HELENUS

High Efficiency Low Emission Nautical SOFC

D6.1 Description of benchmark ocean cruise, dredging and offshore vessels

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Table of contents

List of abbreviations and acronyms 5

Executive Summary 7

1. Introduction 8

2. Ocean cruise vessel 9

2.1 Operating modes 9

2.2 Annual operational profile 10

2.3 Functional benefit description 10

2.4 Modelling plan 10

3. Dredging vessel 11

3.1 Operating modes 12

3.2 Annual operational profile 12

3.3 Functional benefit description 13

3.4 Energy consumption and emission estimation 13

3.5 Modelling plan 14

4. Offshore vessel 15

4.1 Operating modes 16

4.2 Annual operational profile 16

4.3 Functional benefit description 17

4.4 Energy consumption and emission estimation 17

4.5 Modelling plan 17

5. Conclusion 18

6. Future work 19

7. References 20

Index of figures

Figure 1 - MSC ocean cruise vessel 9
Figure 2 - Render of the Beagle 12 11
Figure 3 - Artist impression of inter-array cable lay vessel with two carousels 15

List of abbreviations and acronyms

Abbreviation	Meaning
CLV	Cable lay vessel
CO_2	Carbon dioxide
CPP	Controllable pitch propeller
DF	Dual-fuel
DWT	Deadweight
EU	European Union
FP7	Seventh Framework Programme
GT	Gross tonnage
HE	Horizon Europe
HELENUS	High Efficiency Low Emission Nautical SOFC
HFO	Heavy fuel oil
ICLV	Inter-array cable lay vessel
JOULES	Joint Operation for Ultra Low Emission Shipping
LCPA	Life cycle performance assessment
LOA	Length overall
LPP	Length between perpendiculars
LSMGO	Low sulphur marine gasoil
MDO	Marine diesel oil
MGO	Marine gasoil
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
PM	Particulate matter
PS	Portside
SB	Starboard
SO_2	Sulphur dioxide
SO_X	Sulphur oxides
R&D	Research and Development
SOFC	Solid Oxide Fuel Cell
TSHD	Trailing suction hopper dredger

TTP	tank-to-propeller
VLSFO	Very low sulphur fuel oil
WP	Work package

Executive Summary

The objective of HELENUS work package (WP) 6 is to address the challenge of implementing SOFC-based energy systems on different ship types, and optimizing the energy system for efficiency and emissions. The application cases of WP6 are used as (virtual) validation of technology developed and/or made available by WP2, modelled and verified by WP3 & validated WP4.

This report is deliverable (D6.1) and concludes the work performed within HELENUS Task 6.1. It presents the benchmark vessels selected for the three application case studies. This report will serve as a basis for the other tasks within WP6 and for the collaboration with the other HELENUS work packages. The selected three benchmark vessels are:

- MSC World Class series (ocean cruise vessel)
- Royal IHC standardised trailing suction hopper dredger Beagle 12 (dredging vessel)
- Royal IHC inter-array cable lay vessel (ICLV) T4000-22 (offshore vessel)

The benchmark description for all three application cases includes the vessel's characteristics, the (annual) operational profile and the functional benefit description. This functional benefit description allows for a transparent comparison of the SOFC-based vessel designs with the benchmark vessels.

The future work in HELENUS WP6 consists of the following three tasks:

- Task 6.2: Development of SOFC-based zero emissions design vessel configurations with different (renewable) fuel options
- Task 6.3: Energy grid modelling and simulation of the benchmark- & concept-vessels
- Task 6.4: Assessment of the benchmark and concepts on energy efficiency, greenhouse gas and harmful emissions and economic viability

1. Introduction

The objective of HELENUS work package (WP) 6 is to address the challenge of implementing SOFC-based energy systems on different ship types, and optimizing the energy system for efficiency and emissions. The application cases of WP6 are used as (virtual) validation of technology developed and/or made available by WP2, modelled and verified by WP3 & validated WP4. The application case studies will cover three vessel types, namely:

- Ocean cruise vessel (Section 2)
- Dredging vessel (Section 3)
- Offshore vessel (Section 4)

Work package 6 consists of 4 tasks, namely:

T6.1. Definition of the benchmark for each vessel type
T6.2. Development of SOFC-based zero emissions design vessel configurations with different (renewable) fuel options
T6.3. Energy grid modelling and simulation of the benchmark- & concept-vessels
T6.4. Assessment of the benchmark and concepts on energy efficiency, greenhouse gas and harmful emissions and economic viability

