CNG Transportation under the GASVESSEL Project's perspective

Stavros Niotis
American Bureau of Shipping (ABS)
Spring, TX 77389

Abstract

CNG transportation fills a market niche in carrying smaller gas volumes within limited distances, where the use of LNG concepts or pipelines might not be economically or geopolitically feasible. CNG does not require the use of liquefying and re-gasification plants, which drive up the costs for natural gas, while it is also more flexible than point-to-point pipelines, which are associated with environmental and political difficulties during construction.

GASVESSEL is an EU funded project (www.gasvessel.eu) under the HORIZON 2020 program which aims on researching a cost-efficient gas transport solution to exploit stranded, associated and flared gas where this is currently economically challenging.

The key to securing Europe's energy supply is diversifying supply routes. This includes identifying and building new routes that unlock resources and decrease Europe's dependence on particular individual suppliers of natural gas and other energy resources.

The project is based on an innovative, patented technology for manufacturing pressure cylinders made of stainless steel liner and carbon fibres, which can reduce the total structure weight by close to 25% compared to steel gas cylinders for the same CNG storage capacity. Both the pressure cylinder and the CNG ship concepts have received an Approval in Principle by ABS since 2015.

The main objective of the project is to prove the techno-economic feasibility of the concept. Research and development efforts have taken place for the functional design of the pressure cylinder, the prototype facilities and the ship design including loading/offloading systems. A pilot production line has already been built for the cylinders and the first prototypes have already been produced, while a prototype testing plan is already underway and scheduled to be completed within this year. The program includes design of the vessel, and the design of the ship structures, cargo loading/un-loading and propulsion systems has been fully developed and is currently under Class review, while the required risk assessments and consequence special studies have almost been completed.

The scope of this paper is to deliver an insight of this new concept design and its technological innovations and to also provide an update on the project status and the conclusions of the techno-economic feasibility study that is also within the scope of the project.

Background

According to Eurostat, in 2019 almost three quarters of the EU's imports of natural gas came from Russia (41 %), Norway (16 %), Algeria (8 %) and Qatar (5 %). In the same year, the dependency rate in EU was equal to 61 %, which means that more than half of the EU's energy needs were met by net imports, increased by 5% since 2000 when the dependency rate was equal to 56%. The majority of these net energy imports come by a single supplier. A key part of ensuring secure and affordable supplies of energy to Europeans involves diversifying supply routes. This includes identifying and building new routes that decrease the dependence of EU countries on a single supplier of natural gas and other energy resources.

