TECHNO-ECONOMIC ASSESSMENT OF AN ADVANCED INTEGRATION BETWEEN SOFC AND ICE ONBOARD A SHORT-DISTANCE FERRY

Ahmed G. Elkafas*[1], Massimo Rivarolo[1], Stefano Barberis[1], and Aristide F. Massardo[1]

[1]Thermochemical Power Group, University of Genoa, via Montallegro 1, 16145 Genoa, Italy

*Corresponding Author: ahmed.elkafas@edu.unige.it

ABSTRACT

Although maritime transportation is an efficient form of transport between countries inside and outside the European Union (EU), it contributes to the EU's total carbon dioxide emissions by about 4%. Therefore, it is mandatory to investigate innovative solutions to make the global maritime sector more sustainable and maximize energy efficiency. Motivated by the fact that Solid Oxide Fuel Cell (SOFC) systems already showed their reliability in the maritime sector (in preliminary demonstration projects) and to be integrated with other power systems, the current paper aims to investigate an innovative integration between turbocharged SOFC and internal combustion engine (ICE) to generate the power demand of short-distance ferries (a lake ferry and an island ferry). The hybrid system's operation is proposed to have dual operation modes: (i) during cruise operation modes, it will be based on both ICE and SOFC to maximize energy efficiency thanks to the valorization of anode-off gas from SOFC to be used (mixed with natural gas) as a fuel in ICE; (ii) using SOFC only to generate the electrical power required for hoteling operations in port areas. A techno-economic analysis is performed to simulate the hybrid system at different power capacities of SOFC (targeting 10%-20% of the power required for the ferry). The hybrid system efficiency is evaluated to be between 46.6%-48.9% based on SOFC power share. The economic benefit of increasing SOFC power share is verified for the island ferry which presents an almost similar levelized cost of energy (LCOE) of about 225-231 €/MWh, and it is lower than the lake ferry's LCOE by 30%-43% in different scenarios. Moreover, the gravimetric and volumetric power densities of the hybrid system are 24.3-35.3 kW/ton and 13-20.4 kW/m^3, respectively, based on the investigated scenario and the ferry.

1 INTRODUCTION

Nowadays, the transportation sector has a strong impact on energy consumption, accounting for about 112 EJ, representing nearly 27% of the total worldwide at the end of 2021 (IEA, 2024). The largest part of the sector is powered by fossil fuels, in particular by oil products which have the largest contribution (102 EJ) according to International Energy Agency data (IEA, 2024), with a strong impact in terms of pollutants and greenhouse gas (GHG) emissions. Maritime transportation is responsible for nearly 3% of total carbon dioxide (CO_2) emissions worldwide (1076 Mt in 2018) (European Commission, 2023a). At the European Union (EU) level, maritime transport represents 4% of the EU's total CO_2 emissions, about 124 Mt of CO_2 in 2021 (European Commission, 2023b).

In 2018, according to the DNV report (DNV.GL, 2019), more than 99.5% of ships in operation worldwide were propelled by Internal Combustion Engines (ICEs) fed by conventional oil products fuels, such as marine diesel oil and marine gas oil, taking advantage of different practical advantages, such as the already available infrastructure, the high energy density of the fuels (that can guarantee long-distance vessel journeys), and the well-developed and established technologies on-board. However, in 2023, conventional fuels accounted for 93.5%, with an increase of liquified natural gas (LNG) as an alternative fuel (6%), aiming to reduce both CO_2 and pollutant emissions such as sulfur oxide (SOx), nitrous oxide (NOx), and particulate (DNV, 2023). In 2023, the International Maritime Organization (IMO) released a long-term strategy (IMO, 2023), aiming at reducing GHG emissions from international shipping by 30% by 2030 and 70% by 80% by 2040, compared to 2008 levels. At

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the EU level, since January 2024, the Emissions Trading System (EU-ETS) has been extended to the maritime sector to cover CO_2 emissions from all large ships (of 5,000 gross tonnage and above) entering EU ports, covering 50% of voyages outside the EU and 100% between EU ports (European Commission, 2023a).

To reach the above-reported ambitious targets, it is mandatory to reduce the use of fossil fuels and promote low (natural gas (NG), methanol) and zero-carbon fuels (hydrogen, and ammonia) and high-efficiency technologies for power generation onboard. In this sense, the use of fuel cell technology has attracted many researchers, thanks to their high efficiency and the possibility to be fuelled by all the above-mentioned fuels. Comparing different typologies of fuel cells in different studies (Elkafas et al., 2023b), the most promising are low-temperature Proton Exchange Membrane Fuel Cells (PEMFC), directly fed by hydrogen, and high-temperature Solid Oxide Fuel Cells (SOFC), fed by NG or other hydrocarbons. The use of PEMFC in the maritime field has been investigated widely in the last years, thanks to their quick start-up, fast dynamics, compactness, and good electrical efficiency (45-50%); however, as they require pure hydrogen, the large volumes for hydrogen storage onboard represent an open issue, limiting their application only on small vessels and limited routes (Rivarolo et al., 2023).

Regarding SOFC, their use for maritime was investigated since the early 2000s, thanks to their very high electrical efficiency (55% stand-alone, 60-65% in hybrid system configuration with gas turbines) for limited power sizes. Thanks to the high operative temperature and internal reforming process, they can be operated by natural gas (NG), biogas (Mantelli et al., 2021a), methanol (Qu et al., 2023), and ammonia (Duong et al., 2023), avoiding the problems related to hydrogen storage onboard. Furthermore, the high operating temperature allows for employing SOFC in hybrid configurations with micro gas turbines (mGT) (Mantelli et al., 2021b), and ICEs (Wang et al., 2023). On the other hand, currently on the market modules up to 300 kW have been demonstrated so far (the integration of different modules in parallel is essential to cover vessels' power needs). Furthermore, they need to operate at constant load, and they require a long time (i.e. hours) for the start-up procedure. Thus, they operate mostly as auxiliary power units to satisfy hotel load demands, more than for propulsion. The interest in the use of SOFC in the maritime sector has been demonstrated in the last fifteen years by several national/international research projects as well, as reported in (Elkafas et al., 2023b).

