of ca 800 kg/m3. The latter means obviously that transport of hydrogen is a challenge which needs some careful considerations.

If the hydrogen is not produced on-site – which might be troublesome in a port – the gas must be transported. In principle this can be done by tube-trailer on road or rail, by ship or in pipelines. In this report we will compare transport by ship with a pipeline system from a cost perspective. Transport by road is not considered since it will require up to 50 trailers per 24h, which in practice is impossible due to the local narrow traffic situation. Furthermore, we will discuss the details regarding dimensioning a pipeline system and legislative and regulatory parts concerning hydrogen pipelines.

1.2 Case study

Rederi AB Gotland is currently planning for new hydrogen-powered ferries to operate between mainland Sweden and Gotland. The new system is planned to be implemented from 2030 and presently two different ferries are under development, a traditional RoPax and a high-speed catamaran. The planned RoPax, Gotland Horizon, will have a capacity of 1900 passengers and up to 700 cars with a cruising speed of 28 knots, whilst the catamaran, Horizon X, will carry 1600 passengers and 400 cars in 35 knots (Gotlandsbolaget 2023).

This study is based upon this future Gotland ferry system. It is assumed that filling of hydrogen to the ferries will only take place in the port of Visby. We assume the capacity of the system to be dimensioned for one Gotland Horizon ferry, which means 16 tonnes per roundtrip and up to three roundtrips per 24h during peak season.

1.3 Purpose and goal

With the raising interest in using hydrogen as a maritime fuel it is important to evaluate how an efficient, safe and reliable supply system should be designed. The purpose of this work is to examine possible ways of transporting hydrogen from production to port, estimating the expected investments and costs and examining applicable laws and regulations. Based on the findings, we will give recommendations on how a transport system could be set up for a larger hydrogen supply system, using the future Gotland ferry system as a case study.

2 Cost comparison of distribution pathways of hydrogen

In most cases the hydrogen produced needs to be transported to where it will be used. This report concerns hydrogen as a marine fuel; hence it needs to be available in the port for filling to the ships. The demand for hydrogen for the maritime system is presumed to soon become quite big volumes, which obviously has an impact on the possible distribution pathways. The studied case system will fully implemented have an annual demand of circa 25 000 ton of hydrogen.

Presently hydrogen is mainly used within the chemical or petro-chemical industries, either the hydrogen is produced on-site (steam reformed from natural gas) or transported in tube trailers on road. Producing hydrogen in the port is in our case study not possible due to lack of space and the immediate vicinity of the populated city Visby. A typical tube-trailer can carry about one ton at the pressure of 500 bars. Using trailers would cause more than 25 000 trailers per year, during peak season up to 50 trailers per 24 hours would be needed. Hence, we can of practical reasons also exclude road-trailer based distribution. Remaining solutions are either pipelines, sea transport or by rail. In our case study we can exclude rail since there are no railways on the island Gotland.

This means that we are left with two possible distribution pathways: pipeline or sea transport. For both options we have several possible alternative solutions within them, mainly related to at which pressure we will transport the hydrogen.

2.1 Pipelines or sea transport?

As described above, when it comes to the distribution of hydrogen several options exist. Not only do they differ in regard to technical properties (which of course will be the first deciding factor when a hydrogen project is considered), but they also differ in economical properties.

In this Gotland case, two main pathways are considered in the feasibility study. Either the hydrogen is transported through pipelines or by sea transport. Leaving the question and cost variation of the different hydrogen carriers in shipping aside, some general conclusions can be made when comparing hydrogen distribution by shipping or pipelines. In both cases, the cost of distributing hydrogen is a function of the project size and distance.

Regarding pipelines, the question of the scale of the project is the most important aspect as it directly impacts the diameter of the pipes. The capacity of a pipeline increases by the square of the diameter while the cost of establishing a pipeline (simplified) increases linearly with the distance. Hence, the pipelines hold their best economic efficiency in larger projects in shorter distances as it exhibits a larger cost decrease as the capacity increases. However, when longer distances are considered, more steel is needed for the pipeline and more compression is needed to transport the hydrogen.

In the case of using pipeline, the hydrogen will be in gaseous form compressed to a certain pressure, in most cases less than 80 bars. If, on the other hand, shipping is used for the transport, the hydrogen can be converted into either liquid hydrogen (at -252°C) or to another carrier like ammonia or methanol. By this conversion the energy density will be substantially higher than for compressed gas, a factor of 11.5 for liquid hydrogen and 16 for ammonia.

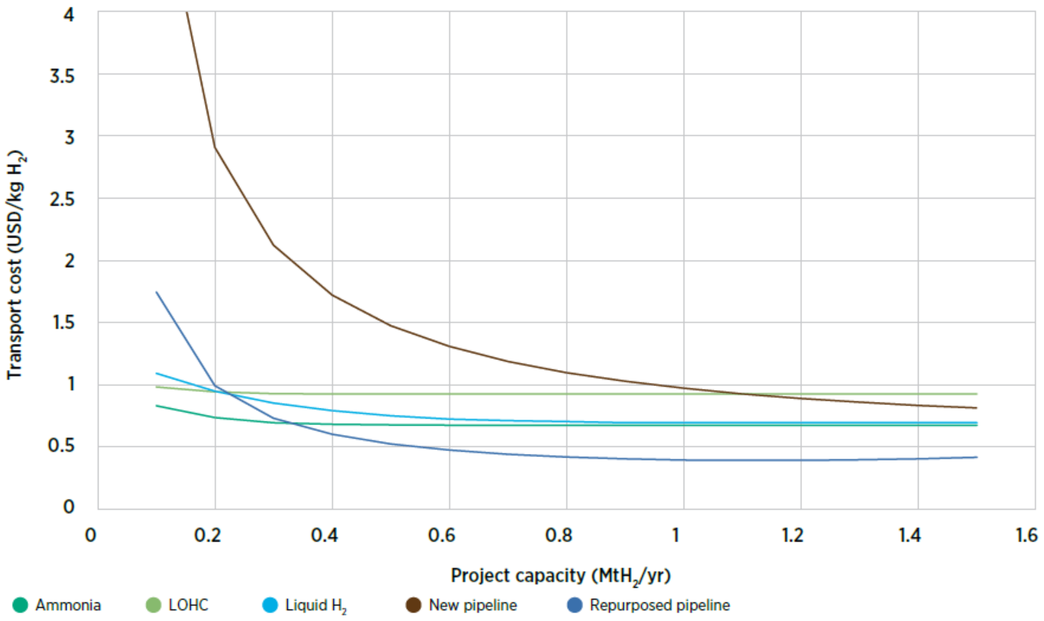
Simplified, the cost of transporting hydrogen by ship differs from pipelines twofold. Firstly, the base cost of a pipeline is relatively small, constituting only the material used and a compressor that secures the right operating pressure. For a ship, the non-negligible cost of conversion of hydrogen (if needed), the storage at the terminal, terminal and port facilities will be the same regardless of the distance the hydrogen has been transported. Secondly, the impact of distance differs between the two alternatives. As described for a pipeline, the cost of hydrogen transport increases linearly with the distance. As for a ship, larger changes in the distance could motivate the need for additional ships to maintain a continuous supply. In addition, as the energy density of the hydrogen onboard a ship (if a hydrogen carrier is used) is much higher than for compressed gas in pipelines, the ship can transport more energy per the energy consumption needed (operational cost) per unit hydrogen.

Due to the large hydrogen volumes needed in the Gotland case, we exclude maritime transport of hydrogen in gaseous form. Such a setup will not be either practical or economical (see the next section of this chapter).

In recent years several cost analyses have been made to determine the economical properties of transporting hydrogen by different hydrogen carriers and ways of transport. The International Renewable Energy Agency published 2022 a report where the hydrogen transport cost for different alternatives was reviewed. The considered alternatives are as gaseous hydrogen in pipeline, either in new pipelines or repurposed ones; as liquified hydrogen; as ammonia or liquid organic hydrogen carriers (LOHC), in this latter alternative the hydrogen is bound to other molecules and must be converted back to hydrogen.

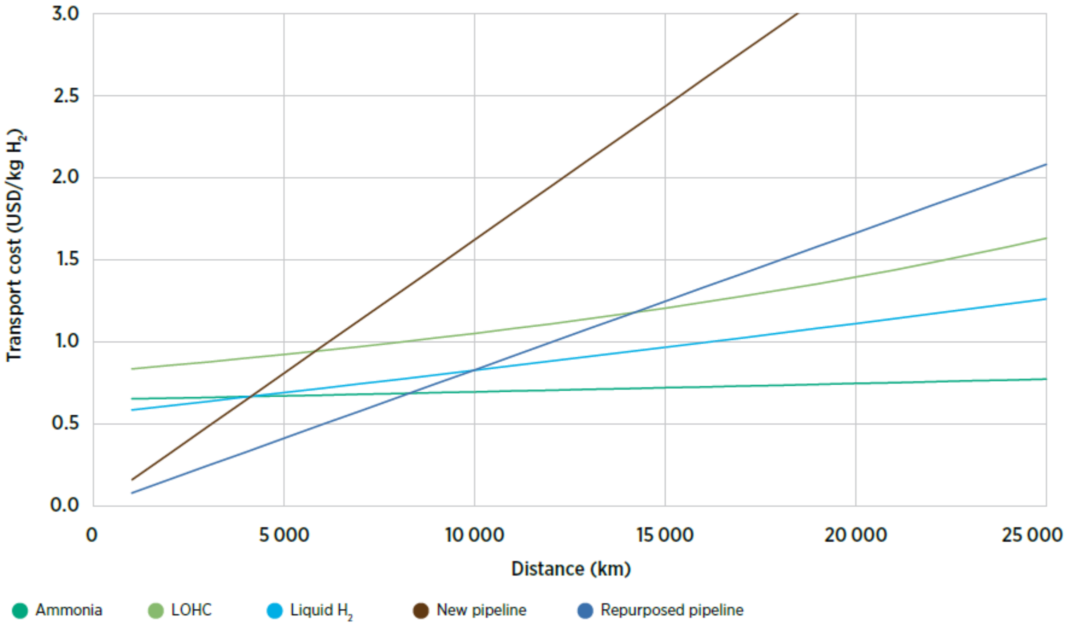
In figure 2.1 and 2.2, a cost comparison of pipelines and sea transport is described for a fixed distance and later for a fixed project capacity (IRENA, 2022). In the figures, the relationship described previously is clear, pipelines hold their highest economical potential at large scale projects in close distance whereas shipping favours a long distance and to some extent also the scale of the project (even if the impact of scale is smaller in terms of sea transport).

Since there is a high uncertainty in the techno-economic data, IRENA presented two different scenarios, the Optimistic and Pessimistic scenarios with almost a factor two difference between them. In figure 2.1 and 2.2 only the optimistic scenario is presented.



Note: Optimistic scenario for costs.