These tasks result in the following deliverables:

D6.1. Description of benchmark ocean cruise, dredging and offshore vessels
D6.2. Description of SOFC-based concepts for ocean cruise, dredging, and offshore vessels
D6.3. Modelling of the benchmark & SOFC-based concepts for ocean cruise, dredging, and offshore vessels
D6.4. Assessment results of the benchmark & SOFC based concepts for ocean cruise, dredging, and offshore vessels

This report is deliverable D6.1, a result of task T6.1 and contains the description of the benchmarks as currently defined for the ocean cruise, dredging and offshore vessels. The information for each vessel includes a description of the vessel design, its size and some key characteristics. Additionally, the (annual) operational profile and an estimation of the (annual) energy consumption and emissions are given. A first insight in the modelling of each application case is also given.

2. Ocean cruise vessel

The ocean cruise vessel selected for this analysis is an MSC ship as shown in Figure 1.

Figure 1 - MSC ocean cruise vessel

The power production on-board will be ensured by an electrical power plant, including internal combustion engines and potential fuel cells. The electric power produced by the converters is then distributed between the different consumers: propulsion systems, hotel load, machinery auxiliaries etc. In addition to the electric power generation, distribution and consumption, cruise vessels require significant thermal power to run several hotel equipment (i.e. galleys, laundry, water heating, etc).

2.1 Operating modes

On an ocean cruise ship, there are usually three operating modes: at berth, manoeuvring, and at sea.

At berth

Power consumption at berth corresponds prominently to the ship hotel load. It is the consumption related to the passengers' hotel, meal preparation and care. It includes mainly the temperature regulation (chillers), galleys and food storages, laundries, entertainment amenities and lights. This power consumption covers both electric and thermal power supplies. The power consumption at berth is highly dependent on the number of passengers and crew on-board the ship and on the weather conditions (i.e. winter or summer conditions). For this ship, the consumption at berth is lower than 25% of the installed power.

Manoeuvring

Manoeuvring is the time when the ship arrives or leaves a port. During this operation the ship use its main propellers, but also the bows thrusters for an additional lateral propulsion. Manoeuvring is the operating mode during which there are the highest power demand peaks, due to the fluctuations of the propulsion systems power load. Power consumption considered during manoeuvring includes the hotel load in addition to the power specifically dedicated to the manoeuvre.

At sea

This is the time at sea between two ports. The time at sea of the cruise ship may vary a lot depending on the cruise profile of the ship, between a few hours (a night at sea) to a few days (ocean crossing). Propulsion power consumption at sea is highly dependent on the ship speed, and on the weather conditions. Together with the hotel load, the total power consumption in severe conditions may reach the total power capacity installed on-board.

2.2 Annual operational profile

The model will consider the specific cruise profile of the ship. This cruise profile is a hypothesis of work defined in collaboration with the ship owner, for the ship design. A cruise profile includes all the operating modes (time at berth, manoeuvring, and time at sea) to simulate the different steps of a real cruise. In the specific cruise profile considered the time at sea is predominant, and more than two times the time spent at port and manoeuvring overall.

2.3 Functional benefit description

In the HELENUS project WP6, several SOFC-based concept vessel designs with different renewable fuel options will be described in words and figures. Functional benefits of those different options and particularly the energy savings will be calculated by both partners using their modelling tools.

2.4 Modelling plan

The simulations will be realized with CdA model, which includes the power generation and consumers on-board the ship. The power demand is based on cruise operational profile(s). This model will then be implemented depending on the vessel-concept analysed (fuel cell power installed, fuel options, waste heat recovery option etc.). The accuracy of the model will depend on the knowledge available currently for the different technologies and fuels taken in account. The results of those different case studies will be compared with the reference ship, for an estimation of the environmental gains.

3. Dredging vessel

The benchmark dredging vessel is Royal IHC’s Beagle 12 (see Figure 2). This is a standardised trailing suction hopper dredger (TSHD) [1]. It is a work vessel that dredges soil from underwater bottoms, such as the sea, rivers or lakes. Dredging is required to keep navigable depths, to extract sand for infrastructural works or other minerals present in the underwater bottoms.

