NAUTILUS

Disclaimer:

This deliverable has been submitted to the European Commission and is currently under review.

The final version after the approval may differ.

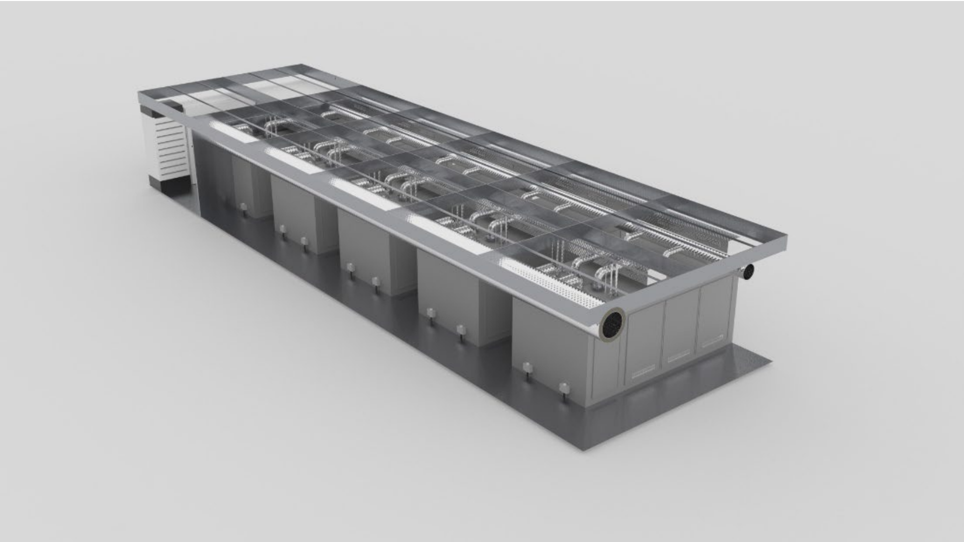
This project has received funding from the European Union's Horizon 2020 research and innovation program under the grant agreement No 861647

Ref. Ares(2024)2289049 - 27/03/2024

NAUTILUS

D3.3: Sizing of genset and scalability to multi-MW

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)
Programme:	Horizon 2020 Framework Programme
Topic:	LC-MG-1-8-2019 Retrofit Solutions and Next Generation Propulsion for Waterborne Transport
Instrument:	Research & Innovation Action (RIA)



This project has received funding from the European Union's Horizon 2020 research and innovation program under the grant agreement No 861647

NAUTILUS

Deliverable D3.3 – Sizing of genset and scalability to multi-MW

Short summary: Commercial SOFC systems are not available on the power scale required for large ships. In this report, the processes of a genset are modelled and optimised, and integrated into a concept that can be scaled to a multi-MW power plant. The developments of this concept were focused on high power density, easy integration, manageable part replacement and maintenance, high fuel conversion efficiency, and air and water flow requirements.

A process flow diagram has been developed for a system with a rated power of 110 kW, which uses anode off-gas recirculation to limit the de-ionised water requirement and COGR to limit the external air requirement. The operational parameters and heat exchanger network have been optimised for high electric efficiency, zero water intake and low external air intake, resulting in a net electric efficiency of 60% at the beginning of life.

A concept design of a 110 kW unit with 6 SOFC stacks is presented along with a 990 kW fuel cell room. Centralising the hot BOP per unit and cold BOP per SOFC room made it possible to achieve significant power density improvements compared with commercial products. It is also discussed how the energy management control strategy of such a unit can be scaled to a MW-scale power plant.

Due date: 31/03/2024
WP, leader: WP3, TUD
Authors: Berend van Veldhuizen (TUD), Lindert van Biert (TUD), Amogh Amladi (RUG), Eduardo Pina (EPFL), Cem Ünlübayir (RWTH)

Dissemination Level

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

Version	Date	Name	Chapters edited	Reason for change
V1.0	24/05/23	Berend van Veldhuizen	All	Draft Version
V2.0	02/03/24	Berend van Veldhuizen	All	Original Version
V3.0	22/03/24	Berend van Veldhuizen	All	Original Version after check by partners

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647

NAUTILUS

List of participants		
Participant No	**Participant organisation name**	**Country**
1 Coordinator	Deutsches Zentrum für Luft –und Raumfahrt (DLR)	DE
2	Chantiers de l'Atlantique (CdA)	FR
3	Carnival Maritime GmbH (CM)	DE
4	Ecole Polytechnique Fédérale de Lausanne (EPFL)	CH
5	GRANT Garant (GG)	CZ
6	Lloyd's Register EMEA (LR)	UK/DE
7	MAN Energy Solutions (MAN)	DE
8	Meyer Werft PAPENBURG (MW)	DE
9	Rijksuniversiteit Groningen (RUG)	NL
10	Rheinisch-Westfälische Technische Hochschule Aachen (RWTH)	DE
11	SolydEra SPA (SE_SPA)*	IT
12	Technische Universiteit Delft (TUD)	NL
13	Lunds Universitet (ULUND)	SE
14	Teknologian tutkimuskeskus VTT (VTT)	FI
15	SolydEra SA (SE_SA)*	CH

* SolydEra SA is fully owned by SolydEra SPA

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647

Definitions

SOFC stack – The assembly of cells, separators, manifolds and a supporting structure that electrochemically converts, typically, hydrogen-rich gas and air-reactants to DC power, heat and other reaction products.