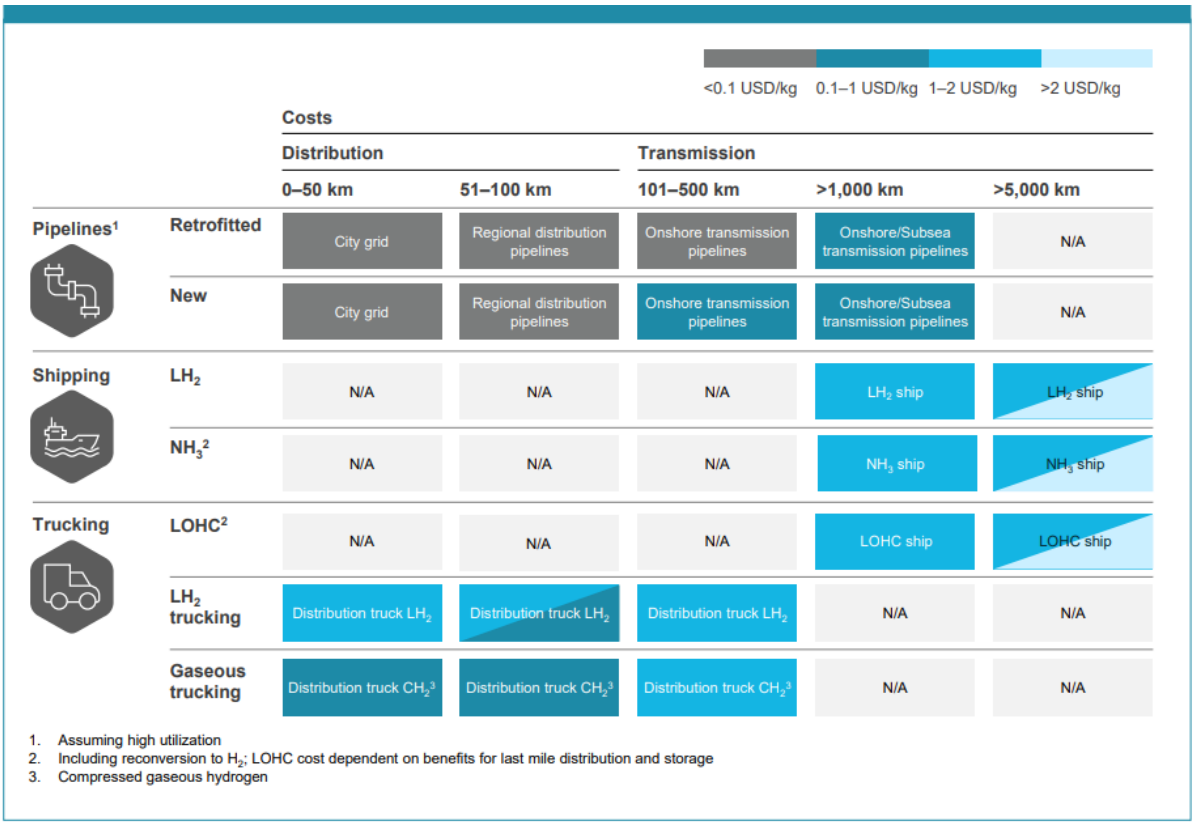
Figure 2.1 Transport cost by pathway as a function of project scale and fixed distance (5 000 km) in 2050.



Note: Optimistic scenario for costs.

Figure 2.2 Transport cost by pathway as a function of distance and a fixed project scale (1,5 MtH_2/yr) in 2050

In addition to this study, similar results were presented in a comparable analysis performed by McKinsey & Co on behalf of the Hydrogen Council 2021 in which different transportation methods were reviewed (see figure 2.3). Even if some differences exist, in general terms the relationships are the same; pipelines are better for shorter distances and shipping alternatives are only cost preferable at longer distances. One significant difference between the two studies is that in the former case, the costs are based on projections for 2050. In the latter, the numbers are based on projections and expected technical advancement towards 2030. With a longer time horizon, uncertainty increases both regarding technology, costs and the market, which makes it difficult to compare these studies



<0.1 USD/kg 0.1–1 USD/kg 1–2 USD/kg >2 USD/kg

		Costs				
		Distribution		Transmission		
		0–50 km	51–100 km	101–500 km	>1,000 km	>5,000 km
Pipelines[1]	**Retrofitted**	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/Subsea transmission pipelines	N/A
	New	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/Subsea transmission pipelines	N/A
Shipping	**LH_2**	N/A	N/A	N/A	LH_2 ship	LH_2 ship
	NH_3[2]	N/A	N/A	N/A	NH_3 ship	NH_3 ship
Trucking	**LOHC**[2]	N/A	N/A	N/A	LOHC ship	LOHC ship
	LH_2 trucking	Distribution truck LH_2	Distribution truck LH_2	Distribution truck LH_2	N/A	N/A
	Gaseous trucking	Distribution truck CH_2[3]	Distribution truck CH_2[3]	Distribution truck CH_2[3]	N/A	N/A

1. Assuming high utilization
2. Including reconversion to H_2; LOHC cost dependent on benefits for last mile distribution and storage
3. Compressed gaseous hydrogen

Figure 2.3 Cost comparison of distribution alternatives

2.2 Gaseous transport by ship

Finally, as noted, none of these comparisons takes into consideration sea transport of hydrogen in gaseous form. The reasons for that, which also is the reason why this alternative most probably not will be relevant for the Gotland case is the practical issues this would cause and, in extension, the high cost this will imply. It all boils down to the low energy density of gaseous hydrogen which should mean that the high volumes of hydrogen needed to supply the Gotland Horizon ferry alone, not to mention several ferries in the future, would require substantial space onboard a bunker ship or storage in the port. As the Gotland ferry also would need a high continuous supply with these volumes, it would also require several ships with large storage volumes at a highly unrealistic scale, not only in technical terms but also economical.

As a brief estimation based on figures from GASUM's LNG distribution by sea transport, M/S Seagas

- A standard trailer tank for gaseous storage contains 1.2 ton hydrogen (700bar)
- A bunker-ship of suitable size holds a capacity of 180 m^2 storage and cost approximately 25 000 euro/day + fuel (including investment cost and operation)
- 180 m^2 storage corresponds to 3.18 trailers which would allow 3.81 ton hydrogen in total per ship
- Gotland Horizon has a hydrogen demand of 16 tons/filling, corresponding to 4.2 ships (of Seagas proportions).
- With the assumption that the cost of the hydrogen bunker ship would be the same as for Gasum's Seagas, that would indicate a cost of approximately 105 000 euros/daily (for one filling), or 7 USD/kg hydrogen calculated with today's currency (1 euro = 1.06 USD)

These numbers are based on rough estimations, but the result still shows practical terms (the number of ships/ship capacity) as well as cost, that distribution of gaseous hydrogen by ship to Gotland Horizon will not be competitive compared with a pipeline solution. Especially, if the hydrogen could be produced locally/regionally, which would decrease the cost of the pipeline and allow for more efficient transport.

2.3 Costs of gaseous hydrogen pipelines

Figure 2.2 and 2.3 shows that hydrogen pipelines can be the most cost-effective way to transport hydrogen, but the costs vary significantly depending on the project scale and the length of the pipeline. Since the Gotland project lies in the lower parts of both capacity and distance it is of interest to calculate the total costs to transport the hydrogen. The technical brief by Khan, Young, and Layzell (2021) presents how to calculate the levelized costs of hydrogen (LCOH) for a pipeline and compressor system dedicated to transport hydrogen. The total installation cost (TIC) is an estimate for the pipeline including material costs for the pipeline, labour costs, miscellaneous, and right of way. The total capital invested (TCI) is the sum of the TIC and indirect costs. The operational expenditures consist of labour costs and fixed operation and management costs. The compressor costs consist of an uninstalled cost (the cost of the compressor itself), an installation factor, and indirect costs. The following table shows the data used when calculating the LCOH for the pipeline system.

Table 2.1: Cost calculation data

Pipeline length	See table 2.2 or 4.2
Mass flow (kg/s)	See table 2.2 or 4.2
Pipeline diameter	See table 2.2 or 4.4
Polytropic compressor power	See table 2.2 or 5.3
Weighted average cost of capital	8% (Khan, Young, & Layzell, 2021)
Pipeline lifetime	50 Years
Compressor lifetime	15 Years
Indirect costs (pipeline and compressor)	40% of TIC (Khan, Young, & Layzell, 2021)
Labour rate (pipeline and compressor)	37.2 USD/h (Khan, Young, & Layzell, 2021)
Indirect labour factor (pipeline and compressor)	50% of Direct labour costs (Khan, Young, & Layzell, 2021)
Fixed O&M costs Pipeline	2.6% of TCI (Khan, Young, & Layzell, 2021)
Fixed O&M costs compressor	4% of TIC and 2.1% of TCI (Khan, Young, & Layzell, 2021)
Compressor installation factor	2 (Khan, Young, & Layzell, 2021)
Compressor scale factor	0.8335 (Khan, Young, & Layzell, 2021)
System availability	90% (Khan, Young, & Layzell, 2021)
Costs of electricity (including taxes)	0.138 US$/kWh (Nordpool, 2023)
Exchange rate	1C$ = 0.75 US$ (as of April 2023)
Offshore pipeline factor	1.5 (Assumed)

The cost calculations are made to give a rough estimate of the LCOH transportation. Since the model by Khan, Young, and Layzell (2021) estimate the compression costs using Canadian dollars, the cost is first calculated and then converted to US$ with the current exchange rate. The model for calculating pipeline costs is based on the HDSAM model (Argonne National Laboratory, 2023). The HDSAM model uses historical data from natural gas pipelines built in the US to estimate the different costs associated with the upcoming hydrogen pipelines.

Since the data used to form the cost model is based on costs from 2009, an inflation rate from US$ 2009 to US$ 2023 is used to adjust for inflation. Costs such as labour rates and land will most likely vary depending on where the pipeline is located but have not been accounted for in this study. Increased hydrogen pressures will decrease the pipeline's lifetime due to hydrogen embrittlement and crack initiation and growth rate (An, et al., 2017). This is however not accounted for in the cost estimate for the pipeline LCOH. Another factor that affects the cost is if the pipeline is located offshore or onshore, IRENA (2022) states that the additional cost of an offshore pipeline can be anywhere between a factor of 1.3 to 3 depending on water depth and specific diameter. For the Gotland case, the factor is assumed to be in the lower range since the pipeline is relatively small and located in shallow waters.

