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NAUTILUS

# D7.3 – Techno-economic analysis

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| **Project Acronym:** | Nautilus |
| **Project Title:** | Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships |
| **Project coordinator:** | Dr. Asif Ansar, Deutsches Zentrum für Luft – und Raumfahrt (DLR) |
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## Deliverable D7.3 – Techno-economic analysis

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| **Short summary:** | In this deliverable, the techno-economic analysis of maritime SOFC systems was performed for five fuels (methane, methanol, diesel, ammonia, and hydrogen). The analysis is divided into two main parts. In the first part, the cost assessment is performed for the 100 $kW_e$ SOFC modules proposed in Deliverable 7.2 "Genset Performance with Future Fuels" of the Nautilus Project. The benefit of implementing cathode-off gas recirculation (COGR), which improves heat regeneration both in terms of quantity and quality, is also verified for the system cost; methanol, hydrogen, and diesel showed the best results, with Levelized Cost of Exergy (*LCOEx*) reductions of about 10%, 9% and 6%. The lowest *LCOEx* were found for ammonia COGR, 0.260 EUR/kWh, and methanol COGR 0.270 EUR/kWh, while hydrogen had the highest *LCOEx* of 0.430 EUR/kWh. Overall, the most promising fuels were ammonia and methanol. In the second part of the analysis, the SOFC systems were approached from the ship's perspective. A mixed-integer linear programming optimization model was formulated to determine the system size and operation that minimizes the total annual cost while covering all the ship's energy requirements (i.e. electricity, hot water and steam). Different hybridisation scenarios included SOFC, battery, gas engines and auxiliary boilers. The results were compared to the state-of-the-art engine-based system. Methanol and diesel showed the best results, with *LCOEx* of about 0.184 EUR/kWh, and simple payback periods of about 11 years. |
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| **WP, leader:** | [WP7, TUD] |
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### Dissemination Level

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| **PU** | Public | ☐ |
| **PP** | Restricted to other programme participants (including the Commission Services) | ☐ |
| **RE** | Restricted to a group specified by the consortium (including the Commission Services) | ☐ |
| **CO** | Confidential, only for members of the consortium (including the Commission Services) | ☒ |

### Document history

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# 1 Introduction

This report contains the techno-economic analysis (TEA) of maritime Solid Oxide Fuel Cell (SOFC) power plants for several fuels (methane, methanol, diesel, ammonia and hydrogen). The TEA performed here is divided into two main parts. First, the TEA is performed for the 100 $kW_e$ SOFC systems that were originally proposed and analysed in the Deliverable 7.2 "Genset Performance with Future Fuels" [1] of the Nautilus project. Then, the analysis is taken to the ship level, where the 100 $kW_e$ SOFC modules are replicated to reach the required ship's energy demands, and combined with other technologies, such as internal combustion engine (ICE), boiler, and battery. An overview of the main objectives of the study is provided as follows:

**PART I: TEA for 100 $kW_e$ SOFC modules**

The goal of PART I is to carry out a detailed assessment of the investment costs of the 100 $kW_e$ SOFC systems for LNG and four alternative fuels developed by TUD in the Deliverable 7.2 "Genset Performance with Future Fuels" [1]. The results obtained in this part will be subsequently used in PART II. A list of the key steps and assumptions is given as follows:

- The analyses are limited to the system configurations that were proposed in the Deliverable 7.2.
- The SOFC cost evaluation accounts for the cost reductions that are expected to take place as the technology matures and the number of units produced annually increases. In this context, the level of maturity of the technology, expressed in terms of the annual production volume (e.g. number of units, $MW_e$), is taken into account.
- The balance of plant (BoP) includes more conventional services. Consequently, BoP components are assumed to be commercially available and the cost estimation is carried out with the six-tenth rule or with cost functions obtained from the scientific literature.
- Once the purchase costs of the SOFC stack and BoP components have been calculated, the system cost can be assessed through several Key Performance Indicators (KPIs), including, but not limited to, the total annual cost, capital expenditures, operational expenditures, and levelized cost of energy.
- Sensitivity analysis is carried out to assess the influence of key parameters on the economic performance of the systems.

**PART II: TEA for ship-integrated energy systems**

The goal of PART II is to take a holistic approach to the ship's energy system. This is achieved by evaluating the role of the SOFC modules, in combination with other technologies, such as battery, boiler, and ICE, in a ship-integrated energy system that must cover the electricity and heating demands of a ship. A list of the key steps and assumptions is given as follows:

- A mixed-integer linear programming (MILP) model is developed using the optimization framework OSMOSE to determine the best configuration and operational strategy of the ship-integrated energy system. The objective function is the total annual cost (TOTEX), which is the sum of the annual investment cost (CAPEX) and the annual operation cost (OPEX).

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- As a preliminary approach to the ship-integrated energy system, it is assumed that the 100 $kW_e$ modules of PART I can be replicated any number of times in order to reach the required installed capacity for the ship. The load regulation is done by turning the modules on and off. In this context, the SOFC modules are incorporated into the MILP model as black boxes, with their corresponding inputs (fuel, air, water) and outputs (electricity, steam, hot water).
- A superstructure of candidate technologies is devised consisting of energy generation technologies (SOFC, boiler, ICE) and energy storage technologies (battery and fuel storage tanks). This gives the possibility of proposing and analyzing several hybridization scenarios.
- The energy demands of the ship are described by typical trips, which are repeated throughout the year. Three boat modes can be identified, namely at berth, at sea and manoeuvre.

PART I begins in Section 2 with a description of the SOFC systems analysed herein. Two different configurations are proposed for each of the five fuels, one including cathode off-gas recirculation (COGR) and the other without it. Thus, a total of ten systems are studied. Section 3 presents the economic model developed to estimate the costs of the SOFC systems. The results for each system are presented and discussed in Section 4, which also includes sensitivity analyses. PART II is developed in Section 5 with an initial discussion about the ship's energy requirements, which is then followed by the superstructure proposal and optimization problem definition. Results and sensitivity analyses are discussed. Finally, Section 6 summarizes the main outcomes and present the conclusions of the work.

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