SOFC module – The part that will be replaced during stack replacement.

SOFC unit – A unit that can be placed in a fuel cell room, containing mainly SOFC stacks and hot balance of plant components.

SOFC room – A room in the ship that contains mainly SOFC units.

Fuel cell power system – A group of components which may contain fuel or hazardous vapours, fuel cell(s), fuel reformers, if fitted, and associated piping systems. Definition according to IMO (2022).

Fuel cell space – A space or enclosure containing fuel cell power systems or parts of fuel cell power systems. Fuel cell space boundaries should be gastight towards other enclosed spaces in the ship. Definition according to IMO (2022).

BOP room – Room containing centralised supporting equipment for the operation of the SOFC units.

SOFC power installation – The fuel cell power system and other components and systems required to supply electrical power to the ship. It includes hot and cold BOP components

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647

Abbreviations

AOGR	Anode Off-Gas Recirculation
ASR	Area Specific Resistance
BoL	Beginning of Life
BOP	Balance of Plant
COGR	Cathode Off-Gas Recirculation
CW	Cooling Water
EoL	End of Life
ER	External Reforming
GFU	Global Fuel Utilisation
HE	Heat Exchanger
HEN	Heat Exchanger Network
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion engine
IMO	International Maritime Organisation
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LSM	Large Stack Module
LT-PEMFC	Low Temperature Proton Exchange Membrane Fuel Cell
MILP	Mixed-Integer Linear Programming
MOGA	Multi-Objective Genetic Algorithm
MOO	Multi-Objective Optimisation
P&ID	Piping and Instrumentation Diagram
PFD	Process Flow Diagram
SoC	State of Charge
SOFC	Solid Oxide Fuel Cell
SOH	State of Health

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647

NAUTILUS

1 Introduction

Researchers consider SOFCs as a promising solution for power generation on seagoing ships (Sapra et al., 2021). Compared to marine diesel engines, these devices offer high efficiency, low emissions, and fuel flexibility. However, SOFCs are not widely applied in ships because current systems are characterised by low power density, high investment cost, limited lifetime, and slow response to dynamic loads (van Biert et al., 2016). There are very few studies that consider an SOFC system that takes the largest share of the onboard energy conversion; SOFCs are mostly considered as auxiliary power units for marine applications (Baldi et al. 2020).

Multi-MW SOFC systems could offer significant scale advantages. For large-scale marine power plants, balance of plant components such as the desulphurisers, filtering equipment, blowers, and control architectures could be centralized for a multitude of SOFC modules, which would positively influence the power density and specific cost of the system at a slight reduction in system reliability (van Veldhuizen et al., 2023a). Nevertheless, smart centralisation is necessary because it could also increase the amount of piping. Large-scale production of SOFC systems could also improve the market position of SOFC systems. A detailed cost analysis by Scataglini et al. (2017) reveals that the expected system cost of SOFC combined heat and power generation products may be reduced from 13000 e/ kW for an annual production volume of 100 units of 1kWe to 500 e/kW for 50,000 units of 250 kWe. In short, there is a need to scale small kW systems to the MW scale for marine applications to improve the power density and specific cost of SOFC systems. The scaling effects from current commercial systems to MW scale power plants are not yet quantified for ships.

The goal of this research is to identify the scale advantages of high-power SOFC systems. We do this by the conceptualization of a scalable high-power SOFC unit and comparing it with current commercial systems. The design constraints of a marine SOFC unit are defined in consultation with shipbuilders and marine regulators. The positive effect of cathode off-gas recirculation is also included, since this was positively evaluated in previous work as a means to decrease the needed airflow to the system. This research does not include other developments in SOFC technology that improve power density, such as metal-supported cells, novel cell materials or novel stack manufacturing techniques. The focus is on the benefits of scaling to a higher-power SOFC system.

Chapter 2 describes the scaling potential and its constraints from the fuel cell development and ship integration perspective and a suitable module size of 110kW is defined. This system is modelled and optimised in Chapter 3, which is needed to establish the operating conditions of the system at the beginning of life as well as the end of life. Chapter 4 describes and illustrates a concept design of a 110 kW cabinet and shows a possible way of integrating several units in the technical spaces of ships. Chapter 5 shows how the control algorithm can be adapted to a multi-MW powerplant. Energy management methods are proposed to control the dynamic behaviour of different units and batteries and it is simulated how battery-aging could be included for power allocation between components. Chapter 6 discusses the performance of the SOFC unit and compares it with existing technologies. Finally, a conclusion is presented in Chapter 7.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 861647