Table 2.2: Cost calculation scenarios

Mass flow (kg/s)	Diameter (m)	Length (km)	Pipe inlet Pressure (bar)	Compressor Power (MW)	Scenario (SC)
0.56	0.126	60	50	0.63	1
1.11	0.164	60	50	1.06	2
1.67	0.191	60	50	1.59	3
0.56	0.139	100	50	0.63	4
1.11	0.181	100	50	1.06	5
1.67	0.211	100	50	1.59	6
0.56	0.088	60	100	1.79	7
1.11	0.115	60	100	2.91	8
1.67	0.134	60	100	4.37	9
0.56	0.097	100	100	1.79	10
1.11	0.127	100	100	2.91	11
1.67	0.148	100	100	4.37	12
0.56	0.066	60	200	3.43	13
1.11	0.086	60	200	5.45	14
1.67	0.100	60	200	8.17	15
0.56	0.073	100	200	3.43	16
1.11	0.095	100	200	5.45	17
1.67	0.111	100	200	8.17	18

Table 2.3: Cost calculation results

	Pipeline			Compressor			Total
SC	Capex (M$)	Opex (M$)	LCOH ($/kg$H_2$)	Capex (M$)	Opex (M$)	LCOH ($/kg$H_2$)	LCOH ($/kg$H_2$)
1	82.93	2.37	0.580	1.87	0.86	0.066	0.647
2	95.61	2.74	0.335	2.86	1.43	0.054	0.389
3	104.91	3.01	0.245	4.02	2.13	0.053	0.298
4	145.67	4.00	1.009	1.87	0.86	0.066	1.076
5	169.25	4.66	0.586	2.86	1.43	0.054	0.641
6	186.59	5.14	0.431	4.02	2.13	0.053	0.484
7	70.65	2.05	0.497	4.43	2.39	0.179	0.675
8	79.37	2.32	0.279	6.66	3.86	0.143	0.422
9	85.74	2.52	0.201	9.34	5.75	0.141	0.342
10	122.80	3.41	0.853	4.43	2.39	0.179	1.032
11	138.95	3.87	0.483	6.66	3.86	0.143	0.626
12	150.76	4.21	0.349	9.34	5.75	0.141	0.490
13	63.45	1.87	0.447	7.63	4.53	0.334	0.782
14	69.89	2.08	0.247	11.23	7.15	0.262	0.509
15	74.57	2.22	0.176	15.74	10.67	0.258	0.434
16	109.44	3.06	0.762	7.63	4.53	0.334	1.096
17	121.33	3.41	0.423	11.23	7.15	0.262	0.684
18	130.00	3.67	0.302	15.74	10.67	0.258	0.560

As expected, the LCOH reduces rapidly for larger flows of hydrogen due to the relation between pipeline diameter and capacity. The costs of compression are relatively low compared to the pipeline costs in this case, since only one compressor is needed due to the relatively short distance and low output pressure from the pipeline. Since the pressure remains the same for increased pipeline length (pressure drop is regulated through larger pipeline diameter), the costs for compression remain constant between the different length scenarios. Pipeline costs however increase rapidly since a longer pipeline increases both the diameter and length resulting in higher material costs.

Comparing scenarios #10-12 with #4-6 shows some interesting results where the LCOH was lower for #10 and #11 than #4 and #5 but for scenario #12 the LCOH was higher than #6. This means that higher pressure in the pipeline was more cost efficient for lower mass flows while the higher mass flow was more cost efficient with lower pressure. Other than #10 and #11, a lower pressure is usually preferred since the cost of increasing compressor size is higher than the cost savings of the smaller pipeline diameter. The lowest LCOH out of all the scenarios was scenario three where mass flow is the highest and pipeline length and pressure are the lowest. This further supports that pipelines are the most cost-efficient alternative for higher capacities and shorter distances.

3 Safety and Regulations

In the following chapter we present acts, regulations, and safety standards related to transporting hydrogen in a pipeline. The rules and regulations mainly consist of governmental documents stating what is required to conduct operations in the field. The rules describe what is considered proper activity from a more general point of view while the regulations are more exact.

To conduct operations according to certain rules, or acts, a concession is required, where concession refers to the permit to perform a certain activity within the scope of said concession. A concession can be applied to multiple acts but does not imply that permission to perform said activity is guaranteed since other regulatory documents might deny operations. To be granted concession, certain criteria must be fulfilled depending on where and how operations are to be conducted. To make it easier to prove that operations hold a certain level of safety or quality, standards are often used. For this purpose, the International Organization of Standardization (ISO) has issued several documents related safe handling of hydrogen and other flammable gases which can be used as guidelines when creating hydrogen pipeline systems that shall comply with future rules and regulations.

3.1 Hydrogen pipelines potential acts and regulations

As of now, there are only a few acts and regulations directly covering hydrogen. There are however regulations connected to flammable and explosive gases that also apply to hydrogen, whilst others cover systems where hydrogen can be applied, such as natural gas systems. Since this case study is based in Sweden, the primary sources of regulatory documents are the Swedish Parliament and the Swedish Civil Contingencies Agency (MSB).

3.1.1 Act on Certain Pipelines

The act on certain pipelines (1978:160) states that a concession is needed for pipelines used for transport of liquids or gases dedicated as fuel. Since the pipeline will be used to supply the ferry with hydrogen as fuel, the act will therefore be relevant. The act states that for operations to be granted a concession, it needs to be deemed appropriate from a general point of view and the applicant need to be appropriate for running the operations.

When applying for a concession the operations shall comply with the Swedish Environmental code, Ch. 2-4., Ch. 5. 3-5 and 18§§, and Ch. 6. 23-47§§. This implies that the operations shall comply with general consideration rules, such as having sufficient knowledge to operate the system and operate it in such a way that waste is reduced while ensuring the safety of everyone involved. The location of the activity must be chosen so that the impact on the surroundings is minimized, and permission must be granted based on what best benefits land and water environments in the long term. Land and water suitable for energy production and distribution shall be priorities for this purpose. Both the Baltic Sea and Gotland are areas where the operations shall take special consideration for tourism and the marine environment. Beyond this, operators shall follow relevant environmental quality standards and conduct an environmental impact assessment.

3.1.2 Act on Natural Gases

Since there are only a few acts presently direct addressing hydrogen, *the Act on Natural Gases* can be used to for indications how a hydrogen act could be formulated. *The Act on Natural Gases* also includes gases that are technically feasible to operate in natural gas systems. Since hydrogen to some extent can be mixed into natural gas systems, it could potentially be affected by this act. If so, hydrogen pipelines will have the same requirements for a concession as a natural gas pipeline. The prerequisites for notification of concessions and necessary conditions in *the Act on Natural Gases* are the same as those in the *Act on Certain Pipelines.*

If concession is granted from either *the Act on Natural Gases* or the *Act on Certain Pipelines*, a concession from the *Act on Flammable and Explosive Goods* (2010:1011 sec 16) is not needed, however, the requirements for permit-required activities in *the Act on Flammable and Explosive goods* still needs to be fulfilled.

3.1.3 MSB Regulations

MSB (The Swedish Civil Contingencies Agency) has issued several regulations regarding the general handling of flammable and explosive goods and according to *MSBFS 2010:4*, hydrogen is classified as flammable goods. The regulation on permission for handling flammable and explosive goods (*MSB 2013:3*) follows the same directives as the *Act on Flammable and Explosive goods (Act 2010:1011)*. Hence, if the system complies with *2010:1011* it will also comply with *MSB 2013:3*.

MSBFS 2020:1 covers the handling of flammable gases and aerosols. The regulation contains general requirements for devices containing flammable gases, such as tightness to prevent leakage, appropriateness for the pressure and temperature of the gas and the use of non-flammable materials. The recommendation for pipelines is that they shall be placed least 0.6 meters below ground for fire protection. Devices containing flammable gases shall also be protected from corrosion, vibrations, and have a manual closing mechanism in case of emergency. The specific chapter on pipelines mentions that pipelines below surface shall be traceable and located a sufficient distance from other installations and buildings.

An exception to *MSBFS 2020:1* is pipelines for natural gas with a pressure exceeding 4 bar, and since hydrogen and natural gas share some similarities, a similar exception might be made for hydrogen. For natural gas pipelines exceeding 4 bar, *MSB 2009:7* regulations on natural gas pipelines apply instead. This regulation expands on the pipeline-related regulations in *MSBFS 2020:1* and sets more strict requirements. For underground pipelines, the coverage depth shall be at least 0.9 meters unless the pipeline is in solid rock, if so a depth of 0.6 meters is sufficient. The pipeline shall never be closer than 25 meters to a densely populated area, and 50 meters from an industry handling flammable or explosive goods. The minimum allowed distance to public roads is 12 meters and from railroads 15.

The distance between venting valves depends on the classification zone of the pipeline segment, where those zones are dependent on the surrounding population density. The distances between two venting valves range from a maximum of 16 km to 4 km depending on the zone.

In the regulation, a certificate *SS-EN ISO/IEC 17020-Type A* version 1 is required to perform supervision of the pipeline. It also states that to operate the pipeline, a quality management system fulfilling the requirements of *ISO 9001* or equivalent is required. The regulation also covers reporting in case of leakage or accidents, operations of pipelines, and requirements when constructing pipelines.

3.2 ISO 15916

The international standard *ISO 15916:2022* contains basic considerations for the safety of hydrogen systems and highlights the hazards and safety issues connected to hydrogen energy applications. Furthermore, it contains a section dedicated to a list of general safety considerations for hydrogen pipelines, joints, and connections. Those sections are related to the placement of the pipeline, materials to avoid, corrosion and leakage, pressure relief devices and tests. The standard does also include safety considerations using gaseous hydrogen and recommended practices for organizations handling hydrogen systems. In these recommended practices it is stated that management must introduce organizational policies and procedures together with approved maintenance and quality control programs for the hydrogen system. *ISO 15916:2022* formulate such programs but other documents such as *AFS 2017:3* may also be helpful in the matter. The latter is a Swedish regulation (from Swedish Work Environment Authority) on pressurized devices, containing general requirements for the use of pressurized devices, guidelines on the monitoring of the pipeline and requirements on operating tests of the equipment.

When using the operational test *AFS 2006:8*, testing with overpressure or suppression, shall be applied. The regulation covers all pressure testing, such as risk assessments, testing sites, and risk areas. It does also contain specific regulations regarding overpressure and suppression, such as what substance to use when testing, how pressure shall be applied, and what to consider when using a gas instead of a liquid.

3.3 ISO 19880-1:2020

ISO 19880-1:2020, gaseous hydrogen – Fueling stations – part 1: general requirements, contains information on how to construct hydrogen refueling stations for light duty vehicles, from a safety perspective. Since the standard serves as a baseline for hydrogen refueling, safety considerations for many of the generic requirements are also applicable to other types of hydrogen applications. The standard also contains a short chapter on hydrogen supply, where safety considerations for the interface between the pipeline and the fueling station is discussed. They mention pressure relief devices to protect against overpressure, requirements on welding, and protection from corrosion. The standard states that those devices shall comply with the requirements in *ISO 15649*.

