Retrofitting towards climate neutrality

D4.3 Third report: End System Requirements & KPI’s

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HISTORY OF CHANGES

Version	Publication Date	Changes
1.0	[04/03/2024]	Draft from D4.2
1.0	[17/05/2024]	Updates added from information from all WPs (meetings and documents)
1.1	[20 – 28 /05/2024]	Inputs from consortium members
1.2	[28/05/2024]	Added and finalised KPIs in executive summary
1.3	[29/05/2024]	Updated version of KPIs and further review
1.3	[19 - 28/06/2024]	Added information about SINTEF Membranes
1.3	[21-28/06/2024]	Review by reviewers specified on page 4
1.4	[01/07/2024]	Revision of draft v1.3
1.5	[16/07/2024]	Revision of draft v1.4
1.5	[30/07/2024]	Submission to EC portal

DETAILS	
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Acronym Table

AI	Artificial Intelligence
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CFD	Computational Fluid Dynamics
H_2	Hydrogen
H_2O	Water
HVAC	Heating, Ventilating and Air Conditioning
ICE	Internal Combustion Engine
IMO	International Maritime Organization
IoT	Internet of Things
KPIs	Key Performance Indicators
LCA	Lifecycle Assessment(s)
MDO	Marine Diesel Oil
NO_x	Nitrous Oxides
Nm^3	Nominal Cubic Meter
PEM	Polymer Electrolyte Membrane
PML	Petronav Shipmanagement Limited
SO_x	Sulphur Oxides
TEA	Technoeconomic Assessment(s)
TEE	Thermoelectric Element
TRL	Technical Readiness Level
UHC	Unburned Hydrocarbon
UV	Ultraviolet radiation
WP	Work Package

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EXECUTIVE SUMMARY

This document is deliverable “D4.3 – Third report: End System Requirements & KPI’s” of the European Union project “Retrofitting towards climate neutrality” (herein referred to as “**Green Marine**”), with **grant agreement No. 101096522**.

The current version of this report contains updates and additions on KPIs and End System Requirements on a per-work package basis. Namely WP1 – WP5 activities:

- WP1 – Demonstrate retrofitting of existing fleets (led by UoS)
- WP2 – Land based testing and integration of solutions (led by CMMI)
- WP3 – Solutions development and scale-up (led by SINTEF)
- WP4 – KPIs, Integration, TEA, SEA, LCA, Risk, Safety (led by UPM)
- WP5 – Software tool catalogue for GHG-emission reduction solutions (led by PDM)

The deliverable mainly targets the technology providers of the consortium which will guide their designs and scale-up for effective land-based testing and eventual integration and retrofit in CalMac’s vessel Coruisk with IMO/LR No.: 9274836. The deliverable also targets the simulation/modelling side in order to guide the consortium for an effective software tool catalogue and estimation of LCAs, for use cases requiring such analysis.

Compared to the previous versions, deliverables D4.1 “First report: End System Requirements & KPI’s” and D4.2 “Second report: End System Requirements & KPI’s” submitted on M1 and M6 respectively contain an updated or extended list of KPIs and End System Requirements as developed during current project activities and discussions. Therefore, the information contained in the current version of the deliverable includes (a) feedback from all Green Marine partners, and (b) information obtained during WP1 – WP5 discussions.

This deliverable is understood to be a “living” document and it is scheduled to be updated on M36 (interim reports) and M48 (final report).

Note that UPM confirmed no changes to the KPIs set in D4.2. CMMI, SINTEF, UoS, SMP/WPS, BX, CalMac, and PDM suggested adjustments, thus a summary of the Key KPIs of the Green Marine project extracted from this report is shown below.