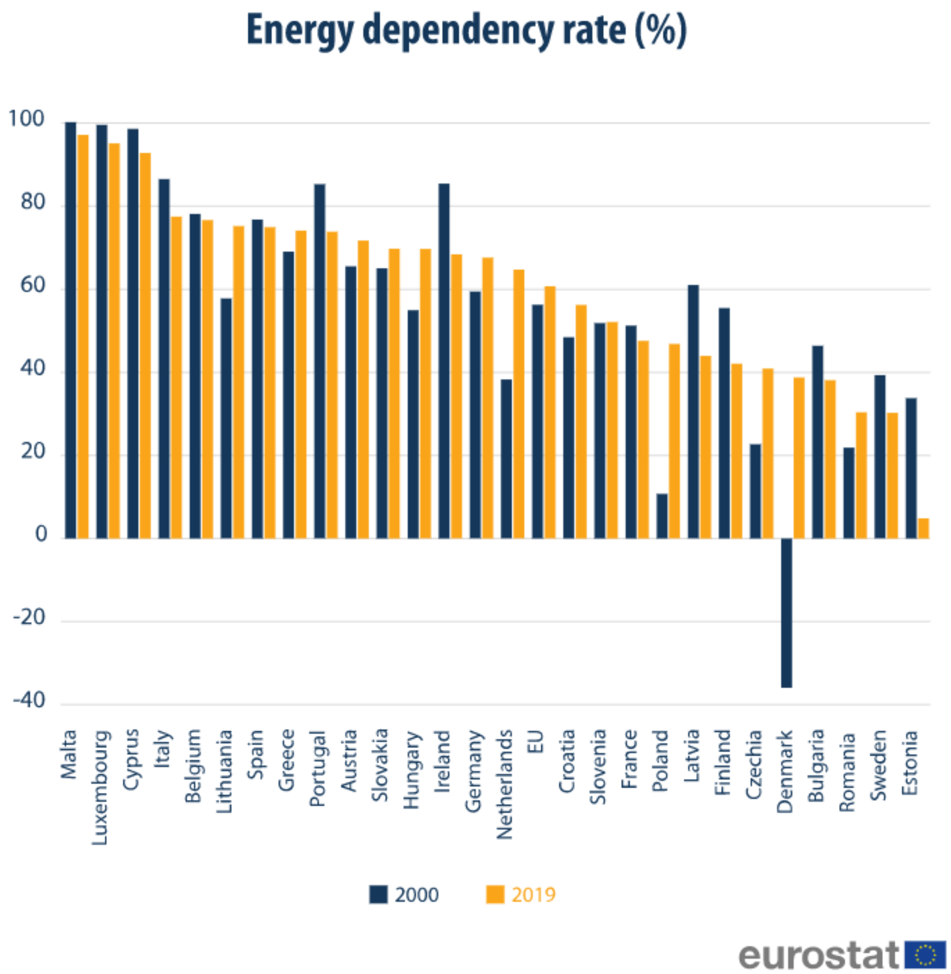

Figure 1. Eurostat Energy dependency statistics 2019

Project Introduction and objectives

It is estimated that removing barriers to cost-effective transport of stranded, associated and flared gas from European sources can unlock up to 2.5 times the amount of gas currently used in Europe. GASVESSEL is an EU funded project (www.gasvessel.eu) under the HORIZON 2020 program which aims to open up new possibilities to exploit gas resources where this is currently not economically feasible (the alternatives are too much expensive) as well as to increase the gas transport possibilities of currently exploited gas fields with a new cost effective CNG (Compressed Natural Gas) transport concept. The GASVESSEL project's objective is to develop a novel, financially viable CNG transportation model to collect, transport and unload natural gas (NG) from either onshore or offshore facilities and unload into the distribution network. The outcome of the project may help to rebalance the European and/or other regional energy security equations.

The project focuses on Europe and a market analysis has been performed in 3 Geo-logistic scenarios around the region;