3.4 ISO 26142:2022

Almost all safety standards demand that hydrogen applications need to have some kind of hydrogen detection unit. *ISO 26142* Hydrogen detection apparatus – stationary applications, describes how such detection units shall function. The standard is primarily intended for hydrogen detection at vehicle refueling stations but can be applied to other areas where hydrogen detection is needed. The standard sets requirements on detection range, corrosion resistance, alarms/fault signals, indicators, labeling, instructions, etcetera. The standard also contains a section on requirements for testing hydrogen detection devices and which equipment, methods and conditions that shall be used when testing.

3.5 EIGA IGC Doc 121/14

The purpose of the *European Industrial Gases Association (EIGA) Doc 121/14* is to give guidance for the design of hydrogen transmission and distribution systems. It gives guidelines on design philosophy, valves and equipment, cleaning, construction, operation and monitoring, and other general protective measures. The design philosophy discusses hydrogen gas embrittlement (HGE) and stress corrosion cracking (SCC) and how to mitigate these with the right choice of welds and material with the right strength and hardness. The design of the pipeline is also important to protect from galvanic corrosion, which is mentioned as one of the most frequent causes of leakage. A risk assessment and hazard analysis shall always follow with the design or greater modification of the pipeline.

The pipeline shall also have an appropriate venting system in case of overpressure, where the system either ventilates the hydrogen into the atmosphere or destroys it in a flare. The pressure relief is handled with relief valves, however not the only valves involved with pipelines; isolation and emergency isolation valves shall be installed together with pressure reducing valves and check valves.

Additional important equipment as described in *IGC Doc 121/14* are strainers and filters, flow measuring devices, rupture discs, insulating joints, and flexible connections. When designing the pipeline, compatibility with cleaning and pressure testing methods is important. The pipeline is considered to be clean when the internal particular matter has been extensively removed. Pressure testing can be done either pneumatic or hydrostatic, in the case of hydrostatic testing clean water shall be used and the pipeline shall be dried as soon as possible to minimize the risk of corrosion in the pipeline. When applying pneumatic testing, nitrogen gas can be used to both purge and pressure test the pipeline.

Furthermore, it is of importance to inform third parties of the location and work related to the pipeline since, according to *IGC Doc 121/14*, two thirds of underground pipeline accidents are due to external events. This information shall contain summaries regarding work done, and not done, adjacent to or on the pipeline and records on requests from contractors and replies to those requests including transmitted documents.

3.6 Compressors

This section discusses hydrogen related issues during compression. For more general compressor requirements in gas infrastructure, see *SS-EN 12583:2022*.

For the pipeline to reach the required inlet and outlet pressure, compression is necessary. Compressors for hydrogen shall follow the previously mentioned safety precautions in *the Act on Natural Gases* and the requirements on compressor stations used for natural gas applications in *MSBFS 2009:7*. The compressor building shall be separated into two sections, control room and the gas installation. The two sections shall be separated with minimum class EI 60 in fire safety, i.e., the individual rooms shall be able to sustain a fire for at least 60 minutes. The section where the gas installation is placed shall also be well ventilated in case of gas leakage from the compressor. Systems to detect issues in the compressor station must also be installed. Furthermore, it is mandatory to have systems installed to prevent maximum pressure to be exceeded. An emergency stop must be installed and include the possibility to empty the compressor of gas, this shall be possible both from inside the control room and from a remote location.

ISO 19880:1 describes the installation of a hydrogen compressor. The hydrogen compressor shall follow the recommendations for equipment in hazardous areas, meaning that all electrical and mechanical equipment shall be protected in accordance with *ISO/IEX 80079* or *IEC 60079* to minimize the risk of igniting a hydrogen/air mixture due to hot surfaces, sparks from rotating machinery, or static discharges. In accordance with *MSBFS 2009:7* a pressure relief device, or equivalent safety measure, shall be installed to prevent over-pressure. The building shall be designed to prevent the formation of hazardous atmospheres, any hydrogen released shall be piped to a safe area. Proper flame or fire detection systems shall be installed to prevent the escalation of hydrogen fires.

A risk assessment of the installation, operation, and maintenance of the compressor must be done, including countermeasures to avoid hazardous events. Such countermeasures include means to fully depressurize the system, purging the system with inert gas, and means to prevent air from entering the system. If air would enter through the inlet of the compressor, it shall automatically shut down. To prevent air from entering the system, compressors shall be mounted in such a way that vibrations or movement caused by compression shall not damage the connected pipeline or other connections. Safety controls of temperature and pressure shall also be installed to ensure that operating discharge temperature and pressure are correct.

When a compressor is used for hydrogen, the EU directive on the harmonization of the laws of the Member States, relating to equipment and protective systems intended, for use in potentially explosive atmospheres (*DIRECTIVE 2014/34/EU*) will apply. This directive states that appropriate measures must be taken to ensure that equipment is properly installed, maintained, and used in accordance with the intended purpose. Additional requirements to ensure the safety of employees and others using the product can be added if it not modifies the product in a way not specified in the directive. In this directive, products are classified into categories depending on the cause and frequency of explosive atmospheres. A hydrogen compressor fits in equipment group 2, which is equipment used in explosive atmospheres caused by mixes of gas and air. The equipment is further categorized into three different categories, where category 1 is when explosive mixtures are frequently present or for long periods, which is the worst-case scenario. Equipment in this category must fulfill certain requisites. If an incident occurs, the compressor shall, in the event of a failure of protection, have at least one additional independent means of protection. If not, the compressor must have a specified level of protection to assure safety in case of two faults occurring independently of each other. The other two categories are when explosive atmospheres are present occasionally or are unlikely to occur and only last for short periods. For these cases, a certain level of protection must be ensured in the event of disturbances or equipment faults during normal operations.

The safety requirements in *2014/34/EU* can be split into three categories, (1) the prevention of explosive atmospheres, (2) prevention of ignition of explosive atmospheres and finally, (3) limiting the range and pressure of explosions. On the first category, preventing explosive atmospheres, the directive states that gas leaks must be prevented as far as possible. The system shall include a manual override in case of equipment deviating from normal operating conditions, hydrogen in the compressor shall be vented to a safe place in case of emergency shutdown. The system shall also be able to maintain safety in the case of a power outage and detection devices shall notify in case an explosive atmosphere is forming. To prevent ignition of the explosive atmosphere, the equipment shall be hard to access for non-authorized people and protected from outside hazards. The compressor shall also be equipped with overload protection and countermeasures to prevent overheating of both it and surrounding surfaces. The system must also be designed in such a way that ignition from static electricity or other sources of ignition cannot occur. In the case of ignition and an explosion would occur, the explosion shall be halted immediately or be as limited as possible regarding the range of explosion flames and pressure. This can be done through decoupling systems that disconnect the compressor from the rest of the system in the initial stages of the explosion. The compressor shall also be placed in such a way that in case of an accident it would not cause a chain reaction.

4 Hydrogen Pipelines

Since pipeline is the most promising option to transport hydrogen, it is of high interest to estimate the necessary dimension of the pipeline. The pipeline costs will not only be dependent on the length of the pipeline but also the diameter and where/how the hydrogen pipeline is installed. The following chapter will describe how the diameter of a hydrogen pipeline, designed to transmit a specific amount of hydrogen with a certain pressure, can be calculated.

4.1 Dimensioning of hydrogen pipelines

The following table introduces the notations used when calculating the pipeline diameter.

Table 4.1: Pipeline Nomenclature

d	Pipeline diameter (m)
q	Volumetric mass flow (m^3/s)
v	Flow velocity (m/s)
Δp	Pressure drop (Pa)
λ	Friction coefficient
l	Pipeline length (m)
δ	Density for current temperature and pressure (kg/m^3)
p	Average pipeline pressure (Pa)
P_1	Inlet pressure (Pa)
P_2	Outlet pressure (Pa)
R	Universal gas constant (J/(kg*K))
T	Temperature of the gas (K)
Re	Reynolds number
u	Kinematic viscosity (m^2/s)
η	Dynamic viscosity (m^2/s)
k	Relative pipeline roughness (m)

Several factors must be considered when dimensioning a hydrogen pipeline, such as pipe diameter, average pipeline pressure, pressure drop throughout the pipeline, and gas velocity inside the pipeline. Since most of the variables are dependent on each other, it is complicated to find a good estimate without making assumptions. In this report we use an iterative process where initial values of some parameters are set and then updated until the changes from one iteration to the next are small enough. The following formulas used in the iterative process can be found in

Ahlberg (1985, pp. 38-41) and Soleimani-Mohseni, Bäckström, and Eklund (2014, p. 30).

$$\frac{\pi d^2}{4} = \frac{q}{v} \rightarrow d = \sqrt{\frac{4 * q}{\pi * v}}$$

[1]

$$\Delta p = \lambda \frac{l}{d} \delta \frac{v^2}{2} \rightarrow v = \sqrt{\frac{\Delta p * d * 2}{\lambda * l * \delta}}$$

[2]

$$Re = \frac{v * d}{u}$$

[3]

$$u = \frac{\eta}{\delta}$$

[4]

$$\lambda = \frac{1}{\left[-2 * log_{10}\left(\frac{2.51}{Re * \sqrt{\lambda}} + \frac{k}{3.7 * d}\right)\right]^2}$$

[5]

$$p = \frac{2}{3} * \frac{P_2^3 - P_1^3}{P_2^2 - P_1^2}$$

[6]

In the calculations, the operating temperature is assumed to be constant due to heat exchange with the surroundings. The average pressure is calculated by equation 6, which gives a more accurate approximation than the arithmetic mean (Menon, 2005). Hight differences in the pipeline is assumed to be negligible across the length of the pipeline and hence not regarded in the calculation. Since hydrogen is not an ideal gas, normal procedures for calculating gas density cannot be applied. A study by Lemmon, Huber, and Leachman (2008) use regression to derive an expression to calculate hydrogen density with only 0.01% error. Values of a_i, b_i, and c_i can be found in their study:

$$\frac{p}{\delta RT} = 1 + \sum_{i=1}^{9} a_i \left(\frac{100K}{T}\right)^{b_i} \left(\frac{p}{1MPa}\right)^{c_i} \leftrightarrow$$

[7]

$$\delta = \frac{p}{RT\left(1 + \sum_{i=1}^{9} a_i \left(\frac{100K}{T}\right)^{b_i} \left(\frac{p}{1MPa}\right)^{c_i}\right)}$$

4.2 Scenarios

To examine the total costs of the case pipeline system, different scenarios are analysed. The scenarios use different initial pressures, volume flow rates, and pipeline lengths.