Flue gas composition

Entry	***Demand / requirement***	***Unit***	***Average value***	***Minimum value***	***Maximum value***
1.1	***Land Based test site WP2***				
1.1.1	Flue gas flow	kg/hr	Not applicable	640	660
1.1.2	Exhaust temperature	°C	Depends on engine load	360	450
1.1.3	CO_2 concentration	% vol.	Depends on engine load	7%	9%
1.1.4	Flue gas flow provided for testing to be provided via a bypass system	Nm^3/hr	Not applicable	50	150
1.1.5	Load bank – resistive	kW	Not applicable	25	200

1.1.6	CO_2 capture rate goal	%	To be determined	35%	To be determined
1.1.7	Impurities in flue gas	ppm	To be determined during measurements (depends on engine load)	CO: 158 NO_x: 145 O_2: 16 UHC: 770 SO_x: 0.0* *MDO used as fuel	CO: 425 NO_x: 957 O_2: 8.5 UHC: 540 SO_x: 0.0*
1.1.8	Water content in flue gas	% vol.	To be determined during testing (depends on weather conditions)	3%	10%
1.1.9	Engine Specs	155 kW engine, 8.3 lt displacement, 6 cylinder turbocharged and aftercooled.			
1.1.10	Maximum backpressure in the engine	kPa	Not applicable	5.0	10.1
1.2	***Onboard MV Coruisk – WP1 demonstrations***				
1.2.1	Flue gas flow*	kg/hr	Not applicable	640	660
1.2.2	Exhaust temperature	°C	Depends on engine load	360	450
1.2.3	CO_2 concentration	% vol.	Depends on engine load	7%	9%
1.2.4	Flue gas flow provided for testing	Nm^3/hr	Not applicable	50	150
1.2.5	Engine load	% of rated engine power	To be determined during demonstrations	65%	80%
1.2.6	CO_2 capture rate goal	%	To be determined	35%	To be determined
1.2.7	Impurities in flue gas	ppm	To be determined during demonstrations (depends on engine load)	To be determined during demonstrations (depends on engine load)	To be determined during demonstrations (depends on engine load)
1.2.8	Water content in flue gas	% vol.	To be determined during testing (depends on weather conditions)	3%	10%
1.2.9	Engine specs	164 kW engine, 8.3 lt displacement, 6 cylinder turbocharged and aftercooled			
1.2.10	Maximum backpressure in the engine	kPa	Not applicable	0.0	10.1

* To be revised/confirmed in future versions of this report.

Carbon Capture Machine

Entry	***Demand / requirement***	***Unit***	***Average value***	***Minimum value***	***Maximum value***
2.1	***CCM – CO_2 capture***				
2.1.1	CO_2 removal from flue -gas	%	>50%**	>35%	
2.1.2	Operating range heat-exchanger: flue-gas engine to CCM unit	°C	25	25	180
2.1.3	CO_2 conversion rate	%	>85%**		
2.1.4	Carbon capture rate	Kg/hour	1 kton/year	60	120
2.1.5	Power consumption	kW	TBD	TBD	TBD
2.1.6	Flue gas flow	Nm^3/hr		50	150
2.2	***CCM – physical attributes***				
2.2.1	Dimensions – complete capture unit	mm	20-foot container		
2.2.2	Weight–capture unit	kg	TBC		
2.2.3	Operating temperature	°C		-10	65
2.2.4	Dimensions – Chemicals storage unit	mm	TBC	TBC	TBC
2.2.5	Weight – Chemicals storage unit	kg	TBC		
2.2.6	Dimensions – Product storage unit	mm	TBC		
2.2.7	Weight – Product storage unit	kg	TBC	TBC	TBC

** target value

SepaRaptor

Entry	***Demand / requirement***	***Unit***	***Average value***	***Minimum value***	***Maximum value***
3.1	***SepaRaptor with UV in ventilation system Coruisk***				
3.1.1	Air filter used in Coruisk	Standard Euro 4 dust/dirt filter to prevent outdoor foreign contaminants			
3.1.2	Particle Efficiency removal SepaRaptor	%	Not applicable	>90% nanoparticles >95% aerosols, viruses	>99.9% viruses >99.99%
3.1.3	HVAC energy savings (air reuse increase). Pressure drop in the HVAC system	%	50 <1%	The vessel has an open loop system. Ventilation system not HVAC. KPI's are not applicable	
3.1.4	Dimensions	mm	900 x 175 x 165		
3.1.5	Weight	kg	8.4		
3.1.6	Temperature	°C		5	65
3.1.7	Humidity range	%		5	99.9
3.1.8	Flow rate of ambient air	m^3/h		1	> 1000
3.1.9	Exposure time for UV to be effective	s	TBD	TBD	TBD

