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Modelling and Simulation Comparison of Conventional and Innovative Transport for Natural Gas

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1. *ABSTRACT:* Nowadays, technology is still heavily dependent on fossil fuels, especially natural gas. Within the last century, the production and consumption of this resource increased decade by decade, using new technologies to increase profits and decrease the costs linked to production and transport. This paper aims to compare two already existing solutions for transporting natural gas, which have a high impact on the environment, with a prototype technology that will soon be available for commercial and industrial use: the airship. The research started by collecting data from previous studies and calculating the parameters needed to determine the cost of the two scenarios considered: one as a system pipeline+compressed natural gas (CNG) carrier, the second as an airship directly delivering the natural gas. The two scenarios have been then simulated in Anylogistix and modelled to examine the profits given the hypothetical but equal demand for natural gas transported by the pipeline+CNG carrier system and by airship. The simulation output has a present slight tendency of choosing the first system for CNG transport due to the careful optimisation of this system which, in real case studies, would not occur.

Keywords: *Natural gas, CNG, Airship, Agent-based Simulation, Modelling, anyLogistixTM.*

2. INTRODUCTION

Natural gas can be found in reservoirs all around the Planet. It can be found on top of oil deposits, in which we would find a superficial layer of natural gas, or in natural gas reservoirs in a range between 2 and 6 km from the surface (both from the surface and the seabed). Given the location of the deposit locations, the extraction process is neither simple nor economic. The difficulties linked to the natural gas deposits are the presence of shale, the extraction of tight gas (available only by fracking and acidizing of rock formations), the location of certain reservoirs in geopressured zones and the hazardous release of methane hydrates [1].

Once the deposit has been found and the cost-benefit analyses declared profitable for the extraction, the production wells are drilled above the deposit and the production site is established.

Independently by the extraction method employed, natural gas must be transported to the consumers. In general, natural gas does not get extracted and given directly to consumers, but it goes through several processes to be safely transported. For example, in the case of maritime transport, it could go under different processes in case it should be transported at a liquified (LNG) or a compressed (CNG) state.

To continue the previous studies done by our department, this paper faces an initial approach to the definition of a new means of transport for natural gas. The employment of airships for the transport of CNG will be compared with a traditional transport system composed of a pipeline.

Existing solutions for transporting natural gas have a high impact on the environment. LNG requires the construction of specific facilities for the liquefaction and regasification processes. Meanwhile, CNG does not require such measures, but specialized equipment for the compression and expansion processes with a low harmful impact than LNG. Natural gas can be carried in its gaseous form as the payload of airships. At certain conditions of temperature and pressure, the specific characteristics of the gas are equivalent to the ones of air. The presented research aims to compare the transport of natural gas through a pipeline and a CNG carrier, and by airship.

This paper will not focus on the extraction process of natural gas from the well. We have performed calculations regarding the exit pressure from the well, which will be necessary for different considerations in the two scenarios. We have not considered the costs related to the energy losses due to the extraction tree being common to the two scenarios.

To simulate transportation time and cost we used AnyLogistix Software. Two scenarios were considered:

- Pipeline scenario: from the well the gas is transported at a pressure of 40 bar through a pipeline to the Harbour where it will be loaded on a CNG transport ship at a pressure of 250 bar. The payload will be transported to the distribution centre (DC) that we placed in Japan and then arrive at the consumer through a second pipeline.

- Airship scenario: form the well the gas is transported at a pressure of 1,4 bar on an airship directly to the DC in Japan and then arrives directly to the consumer.