Table 4.2: Scenario data

Variable:	Scenario 1	Scenario 2	Scenario 3
Initial Pressure	50 Bar	100 Bar	200 Bar
Flow rate	16 ton/8h	32 ton/8h	48 ton/8h
Pipeline length	100 km	60 km	

Most existing pipelines in the USA transporting natural gas operate at a pressure between 42-84 bar, in some cases even 134 bar (Melaina, Antonia, & Penev, 2013). There are however some special cases such as the offshore pipeline Nordstream transporting natural gas between Russia and Germany. This pipeline operates at up to 220 bar (Nordstream, 2016). The Langeled offshore pipeline transporting natural gas between Norway and the UK operates at a maximum pressure of 250 bar (d'Amore-Domenech, Leo, & Pollet, 2021). According to IRENA (2022), typical pressures for hydrogen pipelines are between 70-100 bar. There are however studies studying lower pressure in order to reduce hydrogen leaks and embrittlement. d'Amore-Domenech et al. (2021) studied an offshore pipeline operating at 50 bar.

The different flow rate scenarios are based on the number of ferries to be supplied. One ferry is estimated to consume 16 tons of hydrogen for a round trip from harbour and back. The estimated time for the round trip is 8 hours, thus the pipeline needs to transport 16 tonnes of hydrogen in 8 hours to the storage at harbour to supply enough fuel for one ferry, assuming a constant flow of hydrogen. The other two scenarios are based on two and three hydrogen ferries with the same round trips.

The different scenarios are implemented in a Python script together with values for the constants, table 4.2 and table 4.3 presents the values used in the script.

Table 4.3: Pipeline constants

p_{out}	3 (MPa)
R	4124.2 (J/(kg*K))
T	278.15 (K)
η	8.641 * 10^{-6} (m^2/s)
k	0.0178 (mm) (Khan, Young, & Layzell, 2021)

Table 4.4: Pipeline results

Inputs			Outputs				
Mass flow (kg/s)	Pipeline length (km)	Inlet-pressure (bar)	Pipeline Diameter (m)	Gas Velocity (m/s)	Gas Density (kg/m^3)	Friction-coefficient	Pipeline Storage (kg)
0.56	60	50	0.126	12.90	3.47	0.014	2583
1.11	60	50	0.164	15.22	3.47	0.014	4380
1.67	60	50	0.191	16.75	3.47	0.013	5969
0.56	100	50	0.139	10.52	3.47	0.014	5280
1.11	100	50	0.181	12.42	3.47	0.014	8948
1.67	100	50	0.211	13.67	3.47	0.013	12190
0.56	60	100	0.088	15.30	5.95	0.015	2178
1.11	60	100	0.115	18.02	5.95	0.014	3699
1.67	60	100	0.134	19.82	5.95	0.013	5044
0.56	100	100	0.097	12.51	5.95	0.015	4440
1.11	100	100	0.127	14.74	5.95	0.014	7537
1.67	100	100	0.148	16.22	5.95	0.013	10276
0.56	60	200	0.066	14.97	10.90	0.015	2226
1.11	60	200	0.086	17.63	10.90	0.014	3782
1.67	60	200	0.100	19.38	10.90	0.014	5160
0.56	100	200	0.073	12.27	10.90	0.015	4528
1.11	100	200	0.095	14.44	10.90	0.014	7693
1.67	100	200	0.111	15.88	10.90	0.014	10494

If the pipeline is not being filled or emptied, there will still be a residual hydrogen in the pipeline. This volume, as presented in the pipeline storage column in the above table, is estimated by multiplying the pipeline volume by the hydrogen density. The hydrogen density is calculated for the average pressure in the hydrogen pipeline.

Furthermore, it must be ensured that the gas velocity will not exceed the erosional velocity. If the gas inside the pipeline exceeds this, the degradation of the pipeline (erosion/corrosion) reaches a level that is unsafe and increases the risk of failure. The erosional velocity for gas pipelines is estimated as:

$$v_e = \frac{122}{\sqrt{\delta}}$$

[8]

The erosional velocity represents the maximum allowed gas velocity in the pipeline hence the highest gas speed in the pipeline shall be observed and not the average. The maximum gas velocity can be found where the pressure is the lowest, i.e., at the end of the pipeline. The specific gas velocity in a pipeline is calculated as:

$$v = 14.7349 \frac{q_b * P_b * Z * T}{d^2 * T_b * P}$$

[9]

Where q_b is the flow rate at standard conditions expressed in m^3/day, P_b is the base pressure (1 atm), D is the pipe diameter in mm, T_b the normal temperature (288 K), and the constant represents the area and converting mm^2/s to m^2/day (Menon, 2005).

Since the erosional velocity increases as density decreases, the erosional velocity will be its highest at the end of the pipeline. The same is true for the maximum velocity, but since it increases faster than the erosional velocity only the outlet conditions will be examined. Since the outlet pressure remains constant across all the scenarios the erosional velocity will not change between scenarios and equals 76.1 m/s. The different maximum gas velocities are presented in the tables below.

Table 4.5: Outlet velocity 60 km km

Pressure Mass flow	50	100	200
0.56	17.5	35.5	63.8
1.11	20.6	41.9	75.0
1.67	22.7	46.0	82.5

Table 4.6: Outlet velocity 100 km

Pressure Mass flow	50	100	200
0.56	14.3	29.1	52.2
1.11	16.8	34.2	61.5
1.67	18.5	37.7	67.6

Only one scenario exceeded the erosional velocity, however Menon (2005) mentions that an acceptable operational velocity is usually 50% of the erosional velocity. This means that all the 200 bar and most 100 bar scenarios exceed the recommendation. To reduce the max velocity an increase in pipeline diameter by 5-47% is needed depending on how much the velocity needs to be reduced.

5 Compressor power calculations

Due to the low volumetric energy density of hydrogen it needs to be compressed when stored and transported to reacha higher energy contents per volume unit. When transported through a pipeline a pressure drop will occur and the hydrogen therefore needs to be re-pressurized to maintain a certain pressure.

Several compressor types can be used when compressing hydrogen. Sdanghi et al. (2019) presented a review of current hydrogen compressors. The review shows that oil-free reciprocating compressors are commonly used for hydrogen applications. The reason for the oil-free compressor is due to its higher hydrogen purity compared to oil lubricated compressors and higher durability. However, reciprocating compressors introduces risks due to many moving mechanical parts. The moving parts makes it harder to perform effective maintenance and efficient cooling during compression. Pressure fluctuations caused by the piston inside the compression chamber can also lead to vibrations, noise, and in worst-case explosions. Centrifugal compressors are another type that can be used for hydrogen applications. Bahadori (2014) present benefits of the centrifugal compressor over reciprocating compressors. The centrifugal compressor is better fitted for higher flows, continuous operation, has lower maintenance expenses, and requires lower operating attention. However, they yield a lower efficiency and need more stages to reach higher pressures compared to reciprocating compressors. Reciprocating compressors also has greater flexibility in capacity and pressure range and is capable of handling smaller volumes. The properties result in lower installation and maintenance cost for the centrifugal compressor while the reciprocating requires a lower power cost.

5.1 Mathematical formulation

There are several approaches how to calculate the work required when compressing gas with a compressor and it is depending on if the process is isentropic or polytropic. Isentropic compression assumes that the process is reversible, no heat is transferred during the process, and the entropy is constant. Polytropic compression is also a reversible process, but heat is assumed to be transferred to the surroundings. While both isentropic and polytropic head can be used to express the work compressors perform (where head stands for the work being done per kg of compressed gas), most manufacturers prefer to use polytropic computations (Thomas, 1999). The following table explains the different variables used when calculating both the polytropic and isentropic compressor power.

Table 5.1 Compressor nomenclature

H_{is} (H_p)	Isentropic (Polytropic) head (kJ/kg)
k	Isentropic exponent (Cp/Cv)
M	Molecular mass (g/mole)
p	Average pipeline pressure (Pa)
P_1	Suction pressure (Pa)

P_2	Discharge pressure (Pa)
Z_{avg}	Average compressibility factor
q_m	Mass flow rate of hydrogen (kg/s)
η_{is} (η_p)	Isentropic (Polytropic) efficiency
η_{el}	Electric motor efficiency
R	Universal gas constant (J/(K*mole))
T	Temperature of the gas (K)
n	Polytropic exponent
x	Compression ratio for single stage

Before calculating the compressor power, the compressibility factor of hydrogen needs to be addressed since hydrogen is not an ideal gas. The compressibility factor for hydrogen is estimated using the following formula, where values of a, b and c can be found in Lemmon, Huber, and Leachman (2008):

$$Z = 1 + \sum_{i=1}^{9} \mathrm{a_i} \left(\frac{100\mathrm{K}}{\mathrm{T}}\right)^{\mathrm{b_i}} \left(\frac{p}{10^6}\right)^{\mathrm{c_i}}$$

[10]

The compressibility factor is calculated using the arithmetic average for the temperature and the equation for the average pressure found in equation 6. With the compressibility factor estimated, compressor power can be calculated. The power needed to compress hydrogen from an initial pressure to the required discharge pressure is acquired by equations 9 to 18 gathered from Bahadori (2014) and Khan et al. (2021). The equations present three different ways of calculating compressor power; isentropic, polytropic, and multistage isentropic.

The formula of the isentropic head is shown below. When calculating the head, the average compressibility factor is used:

$$H_{is} = \frac{Z_{avg} R T_1}{M(k-1)/k} \left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right)} - 1 \right]$$

[11]

During compression the temperature will increase, depending on if the process is considered isentropic or polytropic the formula differs. The temperature from the discharged gas for isentropic compression is calculated as follows:

$$T_2 = T_1\left(1 + \frac{\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right)} - 1}{\eta_{is}}\right)$$

[12]

With the isentropic head the actual power needed for compression can be calculated. The compressor is assumed to be powered by an electric motor hence the electric efficiency:

$$Power_{is} = \frac{H_{is}q_m}{\eta_{is}\eta_{el}}$$

[13]

When calculating the compressor head for polytropic compression the isentropic exponent k is exchanged with the polytropic exponent n:

$$H_p = \frac{Z_{avg}RT_1}{M(n-1)/n}\left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right]$$

[14]

Where the polytropic exponent can be estimated by:

$$\frac{n}{n-1} = \frac{k}{k-1} * \eta_p$$

[15]

The discharge temperature for the polytropic compression is estimated as:

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\left(\frac{n-1}{n}\right)}$$

[16]

Follows the calculations for polytropic compressor power:

$$Power_p = \frac{H_p q_m}{\eta_p \eta_{el}}$$

[17]

Compression can also be done in multiple stages. There are some benefits of doing so, such as lower discharge temperature and more efficient compression. The below formula calculates the isentropic calculation for multistage compression assuming intercooling between the compression stages:

$$H_{is} = N\frac{Z_{avg}RT_1}{M(k-1)/k}\left[\left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{Nk}} - 1\right]$$

[18]

Final temperature (multistage):

$$T_2 = T_1\left(1 + \frac{\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{Nk}\right)} - 1}{\eta_{is}}\right)$$

[19]

Calculation of number of stages (rounds up to the closest integer):

$$N = \frac{log\left(\frac{P_2}{P_1}\right)}{log(x)}$$

[20]

5.2 Numerical results

The data for the calculations of compressor power uses the same scenarios as the pipeline, for scenario data see Table 4.2, together with some initial data for the input to the compressor.