3.1.10	Power supply / Input power	V, A		12 V and 12 A, 100 – 240 V, 50/60 Hz 1.4 A	
3.1.11	Power draw	W		15	
3.2	***SepaRaptor – flue-gas CO_2 capture***				
3.2.1	Flow rate of flue gas	Nm^3/hr		50	150
3.2.2	Particle Efficiency removal SepaRaptor	%	>80%		
3.2.3	Dimensions	mm	900 x 175 x 165		
3.2.4	Weight	kg	8.4		
3.2.5	Temperature	°C		5	65
3.2.6	Humidity range	%		5	99.9
3.2.7	Power supply / Input power	V, A		12 V and 12 A, 100 – 240 V, 50/60 Hz 1.4 A	
3.2.8	Power draw	W		15	

Membranes

Entry	***Demand / requirement***	***Unit***	***Average value***	***Minimum value***	***Maximum value***
4.1	***Membranes***				
4.1.1	CO_2 capture rate	%		>35%	>90% (in theory)
4.1.2	CO_2 product purity	%		>40%	>95%
4.1.3	CO_2 concentration diesel exhaust	Vol%(dry)	5	3	8
4.1.4	Specific compressor duty	MJ/kg CO_2	50	To be determined during WP2 tests	To be determined during WP2 tests
4.1.5	Specific membrane area	m^2	10	1	20
4.1.6	Membrane module dimensions (depends on final membrane area; see 4.1.5)	mm	Length 500 to 1000, diameter 100 to 200		
4.1.7	Weight of membrane module	kg	4 to 12		
4.1.8	Retentate pressure	kPa	130		
4.1.9	Permeate pressure	kPa	5 to 25		
4.1.10	Permeate flow rate	m^3(STP)/hr	to be determined during experiments		
4.1.11	Temperature of cooling water	°C	5-15		
4.1.12	Temperature vacuum pump exit	°C	55		
Parameters of flue gas conditioning skid					
4.1.13	Weight - Water cooler (empty/filled)	kg	(32/35)		
4.1.14	Dimensions – Water cooler	Mm	420 x 180 x 480		
4.1.15	Weight - Freshwater circulation pump	kg	to be determined		
4.1.16	Weight - FG cooler (empty/filled)	kg	(16/21)		

4.1.17	Dimensions – FG cooler (empty/filled)	mm	229 x 216 x 363		
	Flue gas fan				
4.1.18	Weight	kg	53		
4.1.19	Dimensions	mm	528 x 656 x 420		
4.1.20	Operating temperature	°C	55		
4.1.21	**Membrane-based CO$_2$ capture unit**				
4.1.22	Weight - Membrane module	kg	4-10		
4.1.23	Weight - Total unit	kg	30		
4.1.24	Weight – vacuum pump	kg	15		
4.1.25	Dimensions – vacuum pump	mm	198 x 328 x 243		
4.1.26	Temperature	°C		15	60
4.1.27	Humidity range	%		50	100%
4.1.28	Flow rate of flue gas	Nm^3/h		50	150
4.1.29	Permeate flow (required to determine analytical equipment)	Liter/hour		1 % of feed	10% of feed
4.1.30	Power supply / Input power for industrial fan	V, A		3 phase, 400V 50 Hz max 1 A	
4.1.31	Power supply / Input power for control systems and vacuum pump	V,A		Residential 200-230V/50/60Hz max 2.5 A	
4.1.32	Power draw	W		To be determined	

Thermo Electric Element (TEE)

Entry	***Demand / requirement***	***Unit***	***Average value***	***Minimum value***	***Maximum value***
5.1	***TEE***				
5.1.1	Number of TEE elements	Number	625		
5.1.2	Dimensions	mm	781 x 510 x 1160		
5.1.3	Weight	kg	110		
5.1.4	Temperature range coolant (direct)	°C	$T_{in} = 95$	75	99
5.1.5	Temperature range fluegas (indirect)	°C	$T_{in} = 105$	45	105
5.1.6	Thermal conversion efficiency	%	Up to 1.6		
5.1.7	Humidity range	%		5	99
5.1.8	Flow rate of coolant	m^3/h	TBC	6.6	10.2
5.1.9	Power output	V		24 V DC	
5.1.10	Power generation	W		500	

