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## The HyMethShip Project: Innovative Emission Free Propulsion for Ships

5 - Low Carbon Combustion - What are the Alternative Fuels for the Future

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This paper has been presented and published at the 29th CIMAC World Congress 2019 in Vancouver, Canada. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2019 event included Digitalization & Connectivity for different applications, System Integration, Electrification & Hybridization, Emission Reduction Technologies, Low Carbon Combustion including Global Sulphur Cap 2020, Case Studies from Operators, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Fuels & Lubricants as well as Basic Research & Advanced Engineering. The copyright of this paper is with CIMAC. For further information please visit <https://www.cimac.com>.

## **ABSTRACT**

The HyMethShip project (Hydrogen-Methanol Ship Propulsion Using On-board Pre-combustion Carbon Capture) is a cooperative R&D project funded by the European Union's Horizon 2020 research and innovation programme.

The project aims to drastically reduce emissions while improving the efficiency of waterborne transport. The HyMethShip system will achieve a reduction in CO<sub>2</sub> of more than 97% and practically eliminate SO<sub>x</sub> and PM emissions. NO<sub>x</sub> emissions will fall by over 80%, below the IMO Tier III limit. The energy efficiency of the HyMethShip system is expected to be more than 45% greater than the best available technology (renewable methanol as the fuel coupled with conventional post-combustion carbon capturing).

The HyMethShip system innovatively combines a membrane reactor, a CO<sub>2</sub> capture system, a storage system for CO<sub>2</sub> and methanol as well as a hydrogen-fueled combustion engine into one system. Methanol is reformed to hydrogen, which is then burned in a conventional reciprocating engine that has been upgraded to burn multiple fuel types and specially optimized for hydrogen use. The basic engine type is the same as the one currently used on the majority of ships. This project will develop this system further and integrate it into shipboard installations. The system will be developed, validated, and demonstrated on-shore on an engine in the range of 1 to 2 MW.

The project started in 2018 and will run for 3 years. The work is structured into 11 work packages that deal with the pre-combustion carbon capture system and the internal combustion engine as well as assess safety, economic and environmental factors and system integration. The consortium consists of 13 partners including a globally operating shipping company, a major shipyard, a ship classification society, research institutes and universities and equipment manufacturers.

The publication will present the structure of the work and preliminary results of the project.

## 1 INTRODUCTION

Transoceanic shipping is very important for international trade and has high energy efficiency per ton and kilometer. Much of the transport work occurs close to land and to densely populated areas. Emissions of sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>) and particulates (PM) from shipping have been identified as having a negative impact on health and the environment. Regulations have been introduced, albeit ones that are less demanding and come much later than those for land transport.

In the Sulfur Emission Control Areas (SECA) in the Baltic Sea, the North Sea and North America-Caribbean Sea, the maximum allowed sulfur content in marine fuels is 0.1 % (compared to 0.001 % for road fuel). From 2020 on, the global sulfur cap will be 0.5 % [1]. The sulfur cap also aims to reduce particulate emissions. Nitrogen oxides (NO<sub>x</sub>) from new ship engines are regulated in relation to engine properties in a three-step process and more severe regulations are gradually coming into effect (IMO Tier III). In November 2016, the IMO designated the Baltic Sea and North Sea as areas that will become a NO<sub>x</sub> Emission Control Area (NECA) starting in 2021.

The IMO is responsible for handling international shipping's climate impact and has developed a scheme for energy efficiency of new ships, EEDI (Energy Efficiency Design Index), which has been in effect since 2016. The EU states that the EEDI is insufficient (also shown in an IMO report [2]) and that there is a need for a system that also covers existing ships. Under the EU MRV (Monitoring, Reporting, Verification) rules, ship owners will have to monitor and report CO<sub>2</sub> emissions for each ship entering a European port on a per voyage and an annual basis starting in 2018. An international reporting system has also been adopted by the IMO.

The fossil oil-based fuels used in ships today make a large contribution to the overall environmental impact. However, there are several alternative fuels which could be substituted for them.

- The use of liquefied natural gas (LNG) is growing and LNG has the potential to eliminate nearly all emissions of SO<sub>2</sub> and reduce emissions of NO<sub>x</sub>, and PM. However, LNG has a very limited greenhouse gas (GHG) reduction potential. Estimates in the literature vary from an increase in life cycle GHG emissions to a potential 30 % decrease compared to current oil-based fuels. [3][4][5][6]

- Biofuels such as biodiesel and vegetable oil have been tested in marine applications and have a high GHG-reduction potential. However, issues remain regarding competition with food and feedstock production as well as the limited supply. [7]
- Methanol is another fuel tested for marine propulsion that is also able to reduce local pollutants (SO<sub>2</sub>, NO<sub>x</sub>, PM). Produced from natural gas it will increase the life cycle GHG emissions, but it can also be generated by biomass or from hydrogen and carbon dioxide using electrical energy from wind and solar power. [8]
- Methanol produced from renewable hydrogen and carbon dioxide referred to here as e-methanol might be the key to providing the shipping sector with an alternative fuel that has a high GHG-reduction potential yet does not compete with food and feedstock production.
- Hydrogen (produced by renewable energy) is a zero GHG emission fuel. However, on-board safety and storage remain huge barriers for broader use in marine applications.

The EU "White Paper on Transport" from 2011 sets the goal of a 40 % (and if possible 50 %) reduction in CO<sub>2</sub> emissions from EU maritime transport in 2050 as compared to 2005. [9] IMO adopted a resolution in April 2018 to reduce GHG emissions by at least 50 % by 2050 compared to 2008. [10] Since maritime transport emissions are part of the global emission challenge, the goal of moving goods from land to sea will reduce total emissions but also impose further requirements on shipping. The goal to reduce emissions of pollutants from shipping (SO<sub>x</sub>, NO<sub>x</sub>, particulates, soot/black carbon, hydrocarbons etc.) is partly met by the present regulations, but in order to fulfill the requirements simultaneously, there is a need for changes in fuel and in innovative technology solutions. In the "Alternative Fuels Strategy" of 2013, the European Commission states that "low CO<sub>2</sub> alternatives to oil are also indispensable for a gradual decarbonization of transport". [11] The directive of 2014 on alternative fuels infrastructure also establishes the goal of minimizing dependence on oil and setting up infrastructure for alternative energy carriers [12].