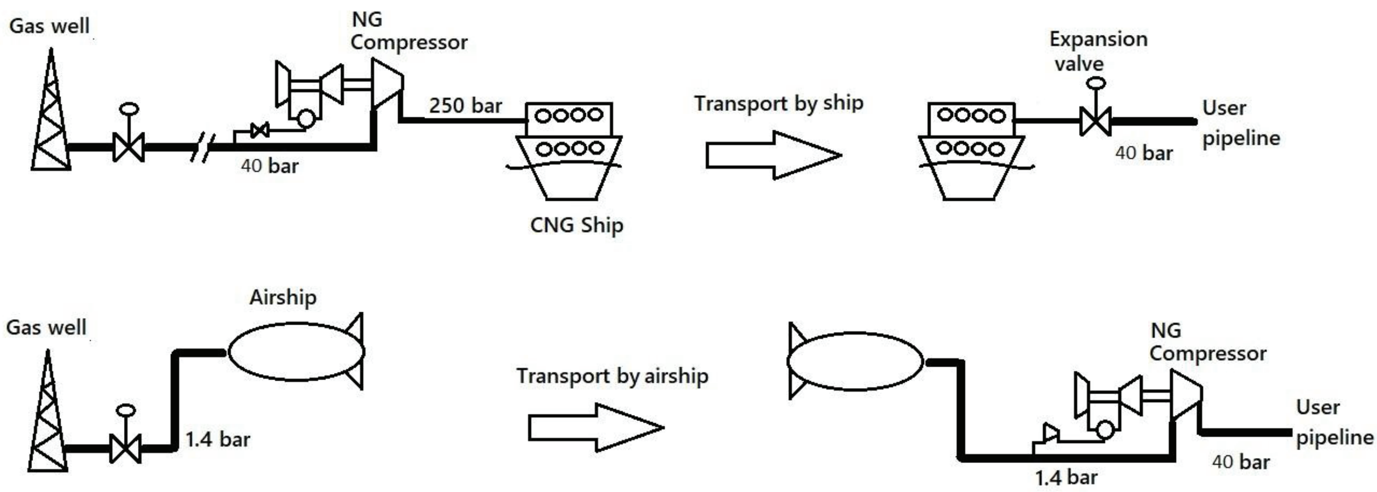

Figure 1: Scenarios model : pipeline + CNG carrier (above); airship (below)

For safety and practical reasons, we have considered the transport of compressed natural gas and not LNG. This is because of the more practical sites which will be developed, avoiding problems related to the liquefied and regasification processes. Another initial constraint is the position of the unspecified well which will be on land and for the deposit parameters we will consider the approximations of existing wells that can be found in the literature.

3. MATERIALS AND METHODS

3.1.Pressure

To develop the model, it is necessary to compute the changes in gas transport under different conditions of pressure. several methodologies are available. The first method is the approximation for which 10 meters of depth corresponds to a variation of pressure of 1 bar from the atmospheric one. Knowing that natural gas is compressible, this first approximation would not be correct because it employs hydrostatic calculations. As proposed by [2] we can apply a derivative of the ideal gas law with all the considerations of the authors about the gas conditions to find a more precise pressure of exit of the flow from the well:

(1) $$p_w = p_0 \exp\left(\frac{Mg(h-h_0)}{ZRT_{avg}}\right)$$

Where:

- pw and h are the exit pressure and the depth for the well;

- p_0 and h_0 are the data for the reference point (in our case 101,325 Pa and 0 m);

- M is the molecular mass of the considered gas, in the case of methane it will be 16.04 g/mol;
- g is the gravitational acceleration;
- Z is the compressibility factor, in the case of methane is about 1 at the reference point;
- R is the ideal gas constant 8.314462 J/(K*mol);
- $T_{avg} = \frac{T+T_0}{2}$ which is the average absolute temperature.

Applying this formula, we obtain the pressure at the exit from the well and this information will be used to calculate the flow rate of the gas in the pipeline. With the data collected, we found that the exit pressure from our well is around 4 MPa.

3.2. Pipeline

The research focuses on the comparison of two scenarios for the transport of natural gas from a well to a consumer. To compare we then must build a cost analysis of the two scenarios. For the pipeline scenario, we must consider the cost related to it. The estimation will be calculated proportionally to its length and diameter.

Pipelines have been, until now, the best mean of transport for hydrocarbon shipping under several circumstances (from an energy efficiency point of view, up to environmental considerations) [3;4]. The costs depend on many factors [5] including the location of the pipeline, in an urban or a rural area. Parker [6] proposed detailed research on the logistics of building a pipeline keeping the focus on the length and diameter parameters. The considerations done are very general and give us a general idea of the concepts to take into consideration. The final formula that we will use to approximate the total cost will consider four main sources of cost: cost of materials, of labour, the miscellaneous costs, and the right of way cost:

(2) $Cost\ (D, L) = Material\ Cost(D, L) + Labour\ Cost(D, L) + Miscellaneous\ Cost(D, L) + Right\ of\ Way\ Cost\ (D, L) = \{[330{,}5\ D^2 + 687D + 26960]\ L + 35000\} + \{[343D^2 + 2704D + 170013]L + 185000\} + \{[8417D + 7324]L + 95000\} + \{[577D^2 + 29788]L + 40000\}$

where D is in inches, L in miles and Cost in dollars. Once obtained the total cost, it is possible to make the approximation in every currency.