Table 5.2 Data for compressor calculation

T_1	Suction temperature (K)	278.15
P_1	Suction pressure (Pa)	3 MPa
P_2	Discharge pressure (Pa)	See table 2
R	Gas constant (kJ/mol*K)	8.314
M	Molar mass (g/mol)	2.01568
k	Specific heat ratio	1.405
q_m	Mass flow (kg/s)	See table 2
η_{is}	Isentropic efficiency	0.6 – 0.7 (Bahadori, 2014)
η_p	Polytropic efficiency	0.63 – 0.74 (Bahadori, 2014)
η_{el}	Electric motor efficiency	0.95 (Khan M. , Young, MacKinnon, & Layzell, 2021)

x	Compression ratio	3.1 (Khan M. , Young, MacKinnon, & Layzell, 2021)

It is assumed that hydrogen inserted in the compressor is produced through electrolysis with an output pressure of 30 bar. The hydrogen is assumed to be cooled down to ambient temperatures, 7.4 °C based on the average temperature on Gotland (SMHI, 2023). For the multistage scenario, hydrogen is assumed to be cooled down to ambient temperature between each compression stage. The compressor is assumed to be a centrifugal compressor due to its better efficiency for higher flows. According to Bahadori (2014), the efficiency of the compressor increases with higher flows where the flow range between 170 - 850 m^3/h yields the isentropic efficiency of 0.6 while flow ranges of 850 - 12 743 m^3/h yield 0.7. For the following scenarios a mass flow of 0.56, 1.11, and 1.67 kg/s with 30 bar of inlet pressure and temperature 280.55 K results in the flow rates of 786, 1571, and 2357 m^3/h. Hence the efficiency of the compressor will be higher for the higher flow rate scenarios resulting in a lower outlet temperature and a lower compressor power required.

Table 5.3 Isentropic Multistage

Inputs				Outputs		
Mass flow (kg/s)	Inlet Pressure (bar)	Outlet Pressure (bar)	Inlet Temperature (K)	Outlet Temperature (K)	Isentropic Power (MW)	Stages
0.56	30	50	280.55	354.73	0.64	1
1.11	30	50	280.55	344.13	1.09	1
1.67	30	50	280.55	344.13	1.63	1
0.56	30	100	280.55	369.15	1.54	2
1.11	30	100	280.55	356.50	2.65	2
1.67	30	100	280.55	356.50	3.97	2
0.56	30	200	280.55	427.59	2.64	2
1.11	30	200	280.55	406.58	4.53	2
1.67	30	200	280.55	406.58	6.80	2

Table 5.4 Isentropic single stage

Inputs				Outputs		
Mass flow (kg/s)	Inlet Pressure (bar)	Outlet Pressure (bar)	Inlet Temperature (K)	Outlet Temperature (K)	Isentropic Power (MW)	Stages
0.56	30	50	280.55	354.73	0.64	1

1.11	30	50	280.55	344.13	1.09	1
1.67	30	50	280.55	344.13	1.63	1
0.56	30	100	280.55	474.55	1.68	1
1.11	30	100	280.55	446.83	2.89	1
1.67	30	100	280.55	446.83	4.33	1
0.56	30	200	280.55	620.86	3.01	1
1.11	30	200	280.55	572.25	5.18	1
1.67	30	200	280.55	572.25	7.77	1

Table 5.5 Polytropic single stage

Inputs				Outputs		
Mass flow (kg/s)	Inlet Pressure (bar)	Outlet Pressure (bar)	Inlet Temperature (K)	Outlet Temperature (K)	Polytropic Power (MW)	Stages
0.56	30	50	280.55	354.42	0.63	1
1.11	30	50	280.55	342.32	1.06	1
1.67	30	50	280.55	342.32	1.59	1
0.56	30	100	280.55	486.69	1.79	1
1.11	30	100	280.55	448.43	2.91	1
1.67	30	100	280.55	448.43	4.37	1
0.56	30	200	280.55	668.33	3.43	1
1.11	30	200	280.55	587.42	5.45	1
1.67	30	200	280.55	587.42	8.17	1

The polytropic process tends to require a higher compressor power to reach the required pressure, but even for the scenario with the highest mass flow and pressure the difference stay within a reasonable difference. The multistage process shows that compressor power can be saved by splitting the compression into sections with cooling between each stage. However, the cooling needs energy and the multistage method needs the cooling between each compression stage to be efficient, so there is a trade-off between the power needed for compression and cooling.

6 Conclusions

Hydrogen has a good potential to become an important part of the necessary transition to a fossil free shipping. However, before a successful implementation can take place, certain challenges must be addressed to not only have an environmentally sustainable, but also a financially sustainable system. In this report we have discussed one of those challenges; how to transport the hydrogen from place of production to the port. Since hydrogen has a very low volumetric density it can be quite costly to transport, in particular for maritime applications due to the very high volumes.

As a case-study we have been using the future Gotland ferry system and the port of Visby. The hydrogen demanded for one Ro-pax is 16 tonnes per round-trip with up to three roundtrips per 24h during peak season.

6.1 Mode of transport

It is assumed that the production of hydrogen will not take place in the port or in its absolute vicinity, hence the hydrogen must be transported to the port.

As discussed in chapter 2, we have in principle four possible modes of transport for the considered volumes: Road, rail, ship or pipeline. Road transport was excluded of practical reasons, with up to 50 tube trailers per 24h the inbound logistic to the port would be extremely difficult. Transporting by rail was excluded since there no longer is any railway at Gotland. This leaves us with two possible alternatives, by ship or pipeline.

18 different scenarios were designed based on two possible locations, offshore 100 km from port or onshore 60 km from port, three different mass flows, and 50 respectively 100 bar pipe inlet pressure (see table 2.2 for details). Using methods suggested by Khan, Young and Layzell (2021) the pipeline and compressor costs were estimated. The results show a cost between 0.3 and 1 $\$/kg_{H2}$ for all scenarios where the most likely scenarios are in the span 0.3-0.7 $\$/kg_{H2}$.

As a comparison we evaluated a scenario where the hydrogen is transported by ship from place of production to the port. A major assumption is that the hydrogen is in its gaseous form, transport of liquid hydrogen has not been considered. An estimated cost for this system is approximately 7 $\$/kg_{H2}$.

Our conclusion is that pipeline is the most efficient mode of transport. Even though the transport cost using ship is a rather approximative estimate, it is quite clear that the transport cost using pipeline is significantly lower compared with transport by ship. In addition, a pipeline system will also to some extent function as a hydrogen storage, which adds a certain value for the system.

6.2 Dimensioning a pipeline system

Dimensioning a pipeline system is a rather complex calculation. In chapter 4 and 5 we present the relevant formulas to dimension the pipeline and the necessary compressor capacity. A Python model that calculates the dimensions of the pipeline and the compressor was developed and is presented with the full code in appendix A.

18 different scenarios were evaluated using the Python model, three different mass flows were considered; 16, 32 respectively 48 tonnes H_2 per 8h, the length is 100 or 60 km and the inlet pressure 50, 100 or 200 bar. Our Python model gave the diameter of the pipeline and the needed compressor capacity.

The results shows that the diameter on the pipeline needs to be in the span 0.1- 0.2 m and the compressor power is between 0.6 and 8.2 MW (for details see tables 2.2, 5.3, 5.4, 5.5). The resulting figures from the Python model are used as input for financial estimates presented in chapter 2 and 6.1.

6.3 Further research

The hydrogen transport solution must be seen in the context of the hydrogen system, meaning that the pipeline system cannot be seen as an isolated part of the supply system. It is necessary to take into consideration the possibility of increased demand for hydrogen and it could therefore be good to design the pipeline for a higher capacity then needed with present demand. The balance of risks needs to be further examined; on the one hand there a risk for loss of capital if demand will not meet capacity; but on the other hand, if future demand exceeds capacity, it is quite costly to increase capacity in a pipeline system.

We should also further investigate the value of using the pipeline as part of the storage system, which could justify a higher capacity of the pipeline system.