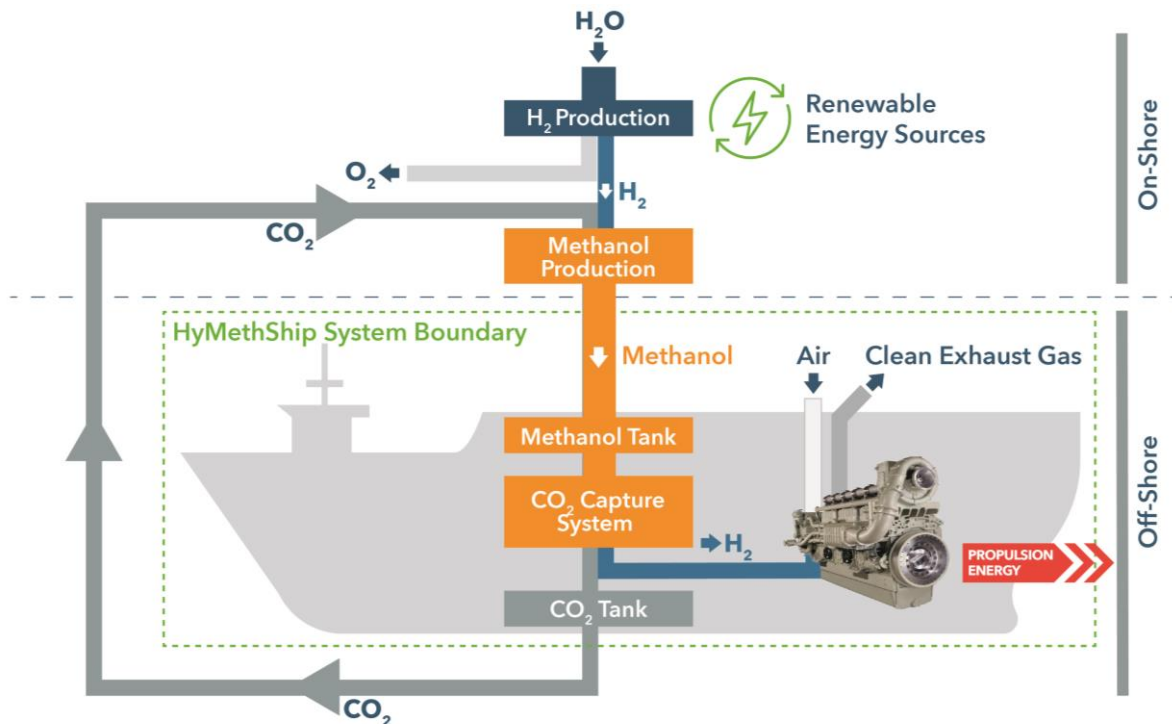


Figure 1. HyMethShip concept

## 2 OBJECTIVES AND TARGETS

The HyMethShip (Hydrogen-Methanol Ship Propulsion System Using On-board Pre-combustion Carbon Capture) project aims to drastically reduce emissions and improve the efficiency of waterborne transport at the same time. This system will be developed, validated, and demonstrated on-shore with an engine in the range of 2 MW.

The HyMethShip system will achieve a reduction in CO<sub>2</sub> of more than 97% and will practically eliminate SO<sub>x</sub> and PM (particulate matter) emissions. NO<sub>x</sub> emissions will be reduced by more than 80% significantly below the IMO Tier III limit. The energy efficiency of the HyMethShip system is expected to be more than 45% better than the best available technology approach (methanol as fuel coupled with conventional post-combustion carbon capturing).

The HyMethShip system innovatively combines a membrane reactor, a CO<sub>2</sub> capture system, a storage system for CO<sub>2</sub> and methanol as well as a hydrogen-fueled combustion engine into one system (Figure 1). The proposed solution reforms methanol to hydrogen, which is then burned in a conventional reciprocating engine that has been upgraded to burn multiple fuel types and specially optimized for hydrogen use.

The HyMethShip system achieves significant reductions in pollutants and therefore eliminates

the need for complex exhaust gas aftertreatment, which is required for conventional fuel systems to achieve equivalent reductions in SO<sub>x</sub>, NO<sub>x</sub> and PM. The drastic CO<sub>2</sub> reduction is a result of using renewable methanol as the energy carrier and implementing pre-combustion CO<sub>2</sub> capture and storage on the ship. The renewable methanol fuel bunkered on the ship is ideally produced on-shore from the captured CO<sub>2</sub>, thus closing the CO<sub>2</sub> loop from the ship propulsion system.

The HyMethShip project will undertake risk and safety assessments to ensure that the system fulfills safety requirements for on-board use and that its safety is at least equivalent to that of conventional ship fuel and propulsion systems. It will also take into account the rules and regulations under development for low flashpoint fuels and is expected to contribute to regulatory development in this area.

The cost effectiveness of the system will also be assessed for different ship types and operational cases. For medium and long-distance waterborne transport, the HyMethShip concept is considered the best approach available that achieves this level of CO<sub>2</sub> reduction and is economically feasible.

Figure 2 compares the GHG emission reduction of HyMethShip to other technologies:

- If LNG is used as a primary fuel, GHG emissions experience a reduction of about 15 % because a certain amount of methane slip must be taken into account
- Concepts using LNG from renewable sources (synthetic natural gas) including conventional carbon capturing systems attain an up to 30 % reduction in GHG emissions
- The best technology available today uses methanol as the primary fuel with conventional post-combustion carbon capturing systems with the end result of an up to 50 % reduction in GHG emissions
- Drastic reduction of GHGs by 97 % is the result of the HyMethShip concept utilizing renewable methanol in combination with pre-combustion carbon capture