To try to overcome some of the above-mentioned challenges and to exploit SOFC advantages (capability to operate with high efficiency), in this paper, an innovative hybrid system fueled by NG and integrating turbocharged SOFC and ICE has been analyzed via a techno-economic approach by investigating two short-distance ferries as case studies. The SOFC is proposed to provide the hotel load demands in the port while the integration between SOFC and ICE is proposed to provide the propulsion and hoteling power in cruise operation modes.

2 METHODOLOGY

This study develops a methodology to assess the techno-economic feasibility of installing the innovative hybrid system between SOFC and ICE onboard short-distance ferries. This methodology consists of different phases as shown in Figure 1. The steps that compose this methodology are as follows.

The first phase is to identify and analyze the reference vessel (case study) from short-distance ferries by describing the ship's characteristics. The second phase is to develop the operational profile depending on the ship's navigational route, the operational data, and the power demand at different operating modes (cruise operation modes and hoteling mode in the port). The third phase deals with designing the integrated system between SOFC and ICE considering the required balance of plant (BoP), followed by defining scenarios for the hybrid system based on changing the power split between the two systems. The findings from phases 2 and 3 result in developing phase 4 which considers the energy profile of the ship powered by the hybrid system at the operational condition and the calculation of energy efficiency, which will be used to evaluate the required fuel energy/consumption. Phase 5 deals with a technical analysis of the hybrid system, which considers the required weight and volume of SOFC, ICE, BoP, power condition equipment (PCE), and fuel storage system (FSS). Based on the results from phases 3 and 4, the economic analysis of each hybrid system scenario is developed through phase 6 by employing the capital expenses (CapEx), operational expenses (OpEx), and voyage expenses (VoyEx) models to evaluate the levelized cost of energy (LCOE).

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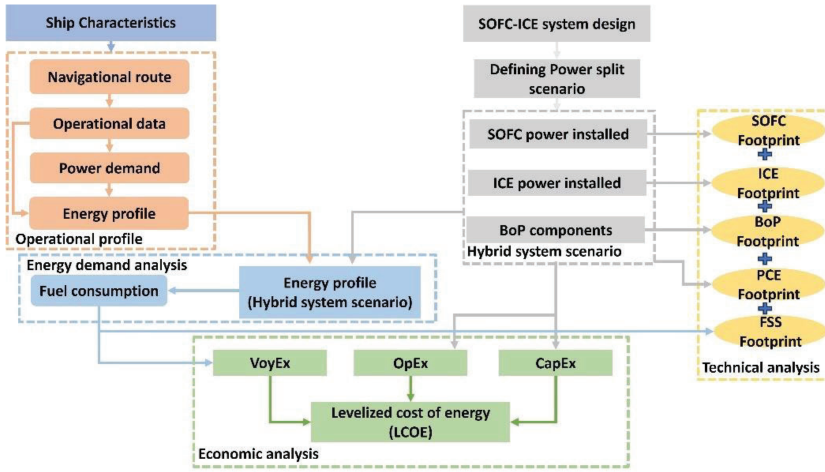


Figure 1: Flowchart of the methodological approach

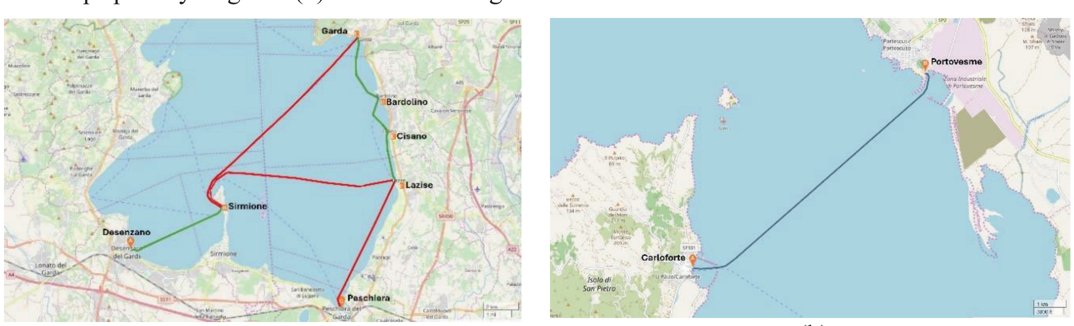
2.1 Ship Characteristics

The study considers the propulsion and onboard power system retrofitting of domestic vessels operating in the Italian national maritime borders and that serve local regional transport sectors at inland waterways and short-sea navigation. The RoPax vessels are examples of vessels that transport several passengers and cars between different lakeside towns or minor islands. As a case study for inland waterways RoPax vessels operated in lakes, the *Tonale* ferry boat operated on Lake Garda in Italy, has been considered (Navigazione laghi, 2024). For short-sea navigation, the *Anna Mur* vessel, operated on Sardinia Island, Italy (MarineTraffic, 2024a) is considered. The main characteristics of reference vessels are shown in Table 1.

Table 1: Reference vessels characteristics

Parameter/Vessel	***Tonale*** (Navigazione laghi, 2024)	***Anna Mur*** (MarineTraffic, 2024a)
Navigation Route	Lake of Garda	San Pietro – Sardinia Island
Length - Breadth - Depth (m)	54 - 10.8 - 2.34	77 – 17.2 – 4.53
Carrying capacity	1000 passengers + 48 cars	771 passenger + 142 cars
Displacement (ton)	558	1,994
Gross tonnage (ton)	-	2,121
Maximum service speed (knots)	9.7	11.5

The first reference vessel *Tonale* is owned and operated by Navigazione Laghi company, and it sails on Lake Garda (Italy) in a daily pattern for seven months per year – April to October - and calls at several towns located on the lakeside as shown in Figure 2(a). The ship sails on short and long trips depending on the trip's origin and destination places; however, the daily sailing operation starts and ends in Desenzano village on Lake Garda's south shore. The second reference vessel *Anna Mur* is owned by Delcomar Srl. It operates in the West Mediterranean Sea between Carloforte port in San Pietro Island and Portovesme port on the southwestern coast of Sardinia Island. This ship sails year-round with 9 round trips per day. Figure 2(b) shows the navigational route of *Anna Mur*.