Software tool catalogue

Entry	*Demand / requirement*	*Unit*	*Average value*	*Minimum value*	*Maximum value*
6.1	*Software framework*				
6.1.1	Opensource user friendly GUI with multiple visual interfaces. Approval rate from end user feedback	%		>80	
6.1.2	Development of high quality technical documentation. Approval rate from end user feedback Measurement of users ability to perform tasks after reading the documentation	%		>80 >70	
6.1.3	Approval rate from end user feedback (time spent on site and number of clicks	Number of clicks and min.	Visit: 3, time: <10min, average clicks: < 30 Visit: 5, time: <5min, average clicks: < 20 Visit: 10, time: <2min, average clicks: < 15		
6.1.4	Organisation management configuration & administration features. Approval rate from Organisation Administrators configuration and features from user feedback	%		> 80%	
6.1.5	Usage of functionalities regarding Organisation management configuration & administration by Organisation Administrators	%		>70%	
6.1.6	Target uptime	%		M37-39: 90% M40-48: 95%	
6.1.7	Simulations per month	Number		M37-39: 60 M40-42: 120 M43-48: 200	
6.1.8	Use case definition	Number		50 user stories 100 technical requirements	

1. INTRODUCTION

The main objective of **Green Marine** is to significantly accelerate climate neutrality of waterborne transport through retrofitting existing fleets with cost and emission control solutions. To support decision makers retrofitting protocols and a software tool catalogue that gathers knowledge will be developed and validated. We will demonstrate these tools and the innovative solutions aimed at carbon capture mineralization, which also aids in deacidifying our seas; energy savings for HVAC systems through air-reuse; carbon and water as a side product capture with membranes, and the use of excess engine heat to produce a syngas to save on fuel consumption. An ultra-sound technology will be tailored to suit vessels (such as cruiseships) allowing air-reuse saving energy for HVAC systems and operated as pre-treatment enhancing a membrane carbon capture process. For MV Coruisk, the Separaptor with UV technology will be tested in the ventilation system of the vessel. The Ca/Mg – alkali solvent capture process is capable of removing 75% of the CO_2 from flue gases. All solutions will be theoretically evaluated before demonstration on a land-based engine followed by the selection of the most suitable solution for a demonstration on a waterborne vessel. The (land-based) demonstrations will be representative for the operation of a majority of vessel engines in use currently. By developing retrofitting protocols, simulations of the solutions, data generated at the demonstrations a software catalogue tool will be developed. Through engagement activities this tool will gain more users and more knowledge, its value and effectiveness will increase for all users. The project aims to bring the different solutions to TRL 8. The demonstrations, the software tool catalogue, and the dissemination and exploitation activities ensure that project results will be replicated globally. The consortium consists of 10 partners from 7 countries with 4 research institutes, 1 shipping company, which will host a demo as end user and 5 SMEs.

The objectives of WP4 – KPIs, Integration, TEA, SEA, LCA, Risk, Safety, & Legal Evaluations are to evaluate the Demos, aid in cross-cutting activities and prepare for software tool integration of data:

- Provide a set of requirements for CCUS and relevant KPIs in terms of materials, end user design and quality monitoring, regulatory compliance, in order to help guide the Green Marine project and conduct evaluations.
- Quality, Safety, Environmental & Health (QSEH) control: ensure project goals in terms of QSEH can be achieved; making use of quality document & standards (align with Project Handbook).
- Risk (and Safety): conduct a Safety assessment for all demonstration activities.
- Perform evaluations on: Techno-economic evaluations (TEA) of at least 2 solutions based on preliminary land-based results and at least 2 assessments for vessels. Conduct Life Cycle Assessment (LCA), social economic assessment (SEA) for the technical solutions.
- Benchmark against alternative CO_2 capture technologies and investigate compatibility of 3rd party data to our platform.
- Internal exploitation: to determine the business case for end-users.