This research was followed by Knoope [7] which provided insight into 2 different ways to determine the cost of a pipeline, considering not only the diameter but also the mass flow passing through it. By considering it as fluid CO2, the authors provided a detailed analysis of different studies, determining cost ranges for diameter variating from 0.11-0.64 M€2010/km for 0.3 m of diameters and 1.5- 13M€2010/km for 1.3 m.

Certain considerations must be done initially. The Handbook for the transportation and distribution of gas [8], proposes the following assumptions: the number of compressor stations is known; the considered layout is horizontal; and the flow rate along the pipeline is constant. The costs of the pipeline for each trip can then be calculated considering the pressure and the temperature at which the gas will be inside the pipeline, deciding on a nominal diameter and calculating, supposedly a hypothetical length, every how many kilometres (or miles) should a compressor be placed to avoid a too high loss of pressure. Once this number is calculated, it is possible to determine the losses of flow to feed the compressors and so the approximate cost of each trip to load the CNG carrier.

The specific data of the pipe considered have been:

- The pressure inside the pipeline of 40 bar (constant);
- Length of 800 km;
- 40 compressors placed every 20 km between which a loss of 10 bar is registered;
- A temperature inside the pipeline of -25°C (248.15 K);
- A flow speed of 10 m/s;
- Nominal diameter of 0.5 m;
- A viscosity of 20*10-6 m2/s;
- The efficiency of the compressors of 0,85 and of the turbo gas needed to feed the compressors of 0.35;
- A lower heating value of 50*106 J/kg.

3.3. CNG transportation

The maritime transport considered in the scenario is a cargo ship for CNG. The technology used to develop this specific type of cargo ship has been studied since the 1960s, always being categorised as too expensive for the final means. Back in the early 2000s, Wagner [9] studied the reignition of the maritime industry towards CNG carriers. The idea behind this research was to provide a view of the evolution of the needed technologies to avoid the costs related to LNG transportation. Compared with LNG carriers, the advantages of CNG carriers increased little by little since the first studies.

For the first decade of the 2000s, there is a record of many studies [10-12] on the progressive state of the art, describing step by step the evolution of maritime carriers. With the advantages of CNG carriers, also the limitations started to be clearer, such as the lower amount of payload. In general, there were already ideas on the possible technologies which could be used, as much as the possibility of employing new technologies, such as go-to-market (GTM) vessels (composite reinforced vessels mainly used for truck transport until then). This technology has been studied by several researchers [13-16], and the possibility of transporting for short distances high volumes of CNG was clear. Initial approximations resulted in half of the energy required for LNG carriers, with the possibility of adjusting the system with different numbers of ships according to the demand and representing a safe investment. For how much CNG used to present challenges in terms of technology and non-existent regulations, they were studied with also the development of prototypes to allow companies to invest in tested projects. Over the years, the technical challenges, the issues related to safety, reliability and risks have been tested and consolidated, allowing the building of many CNG carriers with similar characteristics. In general, nowadays, it is possible to carry by sea from 5 to 20 million nm^3 of CNG per trip at an average pressure of 250 bar (with certain exceptions, for example, the "VOTRANS" carrier) [17]. Given the data collected, the following data were chosen for the study:

- Engines power of 30 MW;
- The efficiency of the engines of 0.45;
- Speed of 13 m/s (40 knots).

For the volume consideration, we considered the exit volume from the pipeline to properly balance our model in the simulation.

3.4. Airship

Nowadays many prototypes of airship carriers have been studied and developed, but with a relatively small production due to the costs, the advancement of technology or also the failure of previous prototypes. Continuing in the direction of the previous research of our university, we considered the characteristics and the data collected and obtained by [18]. From a structural point of view, the characteristics of different airships used in the fields of transport were considered [19-23]. The main idea is to consider a high-volume vehicle (from tot volume to tot volume) and the hypothesis of using a ratio of Hydrogen to natural gas of 40%/60%. The choice of hydrogen as lifting gas was done considering the characteristics of both the lifting gas and the transported gas. Given the high inflammability of both gases, the choice of a cheaper lifting gas was done compared to the choice of helium.