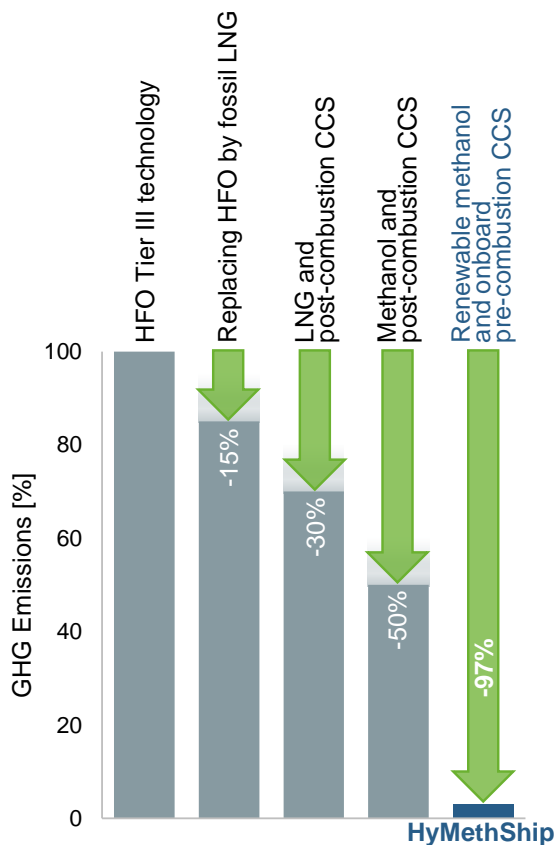


Figure 2. HyMethShip GHG emission reductions

HyMethShip is able to reach an overall efficiency of 51 %. Figure 3 explains how the overall efficiency is determined in more detail:

- Methanol bunkered on board of the vessel is reformed to hydrogen using waste heat from the engine.
- During the reforming process additional hydrogen is created resulting in a surplus energy of more than 12 percentage points. This energy is provided by the thermal dissociation of water at high process temperatures inside the membrane reformer.
- The combustion engine operating with an efficiency of 47 % generates losses in the range of 60 percentage points related to the total amount of hydrogen energy. About 75 % of the engine's waste heat is used to provide the process temperatures required by the carbon capturing system.
- Two percentage points of the generated mechanical energy are used to produce electricity for the pumps and auxiliary devices in the CCS system.

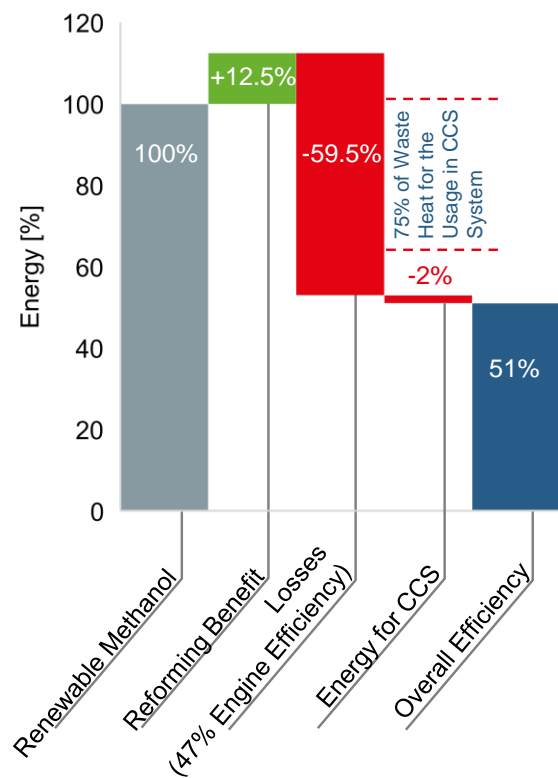


Figure 3. HyMethShip efficiency

During the HyMethShip project, this completely new solution will be developed, realized and validated onshore by a demonstrator with a power output of up to 2 MW thereby proving the operational feasibility of the concept. The project duration of 36 months is not long enough to allow



its full integration into a vessel; however, all relevant marine requirements will be considered in the phase in which the system components are designed. The demonstrated propulsion system will be able to be installed on-board a vessel without major changes.

Over the course of the project, the HyMethShip concept will be assessed according to economic and environmental criteria to prove its suitability for the marine applications of the near future.

### 3 PROJECT ORGANIZATION

The HyMethShip consortium consists of 13 organizations from six EU member states (Figure 4). The partners within the consortium together represent the two dominant parts of the shipping sector value chain, i.e. ship building and operation, they are covering engineering and manufacturing with respect to all technologies that are involved in the HyMethShip propulsion system and they are providing maritime consultancy, especially classification and compliance.

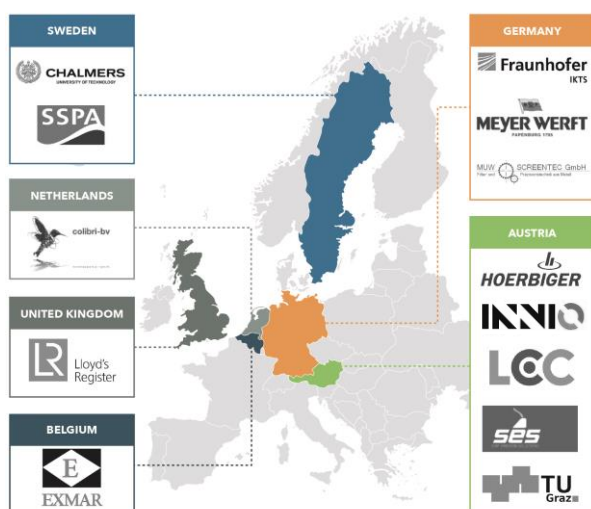


Figure 4. Countries covered by the consortium partners

Additionally, two universities are dealing with sustainability issues and special aspects of mechanical engineering. Each partner has a distinctive role in the project and has the competencies to guarantee the successful outcome of the proposed project.

### 4 STRUCTURE OF WORK

HyMethShip project activities are structured in eleven work packages (WP) each of them divided into specific tasks, covering research and technological development, project management, dissemination and exploitation activities. The

HyMethShip work package structure is shown in Figure 5.

Project management activities are addressed in WP1. This WP will include all management aspects, both internal and external.

The project aims to develop three technology components within the three work packages WP2, WP3 and WP4: CO<sub>2</sub> capture, methanol membrane reforming and H<sub>2</sub> combustion. These work packages are directed by technology specialists with the participation of practitioners. WP5 will develop the design of the CO<sub>2</sub> storage on board. WP9 – Ship Design defines the frame conditions and adaptations required for using the system in a ship environment and will describe design solutions for different ship types, e.g. cargo and/or passenger. Two case studies will develop representative designs for the two ship types.

WP6, 7 and 8 assess safety, environmental and economic aspects of the concept. The safety/economy/environment specialists will be integrated into the technical WP's to ensure that all aspects of technology development are considered.