Figure 2 - Render of the Beagle 12 [2]

The TSHD sails to the dredging location, at the location it deploys a suction system, usually composed of a drag head and suction tube and dredges soil by using centrifugal pumps, or other similar suction technology. After filling the hopper, it sails to a discharge location. At the location, the material stored in the hopper is discharged also using centrifugal pumps (exception to gravel hoppers) via discharge pipes, or by opening the bottom doors to let the cargo fall on the floor below the vessel.

These vessels are quite sturdy and have a high installed power/size ratio, which enables them to dredge many soil types up to depths of several tens of meters. Project specifications and environmental conditions lead to a large variation in the use of the installed power. Typically, 50% to 100% of the installed power is used.

The currently most common drive train for TSHDs is a diesel-direct driven installation. The Beagle 12 can operate on “heated fuels” such as heavy fuel oil (HFO). However due to the global sulphur cap of 0.5%, high sulphur HFO is not allowed, but very low sulphur fuel oil (VLSFO) with up to 0.5%S is allowed. The vessel can also operate on marine diesel oil (MDO) or marine gasoil (MGO). Table 1 contains the main properties of the Beagle 12.

Table 1. Main characteristics of the Beagle 12 [1].

Characteristics	Value	Unit
Length overall, approx. (LOA)	127.0	m
Length between perpendiculars (LPP)	117.0	m
Breadth	28.4	m
Draft (design)	8.0	m
Design speed	15.0	kt.
Suction pipe diameter	2x 900	mm
Hopper capacity (volume)	12,000	m^3
Total installed power	±13,000	kW
Special equipment	Dredge pumps, jet pumps, heavy winches, gantries	

3.1 Operating modes

The TSHD has 4 main operating modes [3], these are:

- Free sailing empty (including manoeuvring empty)
- Dredging
- Free sailing full (including manoeuvring full)
- Discharging through three methods, namely:
    - Shore connection (most common)
    - Rain bowing (when necessary)
    - Dumping (when possible)

The operational profile/engine loads can vary with specific project conditions, such as the distance between dredging and discharge locations (resulting in a relatively larger amount of time for sailing). For the same operational profile, power demand can also vary strongly with soil characteristics and weather conditions. For the HELENUS project, several operational profiles based on real measured dredging cycles will be used for the simulation and evaluation of the concepts with the SOFC-based drive systems.

3.2 Annual operational profile

The annual operation profile of the benchmark TSHD consists of a repetition of dredging cycles. Table 2 contains an estimated operational profile based on the operational profile given in Mestemaker et al. 2022 [3] for a 5600 m^3 TSHD and modified based on the size of the benchmark. The assumption is that the vessel discharges 50% of the time by opening the bottom doors (dumping) and 50% of the time by shore pumping the dredged mixture.

The vessel operates 20 hours per day, 7 days per week and 46 weeks per year repeating the cycle. The remaining time consists of downtime of the vessel for among others maintenance, repair and refuelling. The annual operation profile will be discussed in more detail in Task 6.3.

Table 2. Estimated operational profile of the benchmark TSHD [3]

Activity	Total load [kW]	Duration [min]
Sailing empty	8,000	40
Dredging	11,000	90
Sailing full	9,500	45
Dumping (50% of 30 min)	4,500	15
Shore pumping (50% of 100 min)	11,000	50
Total		240 min

3.3 Functional benefit description

The functional benefit of a dredging vessel is the amount of material delivered to and/or removed from location A to location B. The functional and environmental benefits can be described as:

- kg CO_2/m^3 in-situ material
- kg NO_X/m^3 in-situ material
- etc. (for other emissions)

3.4 Energy consumption and emission estimation

The first estimate of the benchmark TSHD's energy consumption and tank-to-propeller (TTP) emissions for a one-year period may be found in Table 3. These figures are a first estimate and will be refined with more detailed analyses made in Tasks 6.3 and 6.4. This first estimate has been made based the annual operational profile given in Section 4.2 for an IMO NO_X Tier III compliant vessel sailing on low sulphur marine gasoil (LSMGO) with 0.1% fuel sulphur content. The emissions are calculated with factors from the Life Cycle Performance Assessment (LCPA) method as developed within the Seventh Framework Programme (FP7) EU-funded project Joint Operation for Ultra Low Emission Shipping (JOULES) [4].