(a) (b)

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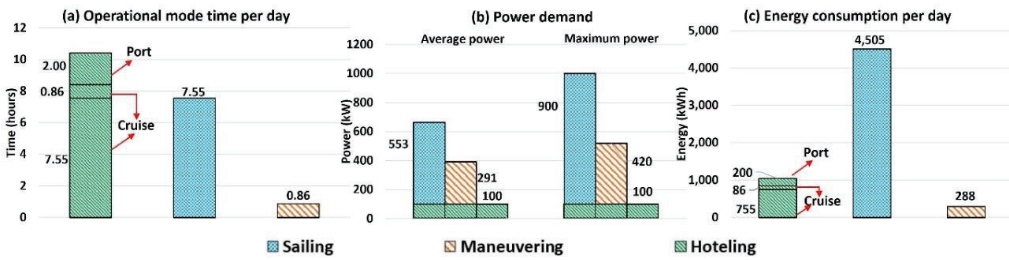
Figure 2: Navigational route of (a) *Tonale*, (b) *Anna Mur*. The red and green paths show the long trip and the short trip, respectively in case 1 (*Tonale*).

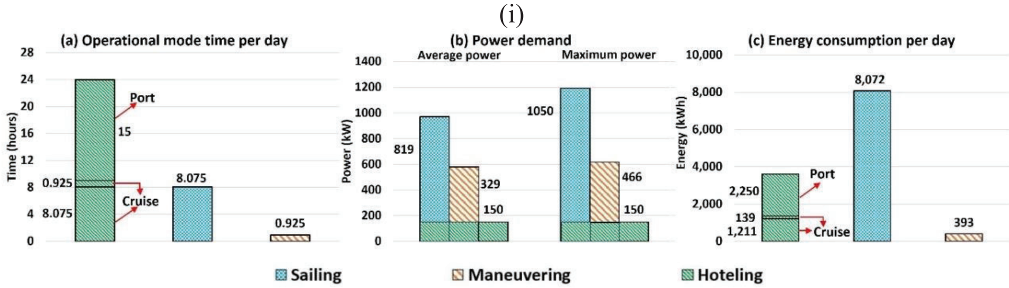
2.2 Operational profile development

The operational data of the vessel's voyages were collected to develop the operational profile from the ship's operator and log sheets from MarineTraffic ("MarineTraffic," 2024b). The operational data include the operation time spent in port or cruise operation modes, service speed, trip distance, and number of trips per day.

The ship's characteristics and the power empirical formulas are employed to create the ship's power profile expressed by correlating the required power at different ship speeds. The power demand for both case studies at each operational mode was evaluated as shown in Figure 3. The power demand in cruise conditions (sailing or maneuvering) is evaluated based on the required power for propulsion and hoteling while the power demand in port is based on the required hoteling power. The maximum power is based on the maximum sailing speed as defined by the ship operator and is considered a target unit for the design of the SOFC-ICE hybrid system. Therefore, the power capacity of the hybrid system must be 1 MW for *Tonale* and 1.2 MW for *Anna Mur* to guarantee the correct operation.



(i)



(ii)

Figure 3: Vessel operational modes data for (i) *Tonale*, (ii) *Anna Mur*

Then, the daily ship's electric energy demand in kWh can be developed by multiplying the required power at each operational mode per trip and the corresponding operation time. Based on the annual operation time of both case studies as reported in section 2.1, the annual energy profile can be developed by assuming that the daily operation profile is repeated along the reported operation time frame.

2.3 Hybrid system scenarios definition

In the current study, the integration between SOFC and ICE is different from other studies (Kistner et al., 2021; Qu et al., 2023; Sapra et al., 2021) in terms (i) integration is based on parallel topology where ICE has high load sharing (80-90% of the hybrid system power) and burns NG after blending it with anode off-gas (AOG) from SOFC to increase the system efficiency, (ii) the simulation of an external turbocharger to provide the compressed airflow for SOFC and ICE, especially the available NG engines in the market are turbocharged aspirated engines. The thermo-economic analysis of the hybrid system is performed by using an in-house software called WTEMP (Web-based Thermoeconomic Modular Program) which was developed by the authors' research group, the preliminary hybrid system configuration is assessed by the authors in (Elkafas Ahmed G. et al., 2023).

Figure 4 shows the flow diagram of the innovative turbocharged SOFC-ICE hybrid system. Methane and water are supplied to an external reformer after they are preheated through heat exchangers (H.X1

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and H.X2), then the reformed fuel enters the anode side of SOFC. The air is supplied through a turbocharger and preheated by using a heat exchanger (H.X3) before entering the cathode side of SOFC. The cathode off-gas (COG) and a portion of AOG are directed to an external combustor to provide the required heat for the reforming process and the preheating process of air. The main flow of AOG is directed into H.X1 and H.X2 to preheat methane and produce steam, respectively. After that, the AOG is directed into a steam separator and a cooler to remove the steam and cool it down, respectively. Then, AOG is mixed with NG in a flow mixer (F.M1) to be combusted in ICE. The compressed air from the turbocharger is cooled down by using a charge air cooler (CAC) before entering the ICE. The exhaust gas from ICE and post-combustor are mixed in a flow mixer (F.M2) to be expanded in the turbine and generate the mechanical power required for turbocharger operation. There is a wastegate valve (WGV) to control the mass flow rate of exhaust gases to be expanded in the turbine and this rate is determined based on the required power to operate the turbocharger.