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Appendix A: Pythoncode

```python
#Packages used for calculations and printing
import math
import xlsxwriter

#Function used to determine the friction coefficient inside the pipeline
def frictionCoeff(v, d, u):
    """
     v: gas velocity m/s
     d: pipe diameter m
     u: kinematic viscosity m^2/s
     Re: reynolds number
     k: Relative roughness of pipeline
    """
    Re = v * d / u
    k = 0.0178*10**-3
    f = 1 #Arbritrary start value
    f0 = 0
    while abs(f-f0) > 0.000001:
        f0 = f
        f = 1/(-2*math.log10((k/(3.7*d))+(2.51/(Re*f0**0.5))))**2
    return f

#Function used to estimate the hydrogen density OR compressability factor
def volumetricDensity(p, R, T, Z):
    """
     p: operting pressure (Pa)
     R: gas constant for hydrogen (J/(g*K))
     T: temperature (K)
     Z: Compressability factor
     Set: Z == True to return Z
          Z == False to return density
    """
    ai = [0.05888460, -0.06136111, -0.002650473, 0.002731125, 0.001802374, -0.001150707,
0.9588528 * 10 ** -4, -0.1109040 * 10 ** -6, 0.1264403 * 10 ** -9]
    bi = [1.325, 1.87, 2.5, 2.8, 2.938, 3.14, 3.37, 3.75, 4.0]
    ci = [1, 1, 2, 2, 2.42, 2.63, 3, 4, 5]
    summa = 0
    for i in range(len(ai)):
        summa += ai[i]*((100/T)**bi[i]) * ((p/10**6)**ci[i])
    if Z:
        return 1 + summa #Kompressability factor
    else:
        return p / (R * T * (1 + summa)) #Density in kg/m^3

#Function used to calculate the pipeline diameter
def diameter(q, v):
    """
     q: gas flow rate in m^3/s (or m^3/h depending on unit of velocity)
     v: average velocity of the gas m/s (or m/h depending on q)
    """
    return (q * 4 / (v * math.pi)) ** (1 / 2)

#Function to determine gas velocity based on pipe diameter
def velocity(d,q):
```

```
"""
     d: pipeline diameter m
     q: gas flow rate in m^3/s (or m^3/h depending on unit of velocity)
"""
    return (4*q / (math.pi*d**2))

#Function to determine gas velocity based on the pressure drop in the pipeline
def velocityP(f, l, d, density, dp):
    """
     f: pipeline friction coefficient
     l: pipeline length (m)
     d: pipeline diameter (m)
     density: gas density (kg/m^3)
     dp: pipeline pressure drop
    """
    return (dp*2*d / (f*l*density))**(1/2)

#Function to determine pressure drop in the pipeline
def deltaP(f, l, d, density, v):
    """
     f: pipeline friction coefficient
     l: pipeline length (m)
     density: gas density (kg/m^3)
     v: average velocity of the gas (m/s)
     d: pipeline diameter (m)
    """
    return (f * l * density * v ** 2) / (2 * d)

#Function to determine pipeline outle pressure
def outletP(Pin, f, l, d, density, v):
    """
     Pin: pipeline inlet pressure (Pa)
     f: pipeline friction coefficient
     l: pipeline length (m)
     density: gas density (kg/m^3)
     v: average velocity of the gas (m/s)
    """
    return Pin - deltaP(f, l, d, density, v)

#Aggregated function to connect above functions
def pipelineSpecs(T, Pin, Pout, l, m, R, n, EV):
    """
     T: Average gas temperature in pipeline (K)
     Pin: pipeline inlet pressure (Pa)
     Pout: pipeline outlet pressure (Pa)
     l: pipeline length (m)
     m: mass flow of the gas through the pipeline (kg/s)
     R: gas constant for hydrogen (J/(g*K))
     n: dynamic viscosity (Pa*s)
     u: kinematik viscosity (m^2/s)
     q: gas flow rate (m^3/s)
     Z: compressability factor
     v: gas velocity (m/s)
     ve: erosional velocity (m/s)
     vmax: maximum working gas velocity (m/s)
     d: pipeline dimater (m)
     EV: True if erosinal velocity is considered
```

```
    """
    p1 = 2*(Pin**3-Pout**3)/(Pin**2-Pout**2)/3  #Average working pressure
    density = volumetricDensity(p1, R, T, False)
    u = n / density
    q = m / density

    #Base values
    Tb = 288.706
    Pb = 101325
    Qb = m*3600*24/volumetricDensity(Pb,R,Tb,False)

    Z = volumetricDensity(Pout,R,T,True)
    v1 = 12  #Arbitrary start value
    d1 = diameter(q, v1)
    ve = 122/(volumetricDensity(Pout,R,T,False))**0.5

    #Placeholders for values in the iterations
    d2 = 0
    v2 = 0

print(math.pi*14.7349*density*3600*24*Pb*Z*T/(volumetricDensity(Pb,R,Tb,False)*Tb*4*10**6)*10**-5, p1*10**-5)
    #Iterative process that terminates when the gas velocity and pipe diameter stagnates
    while (abs(d1 - d2) > 0.0001) or (abs(v1 - v2) > 0.0001):
        d2 = d1
        v2 = v1
        f = frictionCoeff(v2, d2, u)
        v1 = velocityP(f, l, d2, density, (Pin - Pout))
        d1 = diameter(q, v1)
    vmax = 14.734*(Pb/Tb)*Z*T*Qb/(Pout*(d1*10**3)**2)
    #Adjustments to diameter based on erosionla velocity
    if (vmax >= ve*0.5) and EV:
        d1 = 10**-3*(14.7349*Qb*Pb*Z*T/(ve*0.5*Tb*Pout))**0.5
        v1 = velocity(d1,q)
    return [m, T, d1, l, v1, density, Pin, p1, Pout, f]

#Function to calculate single stage polytropic compressor power
def CompressorSizePolytropic(Pin, Pout, Tin, eff, m, effM):
    """
     Pin: compressor inlet pressure (Pa)
     Pout: compressor outlet pressure (Pa)
     Tin: inlet temperature
     eff: polytropic efficiency
     m: gas massflow into compressor (kg/s)
     effM: the compressors electric motor efficiency
     k: specific heat ratio
     R: universal gas constant (J/(mol*K))
     MW: molecularweight (g/mol)
     Tout: outlet temperature (K)
     Pavg: average pressure (Pa)
     Z: compressabilityfactor
     Hp: compressor head (J/kg)
     power: total conpressor power (W)
    """
    k = 1.405
    R = 8.314*10**3
    MW = 2.01568  # Molecular weight (g/mol)
```

```
    Tout = Tin*(Pout/Pin)**((k-1)/(k*eff))
    Tavg = (Tin+Tout)/2
    Pavg = 2*(Pin**3-Pout**3)/(Pin**2-Pout**2)/3
    Z = volumetricDensity(Pavg, R/MW, Tavg, True)
    Hp = Z*R*Tin*k/(k-1)*eff*((Pout/Pin)**((k-1)/(k*eff))-1)/MW
    power = Hp*m/(eff*effM)
    return (power, Tout)

#Function to calculate multi stage insetropic compressor power
def Isentropic(Pin, Pout, Tin, eff, m, effM):
    """
     Pin: compressor inlet pressure (Pa)
     Pout: compressor outlet pressure (Pa)
     Tin: inlet temperature
     eff: polytropic efficiency
     m: gas massflow into compressor (kg/s)
     effM: the compressors electric motor efficiency
     x: copression ratio
     N: number of compression stages
     k: specific heat ratio
     R: universal gas constant (J/(mol*K))
     MW: molecularweight (g/mol)
     Tout: outlet temperature (K)
     Pavg: average pressure (Pa)
     Z: compressabilityfactor
     Hp: compressor head (J/kg)
     power: total compressor power (W)
    """
    x = 3.1
    N = int(math.log10(Pout/Pin)/math.log10(x))+1
    k = 1.405 #Specific heat ratio
    R = 8.314*10**3
    MW = 2.01568  # Molecular weight (g/mol)
    Tout = Tin*(1+((Pout/Pin)**((k-1)/(N*k))-1)/eff)
    Tavg = (Tin+Tout)/2
    Pavg = 2*(Pin**3-Pout**3)/(Pin**2-Pout**2)/3
    Z = volumetricDensity(Pavg, R/MW, Tavg, True) #Z is independant of R
    Hp = N*(k/(k-1))*Z*Tin*R/MW*((Pout/Pin)**((k-1)/(N*k))-1)
    power = Hp*m/(eff*effM)
    return (power, Tout, N)

#Function to calculate single stage isentropic compressor power
def Isentropic2(Pin, Pout, Tin, eff, m, effM):
    """
     Pin: compressor inlet pressure (Pa)
     Pout: compressor outlet pressure (Pa)
     Tin: inlet temperature
     eff: polytropic efficiency
     m: gas massflow into compressor (kg/s)
     effM: the compressors electric motor efficiency
     k: specific heat ratio
     R: universal gas constant (J/(mol*K))
     MW: molecularweight (g/mol)
     Tout: outlet temperature (K)
     Pavg: average pressure (Pa)
     Z: compressabilityfactor
     Hp: compressor head (J/kg)
```

```
     power: total conpressor power (W)
    """
    k = 1.405 #Specific heat ratio
    R = 8.314*10**3
    MW = 2.01568 # Molecular weight (g/mol)
    Tout = Tin*(1+((Pout/Pin)**((k-1)/k)-1)/eff)
    Tavg = (Tin+Tout)/2
    Pavg = 2*(Pin**3-Pout**3)/(Pin**2-Pout**2)/3
    Z = volumetricDensity(Pavg, R/MW, Tavg, True) #Z is independant of R
    Hp = (k/(MW*(k-1)))*Z*Tin*R*((Pout/Pin)**((k-1)/k)-1)
    power = Hp*m/(eff*effM)
    return (power, Tout)

#Function to determine the LCOH for pipelines
def pipelineCosts(qm, d, l, IC, Dr, n, Lr, Ilf, FOM, A, Of):
    """
     qm: Pipeline capacity (kgH2/s)
     d: Diameter (m)
     l: Length (m)
     IC: Indirect costs (fraction of TIC)
     Dr: Discount rate
     n: Life time (Years)
     Lr: Labour rate (US$/h)
     Ilf: Indirect labour factor (Fraction of direct labour)
     FOM: Fixed O&M (Fraction of TIC or TCI)
     A: Availability (Fraction of year)
     Of: Offshore scaling factor (= 1 for onshore pipelines)
    """
    d = d*39.3700787 #Converts from meters to inches
    m = 0.621371192 #Converts from miles to km
    inflation = 1.41 #Dollar value today compared to 2009
    Mc = 1.1*(63027*math.e**(d*0.0697))*inflation*m #Material costs per km
    Lc = 1.1*(-51.393*d**2 + 43523*d +16161)*inflation*m #Labour costs per km
    Misc = 1.1*(303.13*d**2+12908*d+123245)*inflation*m #Miscellaneous costs per km
    RoW  = (-9*10**-13 * d**2 + 4417.1*d + 164241)*inflation*m #Right of way costs per km
    TIC = Of*(Mc + Lc + Misc + RoW)*l*10**-3 #Total installation cost
    TCI = TIC*(1+IC) #Total Capital Invsetment
    Atci = Dr*(1+Dr)**n/((1+Dr)**n-1) * TCI #Annualized TCI
    qm = qm*60*60*24 #Pipeline capacity in kgH2/day
    Dl = 8320*(qm/10**6)**0.25 * Lr #Direct labour costs per year
    OM = TCI * FOM #Fixed O&M
    OPEX = Dl*(1+Ilf)+OM
    CapexH2 = Atci/(A*qm*365) #Capex per kgH2
    OpexH2 = OPEX/(A*qm*365) #Opex per kg H2
    LCOH = CapexH2 + OpexH2 #Levelised costs of hydrogen
    return [TCI, OPEX, LCOH]

#Function to calculate the LCOH of hydrogen compression
def compressorCosts(MCP, CP, SF, IF, IC, Dr, n, qm, Ec, Lr, Ilf, FOM, A):
    """
     MCP: Maximum compressor size
     CP: Compressor power (kW)
     SF: Scale Factor (estimate of economic of scales factor)
     IF: Installation factor (estimate of installation costs)
     IC: Indirect costs (fraction of TIC)
     Dr: Discount rate
     n: Life time (Years)
```

```
     qm: Pipeline capacity (kgH2/s)
     Ec: Electricity cost
     Lr: Labour rate (US$/h)
     Ilf: Indirect labour factor (Fraction of direct labour)
     FOM: Fixed O&M (Fraction of TIC or TCI)
     A: Availability (Fraction of year)
    """
    e = 0.75 #Exchangerate from C$ to US$
    inflation = 1.18 #Dollar value today (April 2023) compared to 2019
    nC = CP/MCP #Number of compressors
    if nC > 1:
        UC = int(nC)*3083.3*MCP**SF+3083.3*(MCP*CP%MCP)**SF*e*inflation #Uninstalled
compressor cost
    else:
        UC = 3083.3*CP**SF*e*inflation #Unistalled compressor cost for single compressor
    TIC = UC*IF #Total installation cost
    TCI = TIC*(1+IC) #Total Capital Investment