Among all the possible choices of airships (considering it as a prolate spheroid), we considered the technical characteristics of:

- The volume of 75000 m3;
- Speed of 120 km/h (33.4 m/s);
- c (major semi-axis) of about 54 m and a (minor semi-axis) around 18 m (a=c/3);
- Transporting a volume of natural gas at ambient temperature at which the methane has the same density as the air, and then it will not influence the balancing for the lift;
- Drag coefficient of 0.022;

4. SIMULATION

To develop the model and study the simulation of our scenarios an agent-based simulation was used. AnyLogistix software was chosen to analyze the performance of the theorized system of the gas transportation supply chain. It allows one to analyze and optimize the supply chain as well as to study the dynamic form of a system. To define our system as accurately as possible, preliminary calculations were developed in Mathcad to get the basic information. Such calculations considered data analyzed from several articles describing already existing systems.

4.1. Calculations

To calculate the pipeline diameter, we chose the average output of Gas flow rate $Q'_{wellhead}$. [1]. The wellhead pressure of p = 4MPa and the average temperature $T_{wellhead}$ = 348.15 K [24.].

The mass flow rate at the wellhead was calculated by the formula:

(3) $$m'_{wellhead} := \rho_{wellhead} \cdot Q_{well}'$$

where $\rho_{wellhead} = p/(R'T_{wellhead})$ is the gas density, and R' is the gas constant relative to the CH4. For our case, we consider natural gas as the ideal liquid containing only methane gas:

(4) $$\rho_{wellhead} := \frac{p}{R' \cdot T_{wellhead}} = 22.11\ \frac{kg}{m^3}$$

The density at -25°C, the transportation temperature [25] will be:

(5) $$\rho_{pipeline} := \frac{p}{R' \cdot T_{pipeline}} = 31.019\ \frac{kg}{m^3}$$

This information can be used to calculate the flow rate inside the pipeline:

(6) $$m'_{wellhead} := \rho_{wellhead} \cdot Q_{well}' = 3.838\ \frac{kg}{s}$$

The mass flow rate in the outlet of the wellhead does not change, but the volumetric flow rate at the pipeline is changing along the pipeline according to the Temperature and Pressure changes.

The volumetric flow rate at the pipeline:

(7) $$Q'_{pipeline} := \frac{m'_{wellhead}}{\rho_{pipeline}} = 0.124\ \frac{m^3}{s}$$

The diameter of the pipeline is determined by the standard for steel pipes for natural gas [26]. By considering also eventual surges, a nominal diameter of 0.5 m in L360 GA was chosen.

Following the abovementioned considerations, the pipeline was divided into sections to maintain a constant gas pressure with small pressure drops, which allowed us to calculate the required number of compressors for the safety of the system. In our model, we considered 40 compressors (one every 20 km). Between each compressor, a drop of 10 bars was registered. Each compressor is moved by a prime motor (e.g. an internal combustion engine which is fueled by the bleeding part of the natural gas flow rate from the pipeline. Therefore, we considered the following calculation to determine the flow of exit from the pipeline:

(8) $$m'\_final_{afterbleeding} := m'_{afterbleeding} - m'_{CH4\_TG} \cdot n_{compressors} = 3.42\ \frac{kg}{s}$$

In particular, each compressor contributed to a loss of 0.1 kg/s from the initial flow.

It has also been possible to determine the power of each compressor. In particular, it was studied how the first compressor would have needed to have a power of 178.7 kW and the last one of 159.2 kW, leaving us to assume that the cost difference between each compressor will not be much, and so we will consider it nearly constant.

Given the exit flow from the pipeline, it was also possible to determine the final volume of natural gas, which would have been the one loaded on the CNG carrier. Considering the abovementioned data, we obtained that the total losses of natural gas from the CNG carrier would be around 123400 m^3.

Considering the information about the airship that we supposed, it was possible to calculate the necessary power of the engine of the airship and considering the efficiency of the engine (35%) and the propellers (70%), find how much of the initial volume of natural gas would have been consumed to propel the airship. In particular, considering the different densities of the pipeline scenario, an initial volume of 45000 m^3 corresponds to a final volume of natural gas at 1.4 bar of 37200 m^3.