- East Mediterranean offshore fields
- Barents Sea offshore fields
- Black Sea

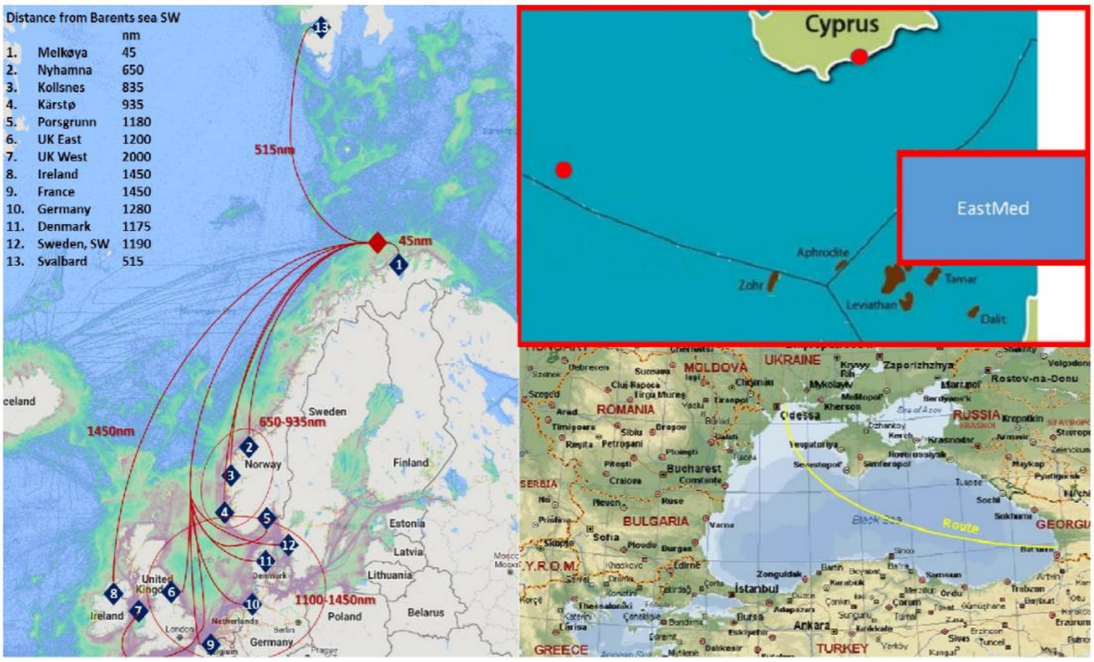

Figure 2. GASVESSEL – Geo-logistic areas assessed under the project for CNG tansportation

The market analysis investigated different case studies regarding the sourcing of the natural gas, the possible transportation options, as well as the potential target markets for each geo-logistic scenario, estimating the costs across the supply and demand value chain by assuming certain technical parts of the CNG technology.

A dedicated software tool (Scenario Decision Support Model) was developed to support optimizing the delivery of gas from the identified source locations to the identified markets using the Gasvessel concept design in different scenarios. The output of the tool is an estimation of the CNG transportation tariff for the identified scenarios, providing essential information like the optimal ship size, the ship speed and the fleet size in order to reach the lowest gas transport costs per unit volume.

Technology innovation and Development

The cargo containment system of this CNG carrier design consists of a specially compressed gas Type 3-cylinder design patented in all main global jurisdictions. The cylinders have a diameter of around 3m and 22m length, installed and fixed vertically within the ship's hull and designed to store CNG at 300bar and 20degC.

The cylinders are made of a very thin stainless-steel liner (6mm thick) wound with carbon fibres and they constitute the key enabling innovation on this CNG carrier concept.

In general, the technology of compressed gas cylinders with non-load sharing metallic liners is well known in industries than shipping, however what makes this design unique is the size of the cylinders and the construction techniques that must be followed during their fabrication. This is to verify that the liner will always have good contact with the various layers of the carbon fibre windings during the cylinder's lifetime and for the intended operation.

The "ultra-thin" liner is fully welded at a predefined form and it reaches its final shape and size after a newly developed hydroforming process, which also constitutes a specialized treatment for the optimization of the steel properties.

The cylinder fabrication includes also state of the art resin and Carbon Fibre (CF) materials and tailored automated filament winding manufacturing techniques, where the strands are wound around a rotating mandrel by a translating guide that can move along one or more axes, providing the capability to wind the carbon fibres at various directions.

At the end of the fabrication process, the wrapped vessels are subjected to the autofrettage treatment, where an internal pressure higher than (generally about 1.5 times) the maximum expected operating pressure (MEOP) is applied to the tank to partially deform the metal liner over its elastic range. The composite overwrap remains in its elastic range and, when the internal pressure is unloaded, tends to its original undeformed shape, inducing on the liner a compressive stress field. When the operating load is applied, the stresses acting on the structure occur to be lower than those obtained on a cylinder without performing the autofrettage treatment.

In continuation of the Scenario Decision Support Model described above for the optimization of the CNG transportation in the predefined operating areas, a dedicated subroutine (loop) was developed to optimize the winding process by minimizing the winding layers for a given winding angle distribution, but respecting the structural constraints, which were to reach maximum admissible stress in the central cylindrical portion of the vessel at burst pressure 900 bar, using an analytical model of the mechanical behavior of the pressure cylinder.

At the current state of the project the hydroforming process equipment for the liner has been fully designed, constructed and tested for the size of the prototype vessels that will be tested. The project team has achieved advanced knowledge of the technological behaviour of the liner base material, which has been tested after the hydroforming process and the properties were satisfactory and in line with the expected values. The welding materials and processes were also tested and validated in the same manner and finally the carbon fibre filament and resins suitable for the pressure cylinders were identified based on material tests and analysis. A pilot production line was built for the fabrication of prototype cylinders of the same diameter but shorter in length compared to the size assessed in the ship concept.