1.1 PURPOSE OF THE DOCUMENT

Task 4.1 is about the definition of End System Requirements & KPIs. In particular, Task 4.1 entails:

- Identification of technology requirements for the proposed retrofitting solutions.
- Definition of KPIs for the demonstrations. Towards the demonstrations and commercial application, the documented requirements will be updated regularly based on progressive insight throughout project execution.
- Definition of requirements and KPIs for the software tool, which will include for e.g., GUI, API interface. These KPIs will be used as evaluation method for future use, validation and application.

This report is an update of deliverables D4.1 “First report: End System Requirements and KPI’s” submitted on M1 and D4.2 “Second report: End System Requirements and KPI’s” submitted on M6. Following updates of this deliverable will be submitted on M36 (interim report) and M48 (final report). Therefore, this is a “live” document which will be monitored and updated as needed throughout project activities. Note, the first and second versions of this report included feedback and preliminary requirements of the technologies to be tested. These have been obtained from partners at the Green Marine Kick-Off Meeting (15th-16th February 2023, Larnaca, Cyprus; physical and online participation) and subsequent meetings. Note that information contained in the current version of the report includes updates or feedback (a) from all Green Marine partners, and (b) information obtained during WP1 – WP5 discussions, which involves all corresponding Work Package and Task Leaders. Also note that feedback from this report and its upcoming revisions will be fed into the aforementioned work packages, namely:

- WP1 – Demonstrate retrofitting of existing fleets (led by UoS)
- WP2 – Land based testing and integration of solutions (led by CMMI)
- WP3 – Solutions development and scale-up (led by SINTEF)
- WP4 – KPIs, Integration, TEA, SEA, LCA, Risk, Safety (led by UPM)
- WP5 – Software tool catalogue for GHG-emission reduction solutions (led by PDM)

Also note that at this early stage of the report, some KPIs and End System Requirements are preliminary and thus qualitive and quantitative KPIs are described.

1.2 DOCUMENT STRUCTURE

§2 describes the KPIs and End System Requirements related to WP3 - Solutions development and scale-up.

§3 describes the KPIs and End System Requirements related to WP2 - Land based testing and integration of solutions

§4 describes the KPIs and End System Requirements related to WP4 - KPIs, Integration, TEA, SEA, LCA, Risk, Safety, in particular to the LCA analyses.

§5 describes the KPIs and End System Requirements related to WP5 - Software tool catalogue for GHG-emission reduction solutions.

§6 describes the KPIs and End System Requirements related to WP1 - Demonstrate retrofitting of existing fleets.

§7 presents the conclusions of this report.

2. KPIS AND SYSTEM REQUIREMENTS ON A PER GREEN MARINE TECHNOLOGICAL SOLUTION LINKED TO WP3

2.1. CARBON CAPTURE MACHINE (CCM)

CCM’s core land-based carbon capture and utilisation (CCU) technology is presently at TRL 5 with several ongoing industrial applications underway to achieve TRL 8-9. However, the focus of Green Marine requires adaptation of this core technology for marine applications which bring specific challenges, regulations, and performance characteristics. In this case, it is essential to verify the broader design specifications prior to implementation of system construction and testing.


3D rendering of CCM 200 kg CO2/day pilot (for reference only).

Family of containerized CCM land-based solutions presently in development

Customized maritime decarbonization CCM concept for Green Marine

Figure 1. The standard CCM process and design will be customized for maritime applications.

CCM has already begun testing of individual components and subsystems to confirm feasibility and performance to TRL 5, but the complete definition of KPIs and end system requirements will mature in later versions of the report. The preliminary KPIs and End System Requirements of Carbon Capture Machine include the following:

- Size: Estimated to fit in the volume of a typical 20ft container; but to be designed in a modular framework to use available space at land-based testing and vessel-based demonstrations/integration.
- The CCM ‘Green Marine’ modules will include:
    - Emission diversion, cooling, treatment
    - CO_2 Capture
    - CO_2 Conversion
    - Carbonate Utilization and Dissemination
- Storage requirements of chemicals
    - The system will require on-board storage of Sodium Hydroxide (NaOH). The size of the storage area and/or tank will be sized in relation to the anticipated test duration (e.g., 250 hours)