Through all the collected data it was then possible to calculate the duration of the single trips for the airship scenario and the pipeline + CNG ship scenario, respectively 6 days and 18 days.

4.2.Model

Once the calculations were done, the data were used in a model to estimate the profits of using an airship as an alternative to CNG carrier transportation. The results and inputs are presented in Table 1.

Table 1. Simulation data

Parameters	Value	Units of measure
Customer pipeline demand	4 872 000	kg
Customer airship demand	158 000	kg
Lead Time Pipeline	18	days
Lead Time Airship	6	days
Selling price	2.08	$/kg
Cost Natural Gas 1.4 bar	0.1	$/kg
Cost Natural Gas 40 bar	0.7	$/kg
Shipping Type	Full Truck Load	-
Pipeline Capacity	123 400	m3
CNG ship Capacity	123 400	m3
Airship Capacity	45 000	m3

Due to the constraints of AnyLogistix, it was not possible for us to directly simulate a pipeline. The structure we adopted for our model considered then the gas through the pipeline as the payload of a truck that will transport the whole column of gas in one trip.

The entities that we placed in our simulation model are the following:

- "Suppliers" are the wells located in Canada, British Columbia [27], from which the gas comes out at a flow rate of 3.85kg/s and with a pressure of 4 MPa to feed one the pipeline and one the airship. We suppose that the wells can always produce the amount of gas required to satisfy the demand.

- "Distribution centres" (DCs) are in two locations in Japan, one for the natural gas by airship and one for the natural gas carried by the CNG carrier.

- The "Factory" in Vancouver is used to compress the gas from 40 to 250 bar and for loading operation to the carrier. This operation in the model is not represented but it calculated the effect of the compression of the gas with different densities (comparison densities) and losses due to the compressors used along the pipeline and the natural gas used for the CNG carrier.

- The "Customers" define the needed demand from the two distribution centres.

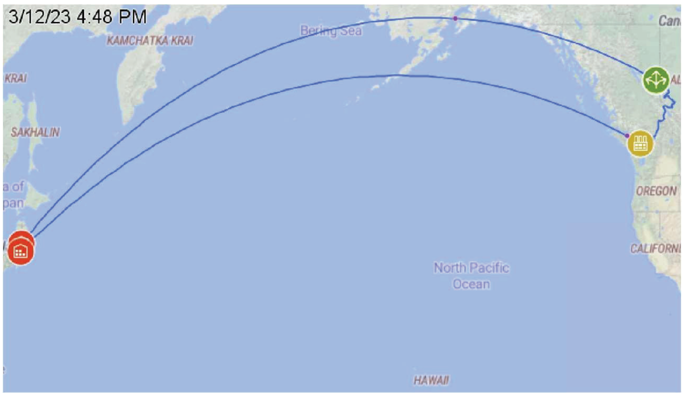

Figure 2: Actual behaviour of the two scenarios (in the figure it is possible to see the airship and the departing CNG carrier)

4.3.Results

The obtained results were calculated in a time range of one year (from the 1st of January 2023 to the 31st of December 2023). Figure 3 represents the Profit of the Pipeline scenario (green) and the Airship scenario (red).