    Atci = Dr*(1+Dr)**n/((1+Dr)**n-1) * TCI #Annualized TCI
    qm = qm*60*60*24 #Pipeline capacity in kgH2/day
    Ei = CP/(qm*60*60) #Energy intensity kWh/kgH2
    Eec = CP*24*365*Ec #Annual electical energy cost
    Dl = 288*(qm/10**6)**0.25 * Lr #Direct labour costs per year
    OM = TIC*FOM[0]+TCI*FOM[1] #Fixed O&M
    OPEX = Dl*(1+Ilf)+OM+Eec
    CapexH2 = Atci/(A*qm*365) #Capex per kgH2
    OpexH2 = OPEX/(A*qm*365) #Opex per kg H2
    LCOH = CapexH2 + OpexH2 #Levelised costs of hydrogen
    return [TCI, OPEX, LCOH]

#Function used to execute the code
def run():
    #Gas properties
    MW = 2.01568
    R = 8.314*10**3 / MW
    n = 8.641 / 10 ** 6

    #The following data was retreived from the report
    MCP = 16000
    IC = 0.4
    Dr = 0.08
    nP = 50
    nC = 15
    Lr = 37.2
    Ilf = 0.5
    FOMP = 0.026
    FOMC = [0.04, 0.021]
    A = 0.9
    Of = 1.5
    SF = 0.8335
    IF = 2
    Ec = 0.138 #0.035
    m = 16 * 10 ** 3 / (60 * 60 * 8)
    l = 100*10**3
    effM = 0.95
    effPoly = 0.63
```

```
    TinComp = 273.15 + 7.4
    TinPipe = 273.15 +  5
    Pin = 30 * 10**5
    Pout = [50*10**5, 100*10**5, 200*10**5]
    InletPressure = [50*10**5, 100*10**5, 200*10**5]
    OutletPressure = [30*10**5]
    Length = [l*0.6,l]
    Massflow = [m, m*2, m*3]
    EV = False #Set False to ignore erosional velocity
    excelPrint = True #Set True to print results to excel
    if excelPrint:
        workbook = xlsxwriter.Workbook('Summary.xlsx')
        costSheet = workbook.add_worksheet(name = "Costs")
        pipeSheet = workbook.add_worksheet(name = "Pipeline")
        compressorSheet = workbook.add_worksheet(name = "Compressor")

        format = workbook.add_format({'bold': True})

        #Cost prints
        row = 0
        column = 0
        format = workbook.add_format({'bold': True})
        costSheet.write(row, column, 'Mass flow (kg/s)', format)
        costSheet.write(row, column + 1, 'Pipe Diameter (m)', format)
        costSheet.write(row, column + 2, 'Pipeline length (km)', format)
        costSheet.write(row, column + 3, 'OutletPressure Compressor (bar)', format)
        costSheet.write(row, column + 4, 'Compressor Power (MW)', format)

        costSheet.write(row, column + 6, 'Capex Pipeline (M$)', format)
        costSheet.write(row, column + 7, 'Opex Pipeline (M$)', format)
        costSheet.write(row, column + 8, 'LCOH pipeline ($/kgH2)', format)

        costSheet.write(row, column + 10, 'Capex Compressor (M$)', format)
        costSheet.write(row, column + 11, 'Opex Compressor (M$)', format)
        costSheet.write(row, column + 12, 'LCOH Comrpessor ($/kgH2)', format)

        costSheet.write(row, column + 14, 'System LCOH (M$/kgH2)', format)

        row += 1

        for Ii in InletPressure:
            for Oi in OutletPressure:
                for Li in Length:
                    for Mi in Massflow:
                        if Mi * 3600 / volumetricDensity(Pin, 4124.2, TinComp, False) > 850:
                            effPoly = 0.74
                        else:
                            effPoly = 0.63
                        pipe = pipelineSpecs(TinPipe, Ii, Oi, Li, Mi, R, n, EV)
                        comp = CompressorSizePolytropic(Pin, Ii, TinComp, effPoly, Mi, effM)
                        pipeCost = pipelineCosts(Mi, pipe[2], Li, IC, Dr, nP, Lr, Ilf, FOMP,
A, Of)
                        compCost = compressorCosts(MCP, comp[0]*10**-3, SF, IF, IC, Dr, nC,
Mi, Ec, Lr, Ilf, FOMC, A)
```

```
                costSheet.write(row, column, Mi)
                costSheet.write(row, column + 1, pipe[2])
                costSheet.write(row, column + 2, Li*10**-3)
                costSheet.write(row, column + 3, Ii*10**-5)
                costSheet.write(row, column + 4, comp[0]*10**-6)

                column += 6
                for item in pipeCost:
                    if column == 8:
                        costSheet.write(row, column, item)
                    else:
                        costSheet.write(row, column, item*10**-6)
                    column += 1
                column += 1
                for item in compCost:
                    if column == 12:
                        costSheet.write(row, column, item)
                    else:
                        costSheet.write(row, column, item*10**-6)
                    column += 1
                column += 1
                costSheet.write(row, column, pipeCost[2]+compCost[2])
                row += 1
                column = 0

#Pipeline prints
row = 0
column = 0
format = workbook.add_format({'bold': True})
pipeSheet.write(row, column, 'Mass flow (kg/s)', format)
pipeSheet.write(row, column + 1, 'Temperature (K)', format)
pipeSheet.write(row, column + 2, 'Diameter (m)', format)
pipeSheet.write(row, column + 3, 'Pipeline length (km)', format)
pipeSheet.write(row, column + 4, 'Velocity (m/s)', format)
pipeSheet.write(row, column + 5, 'Density (kg/m3)', format)
pipeSheet.write(row, column + 6, 'InletPressure (bar)', format)
pipeSheet.write(row, column + 7, 'Average Pressure (bar)', format)
pipeSheet.write(row, column + 8, 'OutletPressure (bar)', format)
pipeSheet.write(row, column + 9, 'Friction koeff', format)
pipeSheet.write(row, column + 10, 'Pipeline Storage (kg)', format)
row += 1

for Ii in InletPressure:
    for Oi in OutletPressure:
        for Li in Length:
            for Mi in Massflow:
                arr = pipelineSpecs(TinPipe, Ii, Oi, Li, Mi, R, n,EV)
                for item in arr:
                    if column == 3: #Converts from m to km
                        item = item / 10 ** 3
                    if column == 6 or column == 7 or column == 8: #Converts Pa to bar
                        item = item / 10 ** 5
                    pipeSheet.write(row, column, item)
                    column += 1
```

```
                        pipeSheet.write(row, column, arr[5] * arr[3] * math.pi * (arr[2] ** 2) / 4) #Linepack
                        row += 1
                        column = 0


        #Compressor prints
        row = 0
        column = 0
        compressorSheet.write(row, column, 'Isentropic Multistage', format)
        row +=1
        compressorSheet.write(row, column, 'Mass flow (kg/s)', format)
        compressorSheet.write(row, column + 1, 'Inlet Pressure (bar)', format)
        compressorSheet.write(row, column + 2, 'Outlet Pressure (bar)', format)
        compressorSheet.write(row, column + 3, 'Inlet Temperature (K)', format)
        compressorSheet.write(row, column + 4, 'Outlet Temperature (K)', format)
        compressorSheet.write(row, column + 5, 'Isentropic Power (MW)', format)
        compressorSheet.write(row, column + 6, 'Stages', format)
        row += 1
        for i in Pout:
            for j in Massflow:
                if j * 3600 / volumetricDensity(Pin, 4124.2, TinComp, False) > 850:
                    effIsen = 0.7
                else:
                    effIsen = 0.6
                item = Isentropic(Pin, i, TinComp, effIsen, j, effM)
                compressorSheet.write(row, column, j)
                compressorSheet.write(row, column+1, Pin*10**-5)
                compressorSheet.write(row, column+2, i*10**-5)
                compressorSheet.write(row, column+3, TinComp)
                compressorSheet.write(row, column+4,item[1])
                compressorSheet.write(row, column+5,item[0]*10**-6)
                compressorSheet.write(row, column+6,item[2])
                row += 1
            row += 1
        compressorSheet.write(row, column, 'Isentropic', format)
        row +=1
        compressorSheet.write(row, column, 'Mass flow (kg/s)', format)
        compressorSheet.write(row, column + 1, 'Inlet Pressure (bar)', format)
        compressorSheet.write(row, column + 2, 'Outlet Pressure (bar)', format)
        compressorSheet.write(row, column + 3, 'Inlet Temperature (K)', format)
        compressorSheet.write(row, column + 4, 'Outlet Temperature (K)', format)
        compressorSheet.write(row, column + 5, 'Isentropic Power (MW)', format)
        compressorSheet.write(row, column + 6, 'Stages', format)
        row += 1
        for i in Pout:
            for j in Massflow:
                if j * 3600 / volumetricDensity(Pin, 4124.2, TinComp, False) > 850:
                    effIsen = 0.7
                else:
                    effIsen = 0.6
                item = Isentropic2(Pin, i, TinComp, effIsen, j, effM)
                compressorSheet.write(row, column, j)
                compressorSheet.write(row, column+1, Pin*10**-5)
                compressorSheet.write(row, column+2, i*10**-5)
```

```python
                compressorSheet.write(row, column+3, TinComp)
                compressorSheet.write(row, column+4,item[1])
                compressorSheet.write(row, column+5,item[0]*10**-6)
                compressorSheet.write(row, column+6,1)
                row += 1
            row += 1
        compressorSheet.write(row, column, 'Polytropic', format)
        row +=1
        compressorSheet.write(row, column, 'Mass flow (kg/s)', format)
        compressorSheet.write(row, column + 1, 'Inlet Pressure (bar)', format)
        compressorSheet.write(row, column + 2, 'Outlet Pressure (bar)', format)
        compressorSheet.write(row, column + 3, 'Inlet Temperature (K)', format)
        compressorSheet.write(row, column + 4, 'Outlet Temperature (K)', format)
        compressorSheet.write(row, column + 5, 'Polytropic power (MW)', format)
        compressorSheet.write(row, column + 6, 'Stages', format)
        row += 1
        for i in Pout:
            for j in Massflow:
                if j * 3600 / volumetricDensity(Pin, 4124.2, TinComp, False) > 850:
                    effPoly = 0.74
                else:
                    effPoly = 0.63
                item = CompressorSizePolytropic(Pin, i, TinComp, effPoly, j, effM)
                compressorSheet.write(row, column, j)
                compressorSheet.write(row, column+1, Pin*10**-5)
                compressorSheet.write(row, column+2, i*10**-5)
                compressorSheet.write(row, column+3, TinComp)
                compressorSheet.write(row, column+4,item[1])
                compressorSheet.write(row, column+5,item[0]*10**-6)
                compressorSheet.write(row, column+6,1)
                row += 1
            row += 1
        workbook.close()

run()
```

Lighthouse gathers leading maritime stakeholders through a Triple-Helix collaboration comprising industry, society, academies and institutes to promote research, development and innovation within the maritime sector with the following vision:

Lighthouse – for a competitive, sustainable and safe maritime sector with a good working environment

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