- The emissions of both the land-based marine genset and the CalMac vessel-based auxiliary engines have a relatively high output temperature, so the CCM system requires a heat exchanger to cool the emission to approximately 25°C.
- Demonstrate GHG emission reduction >35%:
    - Target CO_2 capture efficiency >50%
    - Target CO_2 conversion efficiency >85%
- The CCM solution will optimize energy consumption to ensure demonstrable CO_2 removal (CDR) as verified by Life Cycle Assessment (LCA). Energy efficiency will be a determining factor whether to utilize Reverse Osmosis (RO) or water evaporation technology to produce the necessary concentration of brine.
- Preliminary specification for carbon capture is 60-120 kg CO_2/hr (1 ktCO_2/yr).
- Low CAPEX and OPEX with significant cost advantage versus direct competition due to the production of valuable carbonate end-products.
- Minimum electricity consumption.

2.2. SEPARAPTOR WITH UV (SPM/WPS)

The main benefit of the SepaRaptor is the agglomeration of nano-particles (5-300 nm) to micro-particles (2-6 µm) which will enable their eventual removal from the air and flue gas. Appendix A in D4.2 provides additional explanations on how the SepaRaptor technology works . HEPA, high efficiency performance filters, have a filter gap for air filtration at nano-size range. As per Appendix A, the following KPIs regarding SepaRaptor:

- Typical HVAC filters have an MPPS around 200–300 nm, whereas the MPPS of high efficiency (HEPA and ULPA) filters is smaller, according to ISO 29463 mostly in the range from 120 nm to 250 nm. This is exactly the size of the SARS CoV-2 where the HEPA and ULPA filter exhibit the lowest filter efficiency.
- Efficiency removal: nanoparticles >90% and >95% aerosols, viruses.
- Use low cost and durable equipment, electric consumption piezos: it is estimated a 20 – 40% OPEX improvement on membranes operation for CO_2 capture form flue gas when separator is used as a pretreatment to remove particulate matter in front of membrane separation.
- 50% HVAC energy savings (air reuse increase).
- 99.9% removal of viruses for air ventilation systems.
- The maximum efficiency found in this study was approximately 35% for F7 HEPA Filter systems.

In terms of measurements, a SMPS (scanning mobility particle sizing) device is needed to measure the size of the particles before and after the SepaRaptor for effective monitoring.

Properties that affect toxicity: To be quantified at later versions/updates of this report

- Size is a key factor in determining the potential toxicity of a particle,
- Chemical composition,
- Shape,
- Surface structure,

- Surface charge,
- Aggregation and solubility, and
- Presence or absence of functional groups of other chemicals.

The large number of variables influencing toxicity means that it is difficult to generalize about health risks associated with exposure to nanomaterials – **each new nanomaterial must be assessed individually, and all material properties must be taken into account**.

As there is no HVAC system and no HEPA filter on board of the MV Coruisk the consortium plans to carry out a pilot test, which can serve as a reference for larger ships (e.g. cruise ships). To this end, the Separaptor cubes are to be set up in the crew rooms and the bridge of the vessel. Crew members should also be persuaded to take the devices home and install them there (to be verified in future versions of this report).

A clinical study together with an external laboratory and physician will be performed to assess the results and performance of the standalone system.

These activities aim to save a lot of energy on larger ships with HVAC systems, as air can circulate more frequently and a new airflow would not have to be constantly provided.