WP10 – System Demonstration comes up with a full-scale on-shore propulsion system.

Activities for dissemination and exploitation of the knowledge and results generated in the project are covered by WP11. This WP presents the solution to target audiences and the general public. It also prepares the way for marketing the high impact ship propulsion system with nearly zero emissions.

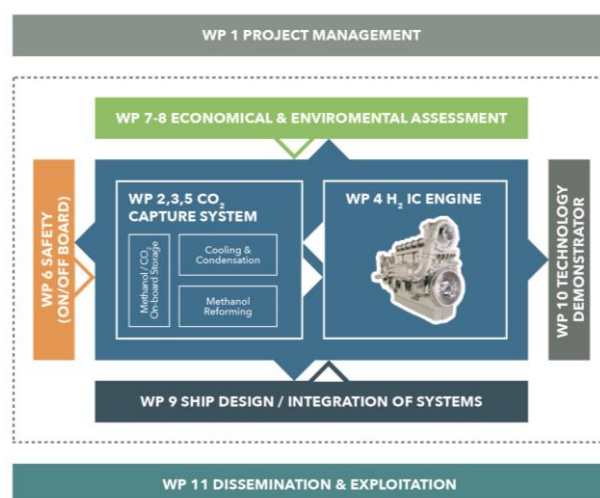


Figure 5. HyMethShip project structure and interrelation of work packages

## 5 DESCRIPTION OF WORK

### 5.1 WP2: Carbon Capture System

The on-board pre-combustion carbon capture system (CCS) is the core of the HyMethShip propulsion system (Figure 6).

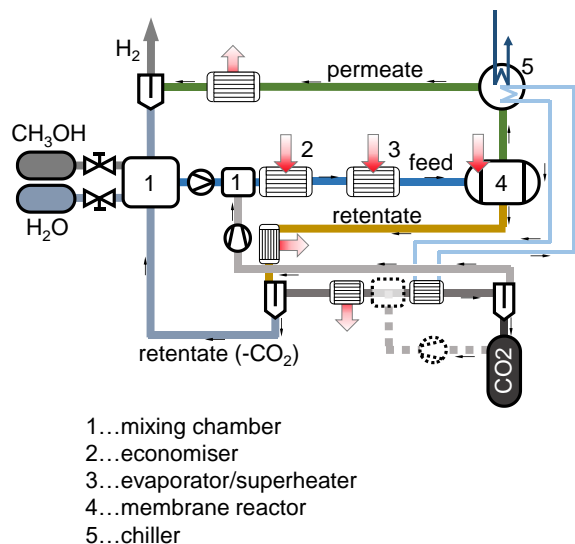


Figure 6. Preliminary schematic of HyMethShip CCS

The carbon capture process involves receiving liquid methanol from the on-board tank system and feeding cold, liquid CO<sub>2</sub> back into the tank system. Gaseous high-pressure hydrogen is released, supplying the internal combustion engine with fuel. Waste heat from the internal combustion engine is then fed back into the system. The CCS comprises the following components:

- **Water storage system:** Water is fed into the mixing chamber for the reaction stream. In the event of a water surplus, water is fed back to the mixing chamber. A surplus may arise when water from the reaction stream permeates through the membrane of the membrane reformer into the permeate stream.
- **Feed-in, evaporation and superheating system for the reaction stream of the membrane reformer:** due to the feedback streams described below (condensate into the reaction stream and residual gas into the reaction stream), the reaction stream of the membrane reformer contains varying proportions of methanol, water, CO<sub>2</sub> and hydrogen depending on the specific separation process that took place in the membrane reformer. Since this process strongly depends on the partial pressures and

thus the chemical composition of the reaction stream, the functioning of the membrane reformer and the chemical consistency of the reaction stream, which is controlled by the feed-in system, may greatly interfere with each another. Furthermore, the latter significantly influences the evaporation qualities of the reaction stream.

- **Cooling and separation system for the permeate stream of the membrane reformer:** The permeate stream mainly consists of hydrogen and varying proportions of water.
- **Several heat recovery and condensation systems for the retentate stream of the membrane reformer:** To recover CO<sub>2</sub> from the retentate stream of the membrane reformer, a stream of water that contains methanol is first condensed out and fed back into the reaction stream of the reformer. The residual gas is then cooled down to approximately -45 to -55 °C so that the CO<sub>2</sub> it contains partially condenses. The residual gas is also fed back into the reaction stream of the membrane reformer.
- **Heat transfer systems:** These systems transfer waste heat from the combustion engine into the evaporation and superheating systems and supply the absorption chiller as well.
- **Cold transfer system:** This system supplies the condensation system of the retentate stream with cold from the absorption chiller.

The two key technical challenges of this carbon capture system are to achieve the required heat transfer into the membrane reformer to control the chemical and physical parameters of these streams (the chemical composition and partial pressures in particular).

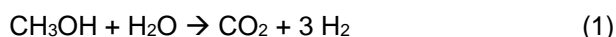
### 5.2 WP3: Methanol Reforming

The membrane reformer directly connects two process steps into one: catalytic methanol reforming and a separation process via membrane permeation take place in the same reactor under reaction conditions. As methanol to which water vapor has been added is converted into hydrogen and CO<sub>2</sub> with an appropriate heterogeneous methanol reforming catalyst, the hydrogen is removed in-situ from the reformation process by using a hydrogen-selective carbon membrane that does not react to the harsh hydrothermal conditions, gases and pressures. The hydrogen-rich gas supplies the internal combustion engine under elevated pressure while the CCS captures

the CO<sub>2</sub> that is produced, storing it on-board for later reconversion to methanol onshore.

The use of waste heat from the combustion engine enables efficient evaporation and heating of the reaction partners methanol and water, thereby allowing the heat to be integrated into the reformation process and the reactor temperature to be managed via heat transfer. With this concept, engine waste heat is converted to useable chemical energy.