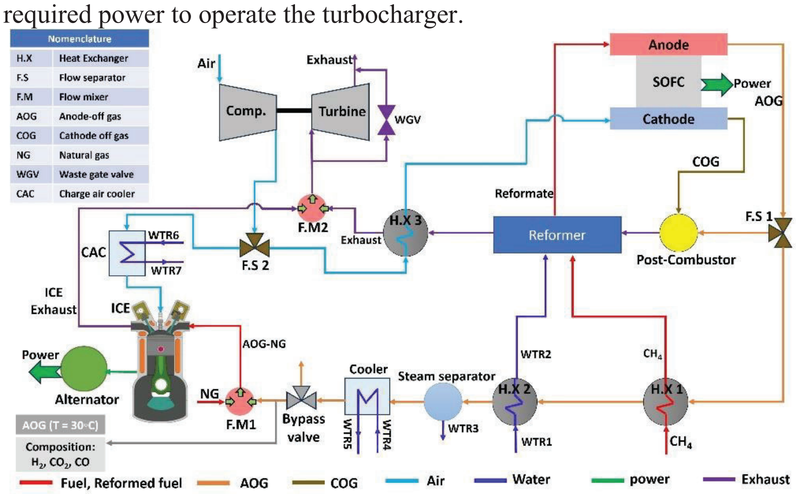

Figure 4: Flow diagram of the innovative turbocharged SOFC-ICE hybrid system

The hybrid system's operation is proposed to have dual operation modes, the first one based on ICE and SOFC to maximize the electrical efficiency and decrease fuel consumption during cruise operating modes (sailing and maneuvering). The second is based on using SOFC only to generate electrical power required for hoteling in the port.

The current study investigates three scenarios for SOFC-ICE integration through cruise operations (sailing or maneuvering) as shown in Table 2. The minimum power capacity of SOFC in the first scenario has been estimated at 100 kW for *Tonale* and 150 kW for *Anna Mur* because these are the hoteling power demands as calculated in section 2.2. The second and third scenarios are proposed by increasing the SOFC power share in cruise operations to investigate its effect from a technical and economic perspective. On the other hand, power demand for hoteling operation mode in the port is proposed to be covered by 100 kW and 150 kW SOFC systems for *Tonale* and *Anna Mur*, respectively.

Table 2: Hybrid system scenarios in cruise operations for *Tonale* and *Anna Mur*

Scenario number	***Tonale***		***Anna Mur***	
	Load % (SOFC-ICE)	**Power (kW)**	**Load % (SOFC-ICE)**	**Power (kW)**
1 (Baseline)	10% - 90%	100 – 900	12.5% - 87.5%	150 - 1050
2	15% - 85%	150 – 850	15% - 85%	180 - 1020
3	20% - 80%	200 - 800	20% - 80%	240 - 960

2.4 Technical analysis approach

The hybrid system includes SOFC, ICE, FSS, PCE, and BoP components. Therefore, the weight and volume of the hybrid system in different scenarios will be evaluated as shown in Equations (1-2) (Elkafas et al., 2023a).

$$W_{HSS} = W_{fss} + \sum_{ps} \frac{P_{ps}}{GD_{ps}} + \sum_{BoP} W_{BoP} + \sum_{pce} \frac{P_{HSS}}{GD_{pce}} \quad (1)$$

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$$V_{HSS} = V_{fss} + \sum_{ps} \frac{P_{ps}}{VD_{ps}} + \sum_{BoP} V_{BoP} + \sum_{pce} \frac{P_{HSS}}{VD_{pce}} \tag{2}$$

Where W_{HSS} and V_{HSS} are weight in (ton) and volume in (m^3) of the hybrid system scenario (HSS), respectively. The weight and volume of SOFC and ICE systems can be calculated by dividing the delivered power of each power system (P_{ps}) by the corresponding gravimetric power density (GD) and volumetric power density (VD), respectively. The gravimetric and volumetric power densities of SOFC are based on the commercial products available in the market, particularly the SOFC systems available from Convion C50 (GD_{SOFC} = 9.5 kW/ton, VD_{SOFC} = 4.4kW/m^3) (Convion, 2024; Elkafas et al., 2023b). Meanwhile, the gravimetric and volumetric power density of the lean burn spark ignition natural gas engine available from Bergen (Bergen, 2024) is used for the current study (GD_{ICE} = 83.4 kW/ton, VD_{ICE} = 64 kW/m^3).

Based on the hybrid system scenario defined in section 2.3 and the ship's operational profile evaluated in section 2.2, the energy profile of the hybrid system scenario and fuel energy required for each operating mode can be developed by dividing the electrical energy demand (EE_j) by the system efficiency at this mode. The resulting fuel energy is used to calculate the weight and volume of the FSS (W_{FSS}, V_{FSS}) as shown in Equations (3-4) considering that the FSS is designed to provide the required energy for all trips per day. The gravimetric and volumetric energy densities of the FSS (fuel required and storage system) are 7400 kWh/ton and 3300 kWh/m^3 in the case of using LNG, respectively (van Biert et al., 2016).

$$W_{FSS} = \sum_{day} \sum_{j=1}^{j} \frac{EE_j}{\eta_{HSS,j} * GD_{FSS}} \times (1 + f_{sc}) \; , V_{FSS} = \sum_{day} \sum_{j=1}^{j} \frac{EE_j}{\eta_{HSS,j} * VD_{FSS}} \times (1 + f_{sc}) \tag{3}$$

$$\eta_{HSS} = \frac{P_{SOFC} + P_{ICE}}{\dot{m}_f \times LHV_f} \tag{4}$$

Where EE_j is the electrical energy demand for each operating mode (*j*) measured in kWh, $\eta_{HSS,j}$ is the energy efficiency of hybrid system scenario in the operating mode (*j*), $\dot{m}_f$ is the mass flow rate of fuel in kg/s, LHV_f is lower heating value of fuel in kJ/kg, and f_{sc} is a spare capacity factor for the stored fuel onboard (assumed to be 15%) (Aarskog et al., 2020).