Table 3. Estimated annual fuel consumption and emissions of the benchmark TSHD

Property	Value	Unit
Fuel consumption	13,000	ton/year
CO_2 emissions	41,000	ton/year
NO_X emissions (as NO_2)	150	ton/year
SO_X emissions (as SO_2)	26	ton/year
PM emissions	17	ton/year

3.5 Modelling plan

The benchmark and SOFC-based concepts will be modelled in MATLAB/Simulink and Python with IHC's proprietary dynamic drive system models/digital twin. Royal IHC has dynamic models of most equipment used on current day dredgers from past internal and external R&D projects.

Some models are currently not available and may have to be developed (in collaboration with the HELENUS partners) such as the fuel cell system model and a suitable control algorithm for the fuel cells.

4. Offshore vessel

The benchmark offshore vessel is Royal IHC's inter-array cable lay vessel (ICLV) T4000-22 (see Figure 3). This type of cable lay vessel (CLV) is utilized for laying cables between the wind turbines in an offshore windfarm [5].

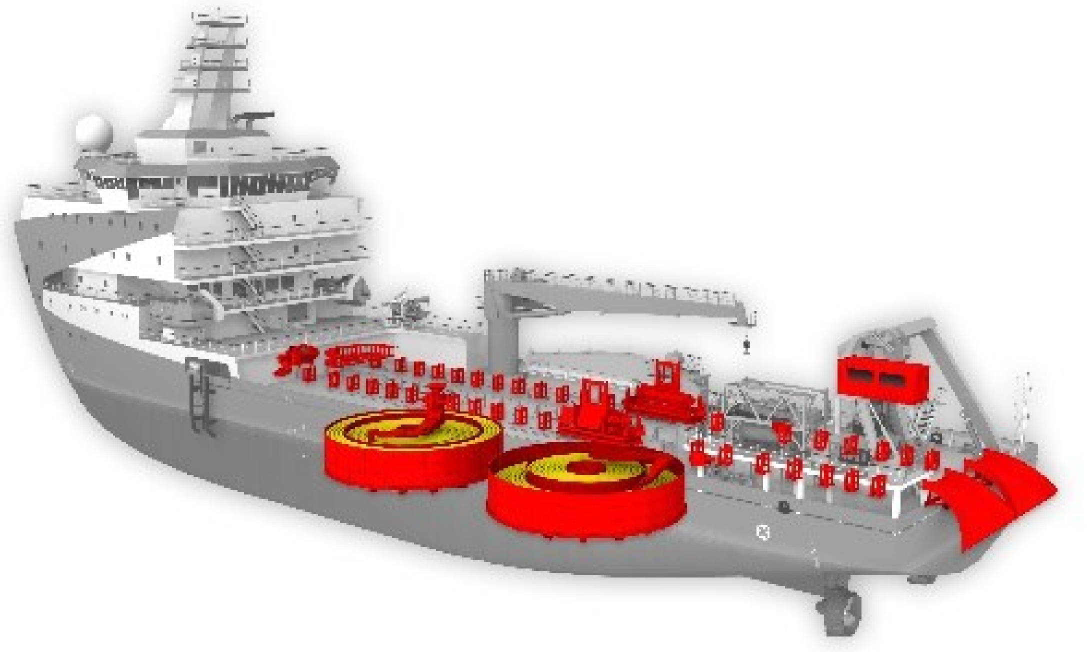

Figure 3 - Artist impression of inter-array cable lay vessel with two carousels

The ICLV sails to the windfarm where it lays cable between the wind turbines and from the wind turbines to the shore connection location. After all the cable has been laid, the ICLV return to port to reload the cables.

These vessels are quite sturdy and have a high installed power/size ratio that enables them to operate in harsh conditions with sufficient power and back-up to be DP3 compliant. Project specifications and environmental conditions lead to a large variation in the use of the installed power. Typically, 50% of the installed power is used.

The currently most common drive train for this type of vessel is a full diesel-electric driven installation. The ICLV can operate on "non-heated fuels" such marine diesel oil (MDO) or marine gasoil (MGO). Table 4 contains the main properties of the Royal IHC ICLV T4000-22.

Table 4. Main characteristics of the Royal IHC ICLV T4000-22 [6]

Characteristics	Value	Unit
Length overall, approx. (LOA)	112.5	m
Length between perpendiculars (LPP)	105.6	m
Breadth	22.0	m
Draft (design)	6.0	m
Design speed	12.0	kt.
Cable capacity	2x 2,000	ton
Total installed power	±6000	kW
Special equipment	Cable lay equipment, cable carrousel, ROV system	

4.1 Operating modes

The ICLV has 5 main operating modes [6], these are:

- Cable laying in calm waters
- Cable laying in harsh waters
- Standby in extreme conditions
- Free sailing (harbour-work location-harbour)
- Loading in harbour

The operational profile/engine load can vary with specific project conditions such as local weather, current and wind conditions, sailing distance between the worksite and the harbour and the cable type and laying depth.