Following this procedure three moles of hydrogen are generated from one mole of methanol during the heat-driven reforming process compared to two moles of “internal” hydrogen in the compound methanol following the sum formula CH<sub>3</sub>OH (CH<sub>4</sub>O), yielding a higher energy gain from methanol than direct burning (Eq. 1 and 2).



$$\Delta H_r = 49.2 \text{ kJ/mol} \quad (2)$$

Although membrane technology for methanol steam reforming has already been accepted to a certain extent, the process concepts suffer from the weaknesses that arise from using palladium or palladium-based membranes. In addition to the high price of precious metals, these membranes – like all precious metals – bring about a high risk of poisoning, e.g. from CO or traces of sulfur, and exhibit low thermal and mechanical stability compared to the ceramic-based carbon membranes envisioned in this project. With the common setups that use palladium membranes, only reaction pressures up to 2 MPa are possible.

The solution presented here is free of precious metals and allows higher reaction pressures up to 5 MPa because the ceramic membrane carrier leads to higher throughput, is smaller to install, and provides a higher hydrogen pressure in the range of at least 1-2 MPa to supply the gas engine, thus going far beyond state-of-the-art membrane technology.

In a first step the reformer concept design will be developed based on the targeted process conditions and the required hydrogen mass flow rates determined by the power demand and the efficiency of the IC engine. In order to avoid usage of an additional hydrogen fuel compressor the pressure of the hydrogen-rich permeate has to be maintained in the range of 1 – 2 MPa. The partial pressure difference across the membrane is the driving force for hydrogen permeation leading to a reaction stream pressure demand in the range of 4 – 5 MPa. At this stage the design layout for the implementation of the engine waste heat also

needs to be established. While heating either the reaction stream or the permeate stream before entering the reformer is feasible, initial assessment of mixture stoichiometry, reaction enthalpy and minimum temperature requirements at the reformer outlet favours a concept design with a heat exchanger integrated in the reformer. Engine exhaust gas or an additional heat transfer medium can be used to supply the required thermal energy to the reformer.

The key feature of the ceramic-based carbon membrane is its ability to separate hydrogen and carbon dioxide. The selectivity of the membranes will be evaluated by permeation measurements and tuned by adaptations to the membrane synthesis in order to achieve a hydrogen purity of at least 90 %. Based on the membrane selectivity and catalyst measurements the performance of the system will be evaluated and the required membrane quantity and catalyst mass for at least 90 % methanol conversion will be determined.

The initial reformer tests will be performed on a small-scale unit consisting of membrane-catalyst cartridges (Figure 7). The ceramic carriers will have outer membrane coating and will work without additional steam purging on the permeate side of the membrane. The experiments will be used to identify the ideal process window and thermal management. Based on the results of the small-scale reformer evaluation the reformer process design will be finalized, the quantity of membranes and catalyst mass determined and the large-scale reformer bodies will be designed and built.

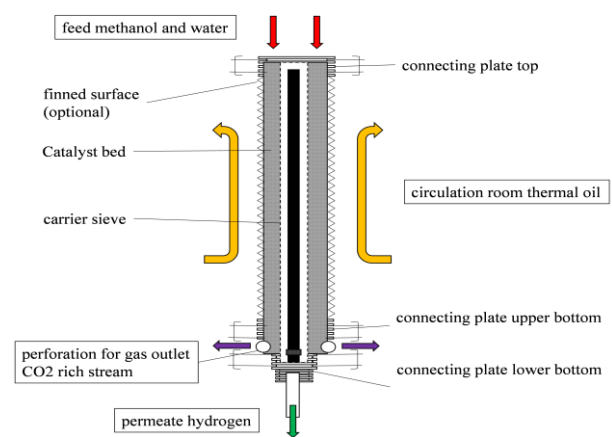


Figure 7. Schematic membrane reformer element

Membrane sealing and easy membrane installation need to receive special attention during the design process. Furthermore, the reformer body also needs to feature flow guiding features to ensure homogenous flow distribution in the reformer. In parallel the membrane



manufacturing process design will be developed to allow in-house pilot production of technical scale quantities at FHG. The complete membrane reformer will be commissioned and implemented in the overall system at LEC as a vital part of the technology demonstration.

### 5.3 WP4: H<sub>2</sub> IC engine

The propulsion system of the HyMethShip concept employs a reciprocating internal combustion engine that is already state-of-the-art for marine applications that use HFO/MDO/diesel or methanol fuel. A conventional diesel or gas engine will be upgraded for HyMethShip to operate on hydrogen, methanol and / or diesel fuel (MDO). The main energy source for the engine will be hydrogen generated by the methanol reformer but the system will be designed to allow operation with a conventional fuel for redundancy in case of emergencies or start-up / warm-up of the reformer and CCS.

Two hydrogen supply systems for the engine are being considered. One concept aims to exploit the hydrogen pressure level of 1 to 2 MPa that the methanol reformer will be able to provide and directly inject the hydrogen into the combustion chamber early in the compression stroke. Hydrogen direct injection can increase volumetric efficiency and reduces the risk of backfiring into the intake manifold that can occur in engines with central mixture formation or port-fuel injection that run on hydrogen-rich gases. Nevertheless, the wide air-fuel ratio range in which a hydrogen combustion can be sustained also increases the risk of early ignition of the hydrogen-air mixture at hot spots in the combustion chamber. The injector technology for this concept has to be developed based on the latest generation of natural gas solenoid injector technology, taking into account the specific requirements for HyMethShip engine operation, e.g. fuel properties, fuel pressure, combustion chamber pressure. Adjustments of the solenoid system, the mechanical design, as well as special coatings are required. The other concept for the hydrogen supply uses cylinder-individual port fuel injection that can potentially improve mixture formation and provide additional flexibility for the system optimization of methanol reformer and combustion engine. The injection technology will have to be adapted from existing port fuel injection technology for natural gas injection.

Currently existing Dual-Fuel engines for marine propulsion use diesel combustion for redundancy. HyMethShip can employ a similar concept with diesel back-up operation. Ignition of the homogeneous hydrogen-air mixture is obtained by injecting a small amount of marine diesel fuel late

in the compression stroke. The diesel fuel penetrates the combustion chamber and the homogeneous mixture is entrained into the diesel jet. Due to the high temperatures in the combustion chamber from the compression of the hydrogen-air mixture, the diesel fuel ignites and subsequently ignites the homogeneous mixture. Afterwards a flame front propagates from the ignition location through the homogeneous hydrogen-air mixture. State-of-the-art Dual-Fuel injection systems use two diesel injectors for "gas operation" and "diesel operation", respectively. In order to allow sufficient space in the cylinder head to install the medium pressure hydrogen injector a solution with one diesel injector with high turn-down-ratio is preferred for the HyMethShip concept. The diesel injector has to enable precise injection of diesel quantities ranging from 1 % to 100 % of the total fuel energy.