The fully wrapped vessels are currently under the prototype testing process, which includes pressure cyclic tests and burst tests, while the experience and lessons learned during the prototype fabrication and testing process will contribute on the development of proper fabrication procedures and requirements for potential future project applications.

Figure 3. Prototype Gas Cylinders fabrication – Welding, Hydroforming, CF Winding

Ship Design, Risk and Safety Evaluation

The ship design has been well developed to a large extent and in detail following the requirements of the ABS Guide for Vessels intended to carry Compressed Natural Gas (CNG) in Bulk, the associated ABS rules and requirements referenced therein including as well parts of the ship not related to the cargo systems (i.e. engine room and machinery equipment) and with the support of ABS guides and software for the ship structure and stability. The overall ship's length for the design assessed is 205m, with 36m maximum breadth and 7.5m design draft and her capacity is 15m N.cu m (natural cubic meters) corresponding to around 530mil. standard cubic feet (mmscf) of compressed natural gas.

The ship's propulsion is based on a Dual Fuel Diesel Electric (DFDE) system making use of the cargo as fuel, while a novel Air Cavity system is also designed to be installed on the ship for improving her hull performance, for which towing tank model tests were performed under the scope of the project while ABS has reviewed the concept and Approved in Principle (AIP).

One of the main ship design aspects on the CNG carriers is the cargo containment system and the cargo piping and handling systems, which need to be specifically assessed during the loading and unloading operations. The ship is equipped with high pressure compressors, which will be able to raise the gas pressure up to 300 bars during the loading operation. The loading/unloading facilities on the offshore or onshore sites that will need to be developed for the CNG transportation concept have been specifically assessed under a dedicated Work Package of the project and taking into consideration the characteristics of the 3 geo-logistic scenarios described above. The ship's loading/unloading systems arrangements and sizing parameters were optimized taking into account the whole CNG supply chain for these scenarios and in general it was finally concluded that the facilities should be able to deliver the gas to ship manifolds compressed up to a 240bars pressure, while the ship's systems will be able to raise this pressure for completing the loading process to the gas cylinders.

Figure 4. Illustration of GASVESSEL CNG Carrier design

In general, the main safety concern associated with CNG carrier designs is the high pressure at which the natural gas is stored so its systems need to be able to handle much higher pressures as compared to other ship types. In accordance with the ABS CNG carrier guide specific risk assessment and special consequence studies need to be organized, performed and reviewed for these ships. Under the scope of the project a Risk Assessment plan was developed at the early stages of the project's preparation, based on which an overall Hazard Identification (HAZID) workshop performed at the beginning of 2019 and a Hazard and Operability study was performed for both the cargo containment and cargo handling equipment at the beginning of 2021 and after the further development of the design and the various analysis and studies as described above. A Hazard Register was developed at the completion of the HAZID workshop for making sure that proper actions are taken in order to implement the recommendations generated during the workshop and also to control and manage the risk associated with any modifications and changes during the development of the design. The recommendations produced at the HAZID workshop provided a good guidance to the project team for performing the preliminary special consequence studies.

A number of possible failure modes associated with the cargo cylinders and cargo piping and handling systems were analysed using CFD simulations and analytical models (taking in account real gas properties and Joule-Thomson effects). The cargo holds are designed to be continuously inerted and slightly over-pressurized above the atmospheric pressure to avoid any flammable mixtures in the area. Specific calculation models were developed by the project team in order to predict the average pressure, temperature and methane concentration in function of time and of the expected size of spot-weld cracks, to understand in what time the structures of the hold may reach a critical overpressure.

At the same time, localized (thermal and dynamic) effects of the gas jets have been analysed, to verify the integrity of the cylinder's supports. Considering an iso-enthalpic expansion of the gas from the cylinders to the surrounding environment, by evaluating the gas state proprieties from real gas equations (Joule Thomson effect), the temperature of the dispersed gas results to be much lower than the original temperature: with a gas temperature of 40°C and 300 bar of pressure inside the cylinders, the gas will exit in the around 1bar Nitrogen protected hold with a (total) temperature of about -52°C. This value must be considered when designing the cylinders' supports, to prevent structural damage in case of prolonged gas jets.