2.5 Economic analysis approach

The levelized cost of energy (LCOE) approach is implemented as an economic indicator for the current study, its value can be calculated as shown in Equation (5) by adjusting all future costs including OpEx, and VoyEx up to current values while taking a discount rate into account.

$$\mathrm{LCOE}_{HSS} = \frac{(\mathrm{CapEx}_{HSS}^{d} + \mathrm{CapEx}_{HSS}^{ind}) + \sum_{\mathrm{n}=1}^{\mathrm{LT}} \frac{\sum_x \mathrm{OpEx}_{x,\mathrm{n}}}{(1+\mathrm{d})^{\mathrm{n}}} + \sum_{\mathrm{n}=1}^{\mathrm{LT}} \frac{\mathrm{VoyEx_n}}{(1+\mathrm{d})^{\mathrm{n}}}}{\sum_{\mathrm{n}=1}^{\mathrm{LT}} \frac{\mathrm{EE}_{HSS,\mathrm{n}}}{(1+\mathrm{d})^{\mathrm{n}}}} \tag{5}$$

Where d and n represent the discount rate and the n-th year of the lifetime, respectively. The current study considers 5% and 25 years as the discount rate (d) and number of lifetime (LT) years for both case studies, respectively. $\mathrm{EE}_{HSS,\mathrm{n}}$ is the annual energy generated by the hybrid system scenario in MWh. Costs associated with the investment required to purchase the hybrid system components including SOFC system, ICE, methane reformer, BoP components, and power conditioning equipment, are referred to the direct capital expenses (CapEx_{HSS}^{d}). Moreover, the investment cost of the FSS is included in CapEx_{HSS}^{d} as shown in Equation (6). While the indirect capital expenses including commissioning, installation, engineering, and design costs are referred to ($\mathrm{CapEx}_{HSS}^{ind}$).

$$\mathrm{CapEx}_{HSS}^{d} = \mathrm{CF}_{FSS} \times \mathrm{FC}_{HSS,day} + \sum_{ps} \mathrm{P}_{ps} \times \mathrm{CF}_{ps} + \sum_{BoP} \mathrm{PEC}_{BoP} + \mathrm{P}_{HSS} \times \sum_{\mathrm{pce}} \mathrm{CF_{pce}} \tag{6}$$

Where CF_{ps}, and $\mathrm{CF_{pce}}$ are cost factors in €/kW for power systems (SOFC, and ICE) and power conditioning equipment (electric motor, DC/DC converter, DC/AC inverter, and alternator), respectively. The cost equations shown in Table 3 are utilized to calculate the purchase cost (PEC_{BoP}) of the balance of plant equipment such as heat exchangers (HX), and pump (Lee et al., 2018), these cost

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factors will be updated to the present value by using Chemical Engineering Plant Cost Indices (CEPCI) which equal to 800 in 2023 (Scott Jenkins, 2023). The purchase cost of other BoP components such as turbocharger, combustor, AOG cooler, and charge air cooler is evaluated by using the economic analyzer within WTEMP software.

The cost of the SOFC system and ICE system were evaluated based on their power capacity in each hybrid system scenario. The FSS cost factor ($\mathrm{CF_{FSS}}$) in €/kWh can be calculated by using the financial maps available in (Rivarolo et al., 2021) and multiplied by the required fuel energy ($\mathrm{FC}_{HSS,day}$) to be stored per day. The cost factors of different components in the hybrid system are reported in Table 3.

Table 3: Capital cost factor of different components in the hybrid system

Component	**Cost factor (CF)**	**Technical parameter**	**Reference**
ICE	350 €/kW	LT=25 years	(Kanchiralla et al., 2022)
SOFC	2,500 €/kW	$\mathrm{LT_{BoP}} = 25$ years	(Kanchiralla et al., 2022)
Alternator	120 €/kW	$\eta = 98\%$, LT=25 years	(Kanchiralla et al., 2022)
DC/DC converter	120 €/kW	$\eta = 98\%$, LT=25 years	(Kanchiralla et al., 2022)
Electric motor	250 €/kW	$\eta = 96\%$, LT=25 years	(Korberg et al., 2021)
Methane reformer	370 €/kW	LT=25 years	(Becker et al., 2012)
HX (fuel or water)	$130 \times \frac{A_{HX}}{0.093}$	$CEPCI_{2005} = 468.2$	(Lee et al., 2018)
HX (air)	$390 \times \frac{A_{HX}}{0.093}$	$CEPCI_{2005} = 468.2$	(Lee et al., 2018)

The $\mathrm{OpEx}_{x,\mathrm{n}}$ is the annual operating and maintenance (O&M) expenses of the x-th component in the hybrid system. SOFC's OpEx per year is considered to be 2% of its CapEx (Kanchiralla et al., 2022), moreover, it has an additional expense for the replacement costs of SOFC stacks considering 40,000 hours as its lifetime (Lee et al., 2018). SOFC stacks' replacement cost is assumed as 50% of SOFC CapEx due to the anticipated growth in the SOFC market size for the transportation industry as well as of the fact that stack cost is usually around 50-60% of the overall SOFC system CAPEX (Elkafas et al., 2023a). While the O&M costs of ICE is 2% of its CapEx (Kanchiralla et al., 2022). The OpEx of BoP and PCE equipment are assumed to be 1% of their CapEx (Kanchiralla et al., 2022). The VoyEx evaluation is based on the annual fuel consumption over each operating mode, therefore, its value can be calculated as shown in Equation (7).

$$\mathrm{VoyEx}_n = \sum_n \sum_{j=1}^{j} \mathrm{FC}_j * (\mathrm{CF}_{LNG} + CF_{pf}) \tag{7}$$

Where FC_j is the daily fuel consumption per mode (j) and measured in MWh, CF_{LNG} is the LNG cost factor of 58 €/MWh (Elkafas et al., 2023a), and CF_{pf} is the port fees for bunkering operation (e.g. 5 €/MWh) (Kistner et al., 2021).