The HyMethShip concept will also allow a different kind of Dual-Fuel engine where methanol combustion is used for redundancy. In that case a spark ignition system will be used for hydrogen as well as for methanol combustion. The advantages of a concept using methanol combustion for redundancy instead of diesel combustion lie in reduced emissions of NO<sub>x</sub>, SO<sub>x</sub> and particulate matter and potentially reduced tank space requirements since no bunkering of diesel is required. The drawbacks could be reduced transient capabilities and the fact that methanol combustion is not considered an established technology in maritime applications yet and ship operators might be hesitant to accept this new technology. Vessel power requirements, operational patterns and available space will determine which back-up fuel will finally be selected.

In addition to the propulsion and / or power generation the engine will also provide heat for the hydrogen production. Engine waste heat, e.g. from exhaust gas or cooling water, will be used for the methanol steam reforming process and the absorption chiller which adds further demands to the combustion system development. Mixture stoichiometry, compression ratio and combustion phasing will have to be adjusted in order to provide adequate exhaust enthalpy to the CCS while at the same time protecting the turbocharging equipment, exhaust valves and the exhaust system from excessive heating.

The definition of the combustion system will start with 0D-combustion and 1D-performance simulations taking previous experience with hydrogen combustion in large engines into account. The best engine configuration including valve timing, compression ratio and combustion

chamber geometry will be determined that can fulfill the vessel power, efficiency and emissions requirements.

The combustion concept in conjunction with the newly developed hydrogen injection technology will be tested in a single cylinder engine (SCE) environment. Parameters like fuel injection timing, compression ratio and valve timings will be investigated to reach an optimized operation with hydrogen and the selected backup fuel. The highly efficient hydrogen combustion will result in significantly lower emissions compared to state-of-the-art diesel engines as well as no hydrocarbon-slip (GHG) when compared to LNG engines. Only NO<sub>x</sub> has to be considered as a relevant pollutant. However, NO<sub>x</sub> emissions will be minimized by engine internal measures, e.g. lean mixture combustion.

The last step of the combustion system development will be the transfer of the technology from a single cylinder to a multi-cylinder engine (MCE), which will include the validated combustion concept and also multi-cylinder relevant components, like turbo-charger, fuel admission and mixture formation. Further, the engine control system will be upgraded to be able to handle multiple fuels and hydrogen. The MCE will be a main component of the technology demonstrator (WP10).

#### 5.4 WP5: Methanol / CO<sub>2</sub> on-board storage

Methanol can be stored on-board in tanks similar to the current bunker/ heavy fuel oil (HFO)/diesel tanks. Since the flash point of methanol is below 60 °C, however, compliance with the IGF code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels) is mandatory. Furthermore, the different corrosion behavior of methanol has to be taken into consideration. Other aspects of system design include:

- Required blanket of inert gas in bunker tanks
- Segregation of tanks from other spaces
- Ventilation arrangements in the pump room
- Double walled fuel lines
- Prevention of galvanic corrosion (cathodic protection)

CO<sub>2</sub> can be stored in a liquid state (at approximately -40 °C and 1 MPa), which is common practice for ships that carry CO<sub>2</sub> as cargo.

For the HyMethShip project a combined methanol/CO<sub>2</sub> on-board storage system concept will be designed and a feasibility study of selected solution will be performed. The storage system will consist of tanks and equipment for handling (pumps, valves, piping, etc.), monitoring (sensors, alarms, etc.) and safety. As a part of the study possible interaction/reaction of CO<sub>2</sub> with methanol on the entire operating range (-55 °C to 30 °C and 0.1 to 1 MPa) will also be investigated. The concept design evaluation will define optimal storage conditions and will take all critical operational procedures into account:

- Bunkering methanol while CO<sub>2</sub> discharging
- Transferring methanol (fuel pumping to the reformer)
- Transferring CO<sub>2</sub> (CO<sub>2</sub> cooling, liquefying)
- CO<sub>2</sub> filling (gassing in, cooling down of tank, filling)
- Preventing of galvanic corrosion

In order to enhance the economic feasibility and to reduce space requirements, the case studies will consider using the same storage tanks for methanol as for liquid CO<sub>2</sub>. The bivalent solution will adopt a modular approach that uses components currently available on the market, thereby enhancing the economic feasibility of implementing the system. The combined storage system will be compared with a separate tank solution.

The on-shore technology demonstration will include the functionality of liquefying and temporary storage of captured CO<sub>2</sub>.

#### 5.5 WP6: Safety on-board / off-board

Novel and complex technologies inevitably create new hazards and increased risks that must not compromise safety. In the HyMethShip project a robust hazard identification, risk assessment and management process will be established to ensure an inherently safer design is achieved and the risk mitigation measures are reliable and effective.

A vast number of standards and regulations are available, by both national and international bodies such as American Society of Mechanical Engineers (ASME), the Compressed Gas Association (CGA), and International Organization for Standardization (ISO). Alternative energy carriers, such as hydrogen, however, are relatively new to the marine industry and as such specific

maritime regulations do not exist presently or are undergoing deliberations at the IMO, as in the case of methanol. Publications such as “The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk” (IGC code) which applies to the transport of gases by ship and also contains requirements for CO<sub>2</sub> when carried in bulk can provide guidance. Furthermore, requirements for the carriage of liquid hydrogen in bulk have been discussed at IMO CCC sub-committee in 2016 which has led to the production of an Interim Resolution document. In addition, guidance can be provided by the “International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels” (IGF Code) which is under review with consideration to methanol fuel. Also, a review of non-maritime specific design, manufacturing and testing standards applicable to the HyMethShip technologies will be carried out.

Following a “Hazard Identification” (HAZID) process in line with ISO 31000:2009 and ISO 31010:2010, hazards associated with the design and operation of the proposed HyMethShip technologies will be identified and the associated risks qualitatively assessed. The risk assessment criteria used will reflect ‘good practice’ in major industries and be recognized by governments and other established health and safety organizations.