The same calculation models have been applied in the cargo compressor room to evaluate concentration of methane in function of time and flange's crack size. In addition, the ventilation system of the room has been simulated by CFD, to verify its efficiency to reduce the critical methane concentration inside the room and prevent risks of explosions. Finally a gas dispersion analysis was also performed to evaluate the the critical concentration of methane, for different combinations of ship and wind speed, considering the maximum flow from the vent mass in case of emergency venting.

The HAZOP workshop that was conducted earlier this year focused on the loading/unloading operation, the inerting equipment and process, the cargo fuel supply equipment, the control and monitoring systems and the safety and emergency venting arrangements. The already developed P&ID diagrams of the cargo piping and the other ship main and auxiliary systems were assessed in detail, together with the Gas detection and Emergency Shut down philosophy. During the workshop it was recognized that one of the most critical items that need to be sufficiently monitored and controlled during the normal loading operation are the high temperatures that are expected to be developed within each cargo cylinder itself and consequently to the cargo holds in general. Therefore the project team has developed specific loading and unloading procedure for this respect. In addition, the development of dedicated blow down system and philosophy was also considered important for the project. The HAZOP workshop generated in total 26 recommendations, including further special consequence studies like fire & explosion and jet fire studies, which have already been performed and are currently under further review and assessment.

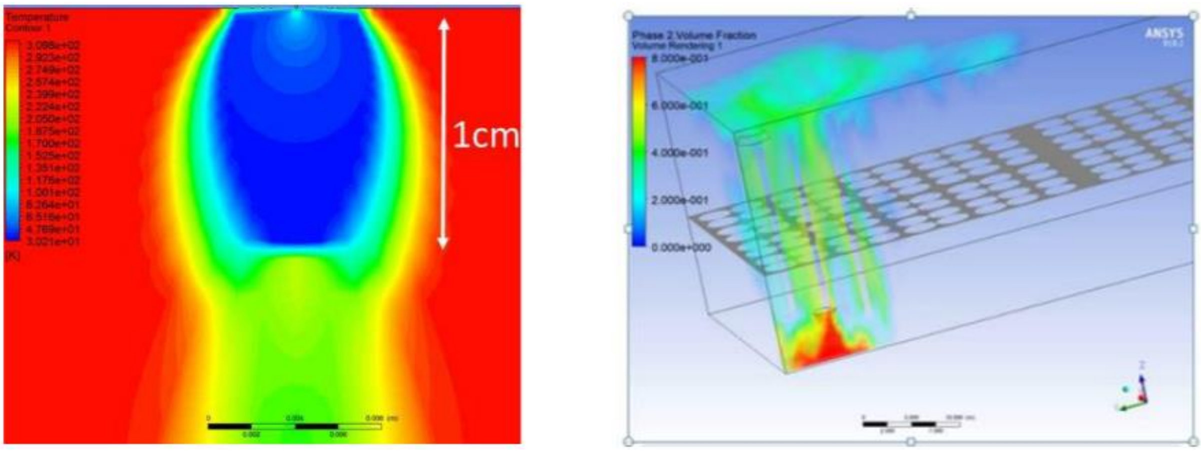

Figure 5. Joule and Thompson effect on gas cylinder leak scenario and CFD gas dispersion in Cargo Hold

Figure 6. CFD gas dispersion analysis - Methane Mass concentration around vent mast

Conclusions

The scope of this paper is to deliver an insight of the GASVESSEL project, a research and innovation project funded by EU H2020 program. The project is close to its completion; A lot of effort has been put by all the 13 main partners and other shareholders that joined this exciting journey over the last 4 years and the results are already noticeable. The project's main objective is to develop a novel, financially viable CNG transportation model. The actions remaining to be completed at this stage are the prototype testing of the gas cylinders which will demonstrate that the technical viability of the innovative design proposed for the CNG carrier concept, the completion of the ABS review on the latest special consequence and safety studies and few remaining ship drawings and calculations and the completion of Cost and Socio-Environmental benefit analysis of this CNG transportation design for the 3 predefined geo-logistic areas, which also aims to make a comparison with the other natural gas transportation alternatives in the region.