4.2 Annual operational profile

The annual operation profile of the ICLV consists of a repetition of campaigns of 30 days for a round trip from loading cable in the harbour to returning empty in a harbour [6] as shown in Table 5. The majority of the operational profile is spent cable laying in relative calm waters. In harsh waters, the cable laying continues, but it must be interrupted during extreme conditions with the vessel in standby as a result.

The vessel may perform up to 10 of these campaigns per year. The remaining time consists of downtime of the vessel for among others maintenance, repair and refuelling. The annual operation profile will be discussed in more detail in Task 6.3.

Table 5. Estimated operational profile of the benchmark inter array cable lay vessel [6]

Activity	Total load [kW]	Duration [days]
Cable lay in calm waters	2,617	18.6
Cable lay in harsh waters	5,029	4.5

In standby extreme conditions	5,224	2.4
Free sailing	3,517	1.5
Loading cable in harbour	745	3
Total		30 days

4.3 Functional benefit description

The functional benefit of an inter-array cable lay vessel is the length of cable that has been laid on the seafloor. The functional and environmental benefits can be described as:

- kg CO_2/km cable
- kg NO_X/km cable
- etc. (for other emissions)

4.4 Energy consumption and emission estimation

The first estimate of the benchmark ICLV's energy consumption and tank-to-propeller (TTP) emissions for a one-year period may be found in Table 6. These figures are a first estimate and will be refined with more detailed analyses made in Tasks 6.3 and 6.4. This first estimate has been made based the annual operational profile given in Section 4.2 for an IMO NO_X Tier III compliant vessel sailing on low sulphur marine gasoil (LSMGO) with 0.1% fuel sulphur content. The emissions are calculated with factors from the Life Cycle Performance Assessment (LCPA) method as developed within the Seventh Framework Programme (FP7) EU-funded project Joint Operation for Ultra Low Emission Shipping (JOULES) [4].

Table 6. Estimated annual fuel consumption and emissions of the benchmark inter array cable lay vessel

Property	**Value**	**Unit**
Fuel consumption	4400	ton/year
CO_2 emissions	14000	ton/year
NO_X emissions (as NO_2)	44	ton/year
SO_X emissions (as SO_2)	9	ton/year
PM emissions	6	ton/year

4.5 Modelling plan

The benchmark and SOFC-based concepts will be modelled in MATLAB/Simulink and Python with IHC's proprietary dynamic drive system models/digital twin. Royal IHC has dynamic models of most equipment used on current day offshore vessels from past internal and external R&D projects.

Some models are currently not available and may have to be developed (in collaboration with the HELENUS partners) such as the fuel cell system model and a suitable control algorithm for the fuel cells.

5. Conclusion

This deliverable (D6.1) concludes the work performed within HELENUS Task 6.1 and presented the benchmark vessels selected for the three application case studies. This report will serve as a basis for the other tasks within WP6 and for the collaboration with the other HELENUS work packages.

6. Future work

The future work in HELENUS WP6 consists of the following three tasks:

T6.2. Development of SOFC-based zero emissions design vessel configurations with different (renewable) fuel options

- Determine relevant SOFC-based zero-emission designs based on alternative fuel options and the previously determined operational profile. Strive for an energy efficiency increase of at least 20% in the new designs
- Create simplified general arrangement of the concepts to determine the impact of the SOFC and fuel options
- Create basic 3D designs of the most relevant concept

T6.3. Energy grid modelling and simulation of the benchmark- & concept-vessels

- Create (dynamic) models to calculate the energy efficiency and fuel consumption of the concepts and determine the response of the SOFC-based power plant on the vessels operational profile
- Determine the required energy buffer size for the operation and evaluate the effect of the energy buffer size on the energy consumption of the concepts

T6.4. Assessment of the benchmark and concepts on energy efficiency, greenhouse gas and harmful emissions and economic viability

- Determine the environmental and economic impact of the vessel concepts
- Determine the price of the CO2 reduction achieved with the novel SOFC-based concepts

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