A preliminary HAZID review was carried out based on the initial concept design of the HyMethShip system in order to identify potential hazards early in the design phase. The system was broken down into nodes and each main component was assessed considering mechanical damage, potential leaks, cross contamination of streams and general hazards during both normal operation and as a result of unplanned events. Opportunities for the reduction of these risks were suggested, focusing on elimination of the risk through an inherently safer design. A final HAZID review and report will be compiled based on the final HyMethShip design.

Furthermore, a hazard and operability study (HAZOP) will be completed for the proposed technologies systems in accordance with IEC 61882:2001. It will identify hazards associated with the integration and operability of the proposed systems with the ship’s existing systems.

A gap analysis on existing maritime standards and regulations against HyMethShip design will be performed within the project to identify further work in way of regulations, in particular, with regards to the use of methanol, hydrogen, and CO<sub>2</sub>. A summarized library of standards will be

created for the project and training requirements for seafarers specific to converting methanol to hydrogen on-board, CO<sub>2</sub> capture and transfer and handling of hydrogen.

## **5.6 WP7 & 8: Economic & environmental assessment**

Life cycle costing (LCC) and life cycle assessment (LCA) are well-established methods for assessing economic and environmental performance, respectively. Traditional LCA addresses only the environmental impacts of a service or production system, and does not include economic and social impacts. For HyMethShip the LCA will be complemented with a life cycle cost assessment which is in line with recent trends in LCA towards more comprehensive life cycle sustainability assessments that also include economic and social aspects. Both LCA and LCC will assess performance of the HyMethShip concept with specific focus on the case study vessel and the comparison with conventional fuel systems. While the framework for both assessments are the same the data collected will differ.

Depending on the life cycle definition data collection of all costs, emissions, energy and raw material use that occur in the life cycle of vessels using the HyMethShip concept can include:

- Ship construction and manufacturing: capital costs (including equipment, piping, safety systems) and all associated costs, emissions, energy and raw material use
- Ship operation (excluding fuel use): operating costs, spares, and maintenance, emissions, energy and raw material use
- Fuel distribution and production: fuel cost, emissions, energy and raw material use
- Ship end-of-life: end-of-life costs, such as decommissioning or disposal, emissions, energy and raw material use

The goal and scope definitions for LCC/LCA describe the system being studied and the purpose of the assessment. The goal should include, for example, the intended application and reasons for the assessment, as well as geographical boundaries and time horizon. The emissions and environmental impact categories that are of most interest in the assessment can be defined. The preliminary scope for HyMethShip as defined by the project shareholders will focus on the fuel life cycle. Relevant alternative technologies for comparison, system boundaries

and functional unit for comparison were also specified.

### 5.6.1 Economic assessment

The goals of the LCC are to verify the economic performance of the HyMethShip concept for the case study vessel, to provide input during the development and design phase in order to minimize total life cycle cost and to give suggestions which vessel categories and types of operational pattern are favorable with regard to cost performance. LCC can account for all the costs of the product or service during its lifetime.

The capital costs (including equipment, piping, safety systems, etc.) and all associated cost (delivery, installation, insurance, etc.) will be estimated by the project partners or collected from stakeholders outside the consortium.

The largest part of the operating cost is the fuel cost and different potential production routes for e-methanol as well as time frames for the fuel cost will be assessed. Other operating costs include, for example, spare parts, maintenance, and training of the marine officers. The fuel consumption for the case study vessels will be estimated for the HyMethShip concept and reference state of the art propulsion systems based on the operational profiles and the selected case study vessel.

All the data collected will be used to build a life cycle model for the cost performance for the HyMethShip concept. All cost occurring during the life cycle of the study case will be compared using net present value (NPV). The model will be used for sensitivity and scenario analyses in order to identify how the life cycle cost can be minimized. Different fuel production sites will be compared due to the importance of the electricity price for the overall fuel production cost of e-methanol. Important parameters to vary when assessing the fuel cost are also the capital cost of electrolyzer, type of electrolyzer, cost for fuel synthesis, the interest rate, etc.

### 5.6.2 Environmental assessment

An LCA addresses the potential environmental impact of a product or service from a cradle-to-grave perspective. This holistic perspective is a unique feature of LCA that is designed to avoid problem-shifting from one environmental problem to another, from one phase in the life cycle to another and from one region to another. The goals of the LCA in this project are to verify the environmental performance of the HyMethShip concept for the case study vessel, to provide input during the development and design phase in order

to further reduce the life cycle environmental impact and to give suggestions which vessel categories and types of operational pattern are most favorable environmental performance.

The life cycle assessment will be performed in accordance with ISO4040/44 standards. Although all life cycle phases will be considered, LCA will deal in detail with the operation phase. System efficiency and emissions will be assessed using inputs from the technology development work, the ship case study design and assessments of other ship types, and results from the prototype testing. Previous LCAs of marine fuels have shown the importance of studying the full life cycle when evaluating the environmental performance of fuels. Several possible production routes for e-methanol will be assessed in order to choose the most cost-effective one. The emissions and discharges from the fuel distribution and production will be estimated based on data from fuel producers and distributors as well as from the open and scientific literature. All the data collected will be used to build a life cycle model for the environmental performance for the HyMethShip concept.

The elemental flows quantified are classified during the impact assessment into various impact categories. Emissions of greenhouse gases, for example, are aggregated into an indicator of global warming. The model will be used for sensitivity and scenario analyses in order to identify how the environmental impact of HyMethShip can be minimized.

## 5.7 WP9: Ship design / integration of systems

The HyMethShip project will develop a detailed design for a case study ship that uses the HyMethShip system, providing a practical example of how the system can be integrated into and operated on a ship. For other ship types, an overview analysis of ship design implications and the feasibility of the HyMethShip system will be carried out. The results of the technology studies and the detailed ship design case study will provide the basis for developing designs for other ship types. A detailed analysis of automatic identification system (AIS) data will be conducted for European emission control areas to identify the most promising vessel types and markets for early application of the HyMethShip system.

The HyMethShip system is expected to be applicable to different vessel types as it is based on a conventional reciprocating engine currently in use on the majority of ships; the additional main equipment of a reformer and CO<sub>2</sub> storage will most likely be placed in areas under deck and



should not impact cargo and passenger capacity to a great extent, as it is assumed that this equipment would take the place of any fuel pre-treatment and emissions treatment (neither of which would be required if the HyMethShip system is used). Thus, it is expected to be applicable to many ship types such as passenger vessels and ferries, RoRo cargo vessels, container vessels, tankers, bunkers, car carriers, and larger offshore support vessels.