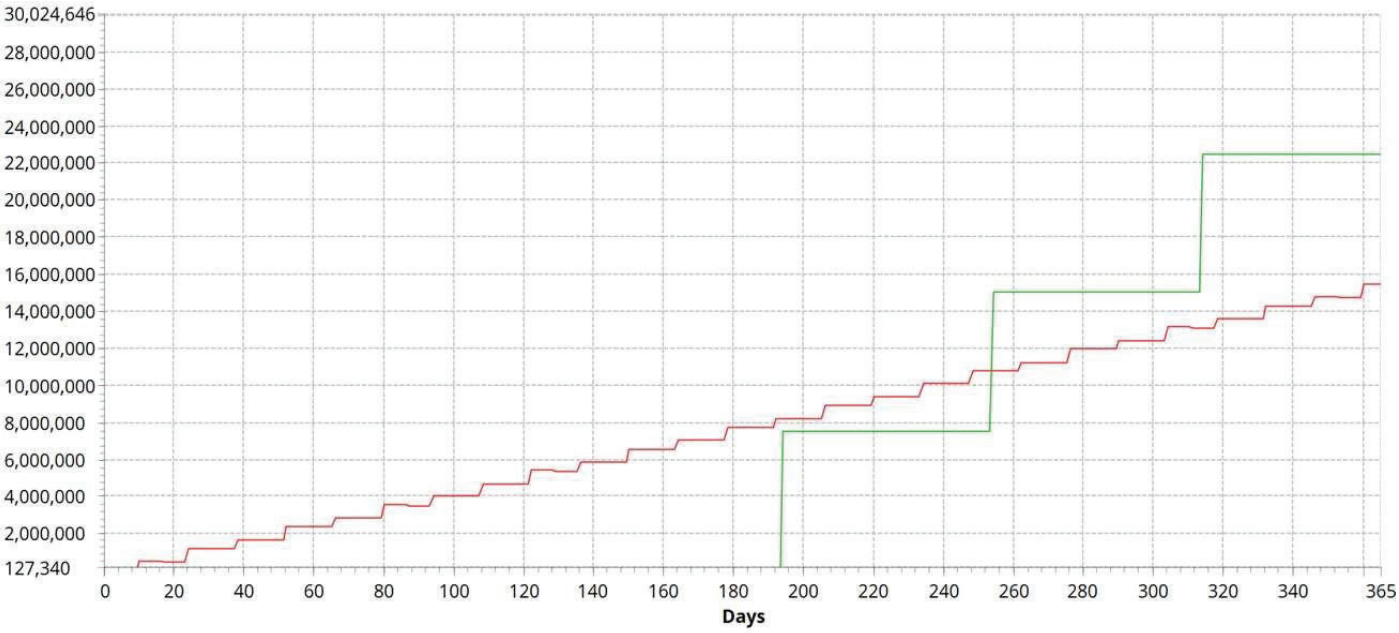

Figure 3: Daily profit: Pipeline scenario (green) and airship scenario (red)

As can be seen from the results, the pipeline and CNG carrier profit results are more than the profit given by the airship. These results may vary depending on more precise information on the costs of the involved structures (the harbour facility and the distribution centres). These results provide the idea of why at present time, given the reliability of airships as means of transport, this technology is not yet used.

Moreover, we can notice the difference in the delay time between the two means of transport: while the pipeline has a greater delay than the one of the airship, because of the loading time of 11 days, on the long period it results in being a more reliable mean of transportation for natural gas in the considered system than the airship.

5. CONCLUSIONS

This research aimed at presenting the calculation and the simulation results of a model comparing two scenarios of transporting CNG from a well to customers. Using data found during the literature research, the well was decided to be considered in Canada and the final customers in Japan. With the appropriate considerations for the two scenarios, calculations were performed to retrieve as much precise as possible data for the description of the model. A model was then described in Anylogistix to compare the profits of the scenario employing a pipeline and a CNG carrier and the one considering the direct transport with an airship.

With the definition of the data and taking into account the constraints given by the case that was studied, we ended up finding as a result of the simulation, that the pipeline scenario resulted in being more profitable than the scenario employing the airship. We consider that a more attentive analysis of the costs should be performed and that the pipeline solution and the employment of a CNG carrier may result profitable, but in the long period, airships would start employing technology which would make obsolete the pipelines and the CNG carriers, due to the lower environmental impact and on the smaller costs in terms of maintenance and initial costs.

Future studies will focus on the improvement of such a model and a more accurate determination of the parameters of the pipeline, CNG carrier and airship to determine the losses and consumptions due to the different means of transport, considering different designs of airships which would improve the power needed by the propulsion system for the airship.

6. REFERENCES

1. Wei X., Xiaodong W., Xiaojuan L., Simplified graphical correlation for determining flow rate in tight gas wells in the Sulige gas field, Pet. Sci. 5, 258–262 (2008)

2. Byrom T. G., Gulf Drilling Guides, Casing and Liners for drilling competion, second edition, 2017

3. Jean-Thomas Bernard, Denis Bolduc, Annie Hardy, The costs of natural gas distribution pipelines: the case of SCGM, Québec, Energy Economics, Volume 24, Issue 5, 2002, Pages 425-438, ISSN 0140-9883

4. Nathan, Parker. (2004). Using Natural Gas Transmission Pipeline Costs to Estimate Hydrogen Pipeline Costs - eScholarship

5. (Pipeline Basics & Specifics About Natural Gas Pipelines, 2015-PST-Briefing-Paper-02- NatGasBasics.pdf (pstrust.org)