2.2.1 Process Flow Diagram for SepaRaptor with UV

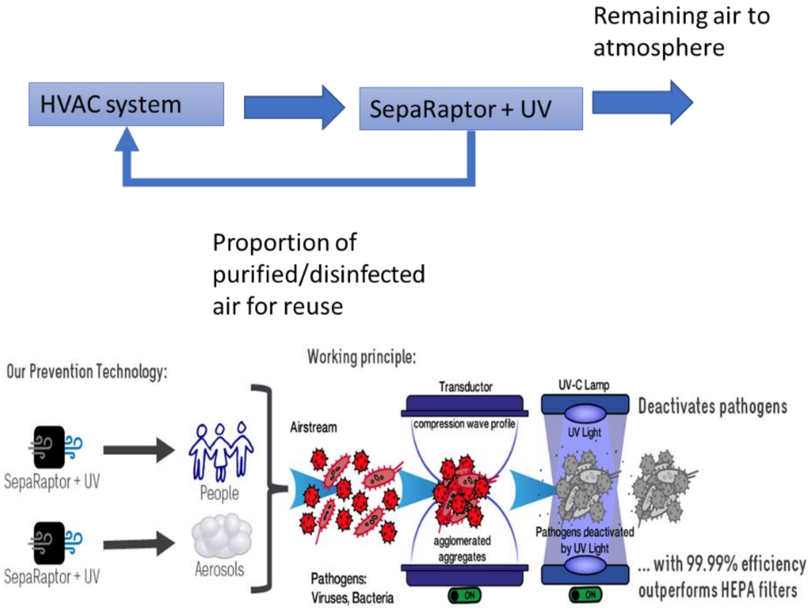


Figure 2. Process Flow Diagram for vessels with HVAC system (such as cruiseships) and relevant retrofits utilizing the SepaRaptor + UV light.

Figure 3. Stand-alone unit Separaptor + UV. Dimensions of 900 mm x 175 mm x 165 mm, weight = 8.4 kg. Operating temperature range 5 – 65 ºC, humidity range 5 – 99.9 %, and ambient air flow rates of 1 – 1,000 m^3/h.

Note that Figure 2 illustrates the concept of SepaRaptor with a UV system for vessels, such as cruise ships, with an HVAC system. MV Coruisk has only a ventilation system, and therefore standalone units (see Figure 3) of the SepaRaptor with UV system will be tested in the crew cabins to prove its effectiveness and reliability.

Preliminary KPIs (to be reassessed in future versions of this report):

- Standalone units in crew cabins/bridge on MV Coruisk
- Power requirements of standalone unit ≈ 15W
- Power supply of 12V and 12 A, 100 – 240 V, 50/60 Hz 1.4 A
- Throughput flow rate of ambient air 1 – 1,000 m^3/h
- Expected Pressure drop: <1%
- Expected exposure time for UV to be effective (to be determined)
- Expected mass (or flow) rate needed to remove 99.99% efficiency that will outperform the HEPA filters, where appropriate (eg cruise ships). No HEPA filters on-board MV Coruisk
- See §5.4.2. for expected KPIs of HVAC system

2.3. SEPARAPTOR WITH FLUE GASES (SPM/WPS)

Preliminary KPIs for flue gases (to be reassessed in future versions of this report):

- Expected dimensions- 900 x 175 x 165 mm (as per Figure 3)
- Expected Weight - 8.4 kg (as per Figure 3)
- Temperature range - 5°C – 65°C (as per Figure 3)
- Humidity range - 5 – 99.9% (as per Figure 3)
- Flow rate of flue gas – 1 - 1512 m^3/h (420 L / sec)
- Power supply - 12 V, 12.0 A
- Input power -100 – 240 V, 50/60 Hz 1.4 A
- Power draw ≈ 15 W

2.3. THERMOELECTRIC ELEMENT - TEE (SPM/WPS)

The genset is water-cooled to avoid a different setup from the demonstrations of WP1. In the event of an air-cooled engine, the TEE heat exchanger will be modified accordingly by designing, building, and testing a new system.

The additional benefit of water-cooled TEE for marine engines is that we close the coolant loop and thus, there is no potential pollution of the environment by chemicals like oils.

The KPI of the electricity energy gain is to be determined in the following reports after the complete definition of the overall system requirements. However, on a preliminary basis, it can be mentioned that 0.5 kW of energy may be generated if the unit is supplied with a constant flow of hot and cold water. Table 1 illustrates the preliminary KPIs.

The two scenarios are described as follows:

- Direct: direct coolant line, that is connected to the engine cooling system.