Specific vessels most likely to be the first adopters of such a system are those operating within emission control areas, including inland waterways, which have stricter emissions standards, and within those segments where higher reductions in emissions and good environmental performance are important. Countries may also set stricter targets for vessels such as road ferries which are part of the national transport system. For example, the Norwegian government has a national transport plan in place (Norwegian National Transport Plan 2018-2029) that states that the government should ensure that new ferries connected to the national public road system use zero or low emission technology. The plan also sets a target that 40 % of ships operating on local routes use low or zero-emission vessels by 2030. Sweden is another example: the Swedish Road Ferries has commissioned a study on the feasibility of reducing CO<sub>2</sub> emissions from their ferries by 15 % in 2020 and 30 % in 2030, compared to the emissions level in 2011. Ships operating in areas with stricter emission regulations will initially benefit the most from the HyMethShip system as they will be required to invest in an emission reduction solution.

As the HyMethShip system requires reception facilities for CO<sub>2</sub> and shore-based supply of methanol (ideally produced from captured CO<sub>2</sub>), those vessels operating on a fixed route (ferries, liner shipping) or out of a "home port" (off shore support vessels, work vessels) are more likely to be the first candidates to adopt the system. In the near term, however, it is expected that many ports will develop their infrastructure to handle captured CO<sub>2</sub> since more CO<sub>2</sub> emitting industries will be required to reduce emissions and the need for carbon capture and storage is growing. To meet the demand for methanol from ships using the HyMethShip system, the CO<sub>2</sub> will be used to produce methanol fuel instead of being transported long distances to storage areas for captured carbon dioxide.

The vessel type and operating routes will determine the requirements for the on-board installation of the HyMethShip system with respect to the fuel supply system, CO<sub>2</sub> storage system,

supply of water to the fuel processing unit, and general control and safety system integration. In addition, the requirements for engine operation regarding different loads such as during cruising, maneuvering, and idling will be defined. The need for redundancy and reliability and transitioning between fuel types will also be specified. In comparison to the land-based technology demonstration (WP 10) there will be some different and unique considerations for a ship-based system, including different regulations, environmental conditions (temperature ranges), and ship motions.

In order to provide the operating conditions for HyMethShip and serve as a baseline for comparison the ship service details including transport work (passengers, cargo), service profile, operational profile (% of time cruising, % of time maneuvering, % of time idling) as well as energy efficiency, cost, and environmental performance for a conventional and state-of-the-art system will be defined.

The detailed ship design for a specific application case adapted for the HyMethShip concept will be developed. This will include specification of system components, tank locations, stability calculations, ventilation, detection systems, firefighting systems, piping and pumping. The operation of the case study ship will be modelled to calculate energy efficiency, emissions, and operational costs resulting from installation of the HyMethShip system. Impacts on operations such as ballast water and passenger and cargo handling, additional tasks such as loading of fuel and unloading of CO<sub>2</sub>, and potential changes to other ship systems will be assessed. The service profile over a one-year period will be considered to include both summer and winter conditions.

Potential opportunities and challenges for application of the HyMethShip system to other ship types will be highlighted. Possibilities for scaling up and down will also be investigated. The feasibility and approximate economics for different vessel types will be analyzed.

## **5.8 WP10: System demonstration**

This work package includes the system design and planning of the demonstrator next to the overall assembly and installation of components and subsystems, developed in detail in WP2 to WP5. System / process simulation and CAD tools are used to design the demonstrator and to support the controls hard- and software development.

A plant level risk assessment is done to define necessary safety devices and safety loops needed



to operate the demonstrator in a safe way. A detailed test plan will lay out test requirements and definition of PASS/FAIL criteria for each of the test.

Before and during the commissioning the standard operating procedures will be created, updated and a detailed test plan will be developed. After the commissioning of the demonstrator (including all sub systems) has been completed first functional tests are performed to check basic system performance and to tune and update control parameters as needed. As a next step, the demonstrator will be used to assess the performance of the overall system according to criteria defined in a test plan and the interactions of the subsystems to each other. A durability run over 150 hours should demonstrate the endurance of such a system.

Finally, the system models will be updated based on the measurement results gained during testing. After the demonstration phase, has been completed inspection of critical parts will be performed to assess wear, potential early failures and address potential design optimization.

## 6 CONCLUSIONS

HyMethShip represents a completely new way of generating propulsion energy that can be entirely based on renewable energy and even provides the opportunity to reduce CO<sub>2</sub> emissions from the atmosphere. HyMethShip is not restricted to any special vessel types nor is it for new ships only. The demonstrator that will be built is able to provide propulsion energy in the power range needed for waterborne transport.

Each ship operated with the HyMethShip propulsion system will reduce its greenhouse gas emissions by 97 % as compared to the conventional technology and will produce practically no polluting emissions (SO<sub>x</sub>, NO<sub>x</sub>, PM).

Since there are many indications that CO<sub>2</sub> emissions from shipping will be regulated more extensive in the near future, it is extremely important to search for innovative solutions.

The HyMethShip consortium is extremely well suited to address this challenge, as it includes a globally operating shipping company, a major shipyard, a ship classification society, research institutes and universities, and equipment manufacturers. Further stakeholders will be represented in the External Expert Advisory Board and will be addressed by dissemination activities respectively.

## 7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CAD	Computer aided design
CCS	Carbon capture system
CH <sub>3</sub> OH	Methanol
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
GHG	Green house gas
H <sub>2</sub>	Hydrogen
H <sub>2</sub> O	Water
HAZID	Hazard identification
HAZOP	Hazard and operability study
HFO	Heavy fuel oil
LCA	Life cycle assessment
LCC	Life cycle costing
LNG	Liquefied natural gas
MCE	Multi-cylinder engine
MDO	Marine diesel oil
NO <sub>x</sub>	Nitrogen oxides
NPV	Net present value
PM	Particulate matter
RoRo	road-to-road
SCE	Single cylinder engine
SO <sub>x</sub>	Sulfur oxides
ΔH <sub>r</sub>	Reaction enthalpy

## 8 ACKNOWLEDGEMENTS

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 768945

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