3 RESULTS AND DISCUSSION

3.1 Technical analysis results

In this subsection, the technical analysis results are presented based on the methodological approach discussed in section 2.4. For the retrofitting process of *Tonale* and *Anna Mur*, the weight and volume of hybrid system components must be evaluated including SOFC, ICE, FSS, BoP, and PCE.

The weight and volume of FSS are based on daily fuel consumption which is influenced by system efficiency at different operating modes as shown in Eq. (3-4). The real performance curves of the Convion C50 SOFC system (Convion, 2024) conducted in the European DEMOSOFC and ComSos projects (Marocco et al., 2022) demonstrate the SOFC's high efficiency at part load conditions (60-85% of rated power). When the SOFC power capacity is increased as represented in scenarios 2 and 3, the SOFC system in the port must be operated in a part load condition to fulfill the required hoteling power. Therefore, the system efficiency rises, and the port's daily fuel energy required is reduced as shown in Figure 5. Similarly, with the increment in SOFC power share, the hybrid system efficiency for cruise operating modes increases as shown in Figure 5 because the highly efficient SOFC contributes by a

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high load share and a high fraction of AOG is available to be combusted in the integrated engine; thus, daily fuel energy required for cruise operation modes reduces as shown in Figure 5.

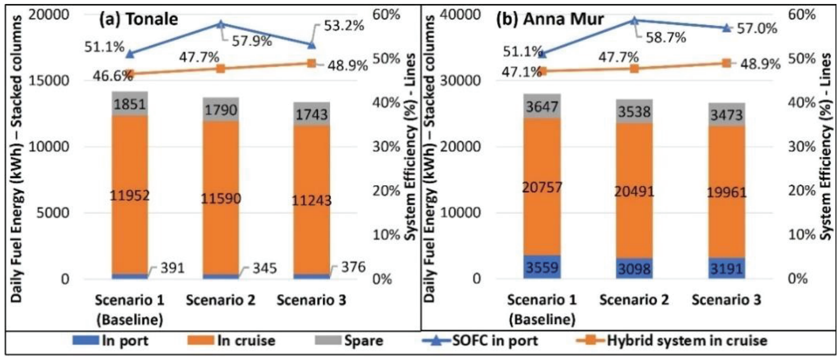

Figure 5: System efficiency and daily fuel energy required for (a) *Tonale* and (b) *Anna Mur*

This argument is proved by the weight and volume results of hybrid system scenarios, shown in Figure 6. The weight and volume of fuel and fuel storage system for *Tonale* and *Anna Mur* are reduced by increasing SOFC power share as represented in scenarios 2 and 3.

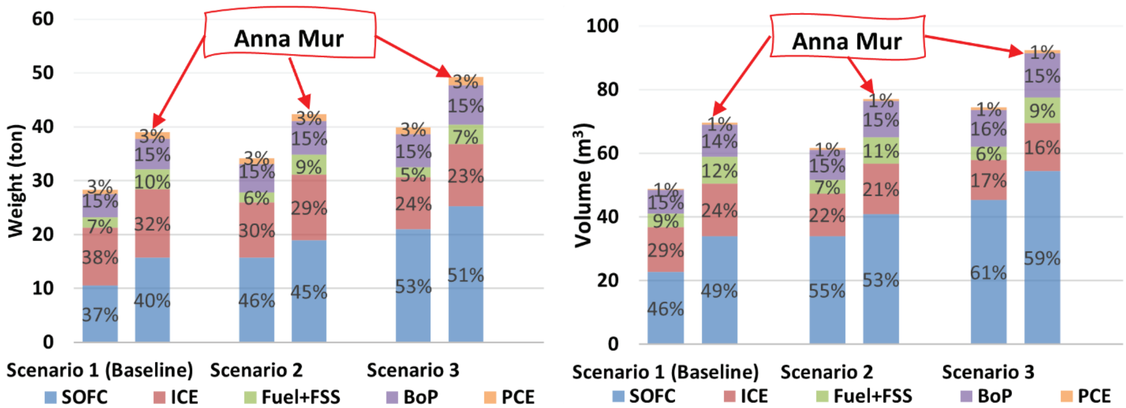

Figure 6: The results of (a) Weight and (b) Volume, of different hybrid system scenarios for *Tonale* and *Anna Mur*. *Percentage values inside columns denote each category's weight/volume percentage*.

As shown in Figure 6, the reduction in weight of fuel storage system in scenarios 2 and 3 cannot compensate for the increment in SOFC weight as the total weight in the case of *Tonale* increases by 20.4% and 40.8% compared to the baseline scenario, respectively. Similarly, the total volume increases by 26% and 52.1%, respectively. While the effect of fuel storage system reduction is more beneficial in the case of *Anna Mur* as the increment in total weight/volume is lower than that of *Tonale*, the weight increases by 8.7% and 26.5%, and the volume increases by 10.7%, and 32.5% for scenarios 2 and 3 compared to the baseline scenario, respectively. The gravimetric and volumetric power densities of the hybrid system scenarios are reported in Table 4.

Table 4: Gravimetric and volumetric power density (GD and VD) of hybrid system scenarios

Case study	***Tonale***			***Anna Mur***		
Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
GD (kW/ton)	35.25	29.27	25.03	30.76	28.30	24.33
VD (kW/m³)	20.43	16.21	13.43	17.21	15.55	12.98

3.2 Economic analysis results

In this subsection, the economic analysis results are presented based on the methodological approach discussed in section 2.5. The results of direct CapEx for the different hybrid system scenarios along with cost breakdown for the system components are shown in Figure 7 for each investigated ship.