6. Parker, N. (2004). Using Natural Gas Transmission Pipeline Costs to Estimate Hydrogen Pipeline Costs. UC Davis: Institute of Transportation Studies. Retrieved February 8, 2023, from https://escholarship.org/uc/item/9m40m75r

7. M.M.J. Knoope, A. Ramírez, A.P.C. Faaij, A state-of-the-art review of techno-economic models predicting the costs of CO2 pipeline transport, International Journal of Greenhouse Gas Control, Volume 16, 2013, Pages 241-270

8. Chapon M (1990) Conception et Construction des réseaux de transport de gaz, Manuel pour le transport et la distribution du gaz, Livre IX. Association Technique de l'industrie du gaz en France. ISBN 2-86655- 048-X

9. Wagner, Jan & van Wagensveld, Steven. (2002). Marine Transportation of Compressed Natural Gas A Viable Alternative to Pipeline or LNG. 10.2523/77925-MS.

10. Young, C., and P. Eng. "Marine CNG: Technically Sound, Commercially Viable, and Imminent." Paper presented at the Offshore Technology Conference, Houston, Texas, U.S.A., April 2007

11. Cano, G., and G. Stephen. "CNG Marine Transport--A Gas Transportation Company Perspective." Paper presented at the Offshore Technology Conference, Houston, Texas, May 2005

12. Stephen, G., and G. Cano. "CNG Marine Transport-Demonstration Project Development." Paper presented at the Offshore Technology Conference, Houston, Texas, USA, May 2006

13. Stenning, D. (1999). The Coselle CNG carrier: a new way to ship natural gas by sea. Proceedings of the 1999 CERI North American natural gas conference and Calgary gasexpo '99 : cresting the capacity wave, (p. 300). Canada: Canadian Energy Research Inst

14. Stenning D.G., COSELLE CNG: Economics and Opportunities A New Way To Ship Natural Gas By Sea, Stenning.pdf (ntnu.no)

15. Trincas G., Comparison of Marine Technologies for Mediterranean Offshore Gas Export, Ebook:

Technology and Science for the Ships of the Future, pp. 577-586, 2021

16. Man Diesel & Turbo, Propulsion Trends in LNG Carriers Two-stroke Engines

17. Żuchowicki, J., & Lelonek, T. (2011). CNG - a new way of maritime natural gas supplies. Rocznik Ochrona Środowiska, Tom 13, 137–148

18. Capitta G., Damiani L., Laudani S., Lertora E., Mandolfino C., Morra E., Revetria R., Structural and Operational Design of an Innovative Airship Drone for Natural Gas Transport over Long Distances, Engineering letters 25:3, 2017

19. Petrolo M., Azzara R., Nagaraj M.H., SkySaver- An airship to revolutionize cargo transport and humanitarian relief operations, Thesis, 2021

20. Prentice, B.E. and Knotts, R. (2014) Cargo Airships: International Competition. Journal of Transportation Technologies, 4, 187-195all my airships tuff; Prentice, B.E.; Lau, Y.- Y.

21. Ng, A.K.Y. Transport Airships for Scheduled Supply and Emergency Response in the Arctic. Sustainability 2021, 13, 5301

22. A A Didkovskij et al 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1129 012066

23. Capitta G., Laudani S., Progettazione meccanica di una piattaforma innovativa per il trasporto di CNG su lunghe distanze: aspetti logistici, costruttivi ed operative, 2016

24. Jing, J.; Shan, H.; Zhu, X.; Huangpu, Y.; Tian, Y. Wellbore Temperature and Pressure Calculation of Offshore Gas Well Based on Gas–Liquid Separated Flow Model. Processes 2022, 10, 2043

25. Li, Xiaxi & Xiong, Yaxuan & Xing, Linlin & Li, Bo & Zhang, Hui & Qian, Di & Liu, Rong. (2015). Analysis of gas expander substituting for natural gas valve in a natural gas pressure regulating station. 10.2991/aeece-15.2015.8

26. B. E. 10208-1:2009, Steel pipes for pipelines for combustible fluids. Technical delivery conditions. Pipes of requirement class A, 2009

27. Oil and gas wells. BOE Report. (2022, October 1). Retrieved February 10, 2023, from https://boereport.com/well-map/