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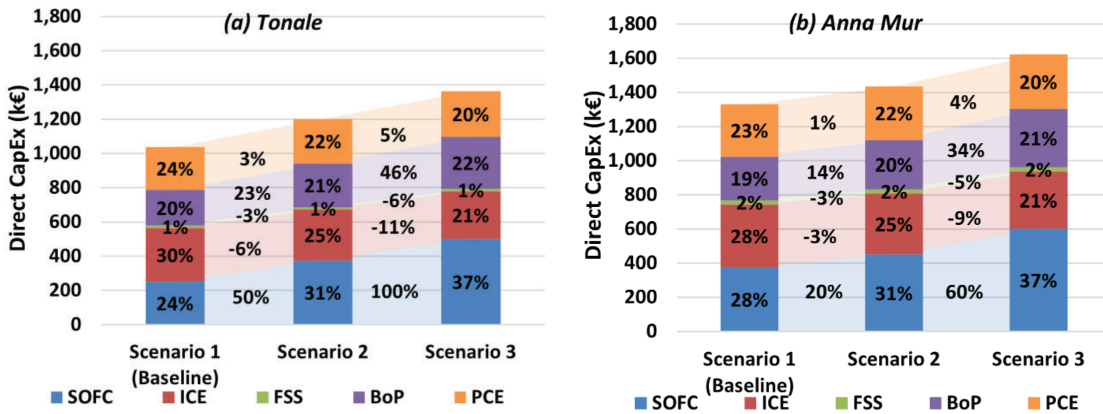

Figure 7: Direct CapEx results for (a) *Tonale* and (b) *Anna Mur*. *Percentage values inside columns denote each category cost percentage while percentage values between columns denote variation of each cost category against the baseline scenario*.

The results presented in Figure 7 demonstrate that the total direct CapEx of the baseline scenario for *Tonale* and *Anna Mur* is about 1.04 M€ and 1.33 M€, respectively. By increasing SOFC load share in the case of *Tonale* as presented in both Scenarios 2 and 3, the total direct CapEx increases by about 16% and 31% compared to the baseline scenario, respectively, which are mainly attributed to the high costs due to SOFC system. Likewise for *Anna Mur*, the total direct CapEx increases by 8% and 22% for scenarios 2 and 3 compared to the baseline scenario, respectively. Although the cost of installed ICE is reduced in the case of scenarios 2 and 3 for both ships, it cannot compensate for the increment in the cost of the SOFC system.

For the baseline scenario of *Tonale*, the annual OpEx is 16.3 k€ in which ICE has the highest contribution at 38.6%, followed by the SOFC system at 30.6%. By increasing SOFC power share for *Tonale*, the OpEx of ICE reduces by about 6 and 11% for Scenario 2 and 3 compared to the baseline scenario, respectively. However, this reduction cannot compensate for the increment of SOFC's OpEx as 46% and 61.3% of the annual OpEx are pertinent to the SOFC system for Scenario 2 and 3, respectively. In the case of *Anna Mur*, the annual OpEx increases by 9% (22.9 k€) and 25% (26.3 k€) when increasing SOFC power share in Scenarios 2 and 3 compared to the baseline scenario (21.1 k€), respectively. Moreover, the OpEx of SOFC system has the highest contribution by about 35.6%, 42.7%, and 56.9% for Scenarios 1,2, and 3, respectively.

The VoyEx results are dependent on the yearly fuel consumption, which is influenced by the efficiency of the system as discussed in section 3.1, therefore, the VoyEx for scenarios 2 and 3 are expected to be lower than the baseline scenario. This has been proved as shown in Figure 8, in which VoyEx in the case of *Tonale* for scenarios 2 and 3 are lower than the baseline scenario by 3.3% and 5.9%, respectively. Likewise, the VoyEx in the case of *Anna Mur* in scenarios 2 and 3 are lower than the baseline scenario by 3% and 4.8%, respectively.

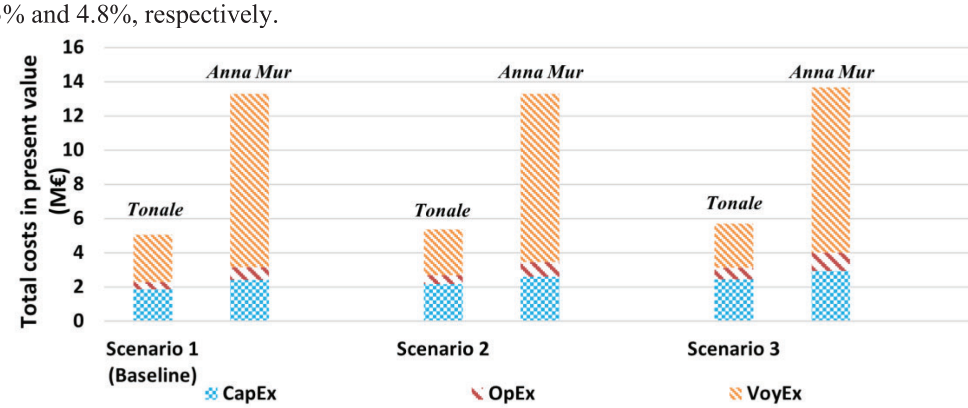

Figure 8: Total costs at present value of different scenarios for *Tonale* and *Anna Mur*.

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For *Tonale*, these reductions in VoyEx cannot compensate for the increment in CapEx and OpEx as shown in Figure 8, therefore, the total costs for scenarios 2 and 3 (5.37 M€ and 5.71 M€) rises by 6.3% and 12.9% compared to baseline scenario, respectively. On the other hand, the VoyEx reductions in the case of *Anna Mur* compensate for the increase in CapEx and VoyEx when SOFC power share increased to be 15% (Scenario 2) as its total costs is 13.3 M€ which is lower than the baseline scenario (13.31 M€) by 0.05%. While the total costs of scenario 3 (13.67 M€) is more than the baseline scenario by 2.8%.

Although the total costs for implementing a hybrid system onboard *Anna Mur* is higher than the total costs in the case of *Tonale*, the operating hours of the system in ports onboard *Anna Mur* are higher than that *Tonale* ones as well as taking advantage of the high efficiency of the system as elaborated in Figure 5. Thus, the annual energy generated from the system onboard *Anna Mur* is higher than that in the case of *Tonale*, resulting in lower LCOE values in the case of *Anna Mur*, as shown in Figure 9. The LCOE in the baseline scenario for *Anna Mur* is 225.44 €/MWh which is significantly lower than LCOE for *Tonale* (292.79 €/MWh).

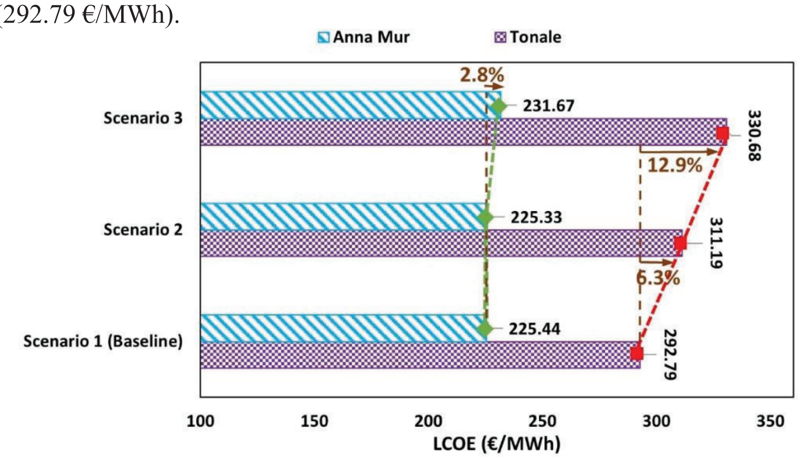

Figure 9: Levelized cost of energy of different scenarios for *Tonale* and *Anna Mur.*

As shown in Figure 9, by increasing the SOFC power share, the hybrid system LCOE of *Anna Mur* is lower than the LCOE of *Tonale* by 85.9 €/MWh and 99 €/MWh for scenarios 2 and 3, respectively, because the operating hours of the hybrid system, operating hours in port, and the generated power in the case of *Anna Mur* is higher than that on *Tonale*. Moreover, the hybrid system LCOE of *Anna Mur* in scenario 2 is almost similar to the LCOE of the baseline scenario because the VoyEx of scenario 2 is lower than the VoyEx of the baseline scenario and it compensates for the increment in CapEx and OpEx as reported in Figure 8. LCOE in scenario 3 is higher than that of the baseline scenario by 2.8% as its CapEx and OpEx are higher than that of the baseline scenario by 21.8% and 43.3%, respectively, although the VoyEx of scenario 3 is lower than VoyEx of baseline by 4.8%.

4 CONCLUSIONS

The current study aims to conduct a techno-economic analysis for an innovative hybrid system with turbocharged SOFC and ICE to be applied onboard short-distance ferries by using technical key indicators (energy efficiency, weight, and volume) and economic indicators (CapEx, OpEx, VoyEx, and LCOE). The SOFC is proposed to be used alone in the port while there are three scenarios to use the hybrid system in sailing and maneuvering operating modes based on changing the power share of SOFC in the hybrid system (targeting 10-20%). In the proposed hybrid system scenarios, the ICE burns natural gas blending with the anode off-gas from SOFC to produce additional power, increasing global electrical efficiency, and reducing fuel consumption. The main findings of the study are summarized as follows:

- From a technical point of view, the gravimetric and volumetric power densities of the baseline hybrid system scenario are 35.26 kW/ton, and 20.44 kW/m^3 in the case of lake ferry (*Tonale*), while

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they are 30.76 kW/ton, and 17.12 kW/m^3 in the case of island ferry (*Anna Mur*). Moreover, the system efficiency is 46.6% for *Tonale* (10% SOFC) and 47.1% for *Anna Mur* (12.5% SOFC).

- By increasing SOFC power share in scenarios 2 and 3 in the case of *Tonale*, the gravimetric density reduces by 16.9%, and 29% while volumetric density reduces by 20.6% and 34.2%, respectively. For *Anna Mur*, the gravimetric density of scenarios 2 and 3 are lower than the baseline scenario by 8% and 20.9% while volumetric density is lower by 9.6% and 24.6%, respectively. The system efficiency is increased to 47.7% and 48.9% in scenarios 2 and 3 for both ferries, respectively.
- From an economic perspective, the CapEx of the hybrid system is increased by 16% and 31% for *Tonale* and 8% and 22% for *Anna Mur* when compared to the baseline scenario by increasing the SOFC power share in scenarios 2 and 3, respectively, this increment is mainly attributed to the SOFC system. For *Anna Mur* case study, the VoyEx reductions make up for the rise in CapEx and OpEx when SOFC power share increased to 15% (Scenario 2) as its total costs is 13.3 M€ which is lower the total costs of the baseline scenario (13.31 M€) by 0.05%.
- The LCOE of the hybrid system in the case of *Anna Mur* is 225.44 €/MWh, 225.33 €/MWh, and 231.67 €/MWh for scenarios 1,2, and 3, respectively which is lower than LCOE in the case of *Tonale* by 30%, 38%, and 43%, respectively.

Generally speaking, the proposed hybrid system gains competitivity at economic and energy efficiency levels not only for vessels having a large yearly number of operating hours but particularly for vessels having a daily operating profile (like *Anna Mur* ones) where the harbor/hotelling operation is relevant (e.g. 62.5% of the overall daily operating hours for *Anna Mur*) as in this phase the SOFC system is significantly more efficient than the ICE while during the sailing period the increase of the efficiency is less relevant. In this way, the impact on the annual energy efficiency of the vessel is more valuable and the proposed retrofitting becomes more economically attractive.

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