- Indirect: a coolant line that exchanges heat with either flue gas or engine heat but is not directly connected to the engine

Table 1. Preliminary KPIs for the TEE. Water as working fluid selection. Protection of piping from thermal, mechanical and chemical effects with coating

Parameter	**Value**
Dimensions (length x width x height)	781 x 510 x 1160 mm
Weight	110 kg
Temperature range coolant (direct)	75 – 99 °C T_{in} = 95 °C
Temperature range fluegas (indirect)	45 – 105 °C T_{in} = 105 °C
Humidity range	5 – 99%
Coolant flow	Successful tests up to now: 6.6 L/min
Power generation (per unit)	0.5 kW
Output	24 V DC

2.4. PEM MEMBRANES - (SMP/WPS)

Syngas and its associated pathways including PEM membranes have been evaluated in D2.1 “Preliminary report on results of land-based testing” due to technical difficulties for on-board syngas production as well an overall negative energy balance from production and consumption of syngas on-board. As such PEM membranes will not be further examined.

2.5. THORSPIN UNIT - (SMP/WPS)

Syngas and its associated pathways including the ThorSpin unit have been evaluated in D2.1 “Preliminary report on results of land-based testing” and due to technical difficulties for on-board syngas production as well an overall negative energy balance from production and consumption of syngas on-board. As such the ThorSpin Unit will not be further examined.

2.6. CO_2 MEMBRANES - (SINTEF)

The following KPIs and end system requirements are expected (or defined if not yet known):

- The base case for the current capture technology assessment is a capture from flue gas for a ship engine running at 66% load producing 50-150 Nm^3/h flue gas with a CO_2 content in the range 3-9 vol% (wet) with Diesel as fuel.
- Aim is a CO_2 recovery of >35%
- Membrane KPIs: CO_2/N_2 selectivity 50-100, CO_2 permeability up to 1000 Barrer. Maintain or increase permeability & selectivity ≥100
- Membrane area: >1.0 and up10 m^2 per module for land-based testing, up to 2x 10 m^2 semi-commercial module size on ship testing
    - Membrane area installed per module will depend on commercial membrane manufacturer specifications and availability. Several smaller modules can be combined to achieve the required membrane area.
    - Two membrane geometries are developed in parallel and tested in the SINTEF laboratory at a laboratory scale (20- 500 cm^2 area) using synthetic exhaust gas 5% and 10% CO_2 in N_2, fully humidified at temperatures between 25 and 55 °C and at atmospheric pressure:
        - flat sheet membrane: facile fabrication in the laboratory but more challenging to upscale the module area. Membranes will be packed in frame-by-frame or spiral wound type of membrane modules
        - hollow fibre modules: more challenging membrane fabrication but more facile upscaling of the module membrane area
    - Performance of both options to be determined and then decide the optimum membrane geometry and area to be used in WP2.
    - Process simulation for CO_2 capture using membranes is ongoing using the CoCo simulator based on flat sheet membrane lab-based results. Several process configurations with one or multiple membrane separation stages are investigated in terms of energy consumption, membrane area needed, and CO_2 capture rate and purity.
- Water recovery as a by-product: The possibility of recovering water vapour is to be determined to avoid membrane flooding. Drainage or onboard storage will be needed to handle the condensed water vapour from the flue gas and recover the high-water purity water for other use on the ship.
- The polymer membranes operate in the temperature range 25 - 100 °C and cooling of the engine exhaust is therefore required. For the current assessment this is accomplished using a water cooling circuit where surplus heat is released to seawater in the case of the offshore testing (this will be achieved via a commercial standard heat exchanger).

The effect of pretreatment of diesel exhaust for particulate removal by SepaRaptor in front of membrane separation will be possible to investigate only on WP2 land-based testing using real diesel exhaust gas. Test with and without flue gas pretreatments should be performed to assess the effect of pretreatment on membrane performances and lifetime: KPIs strongly depend on genset final specifications and engine size (amount of CO_2 in flue gases).

The KPIs and end system requirements are derived from SINTEF research activities related to CO_2 capture [1, 2, 3, 4].

Regarding the CO_2 capture membranes, it is proposed to have either a one-stage or two-stage process. Depending on the number of stages CO_2 content can reach up to 80% (see Figure 4) or over 95 %, as required for transport and storage in CCUS.

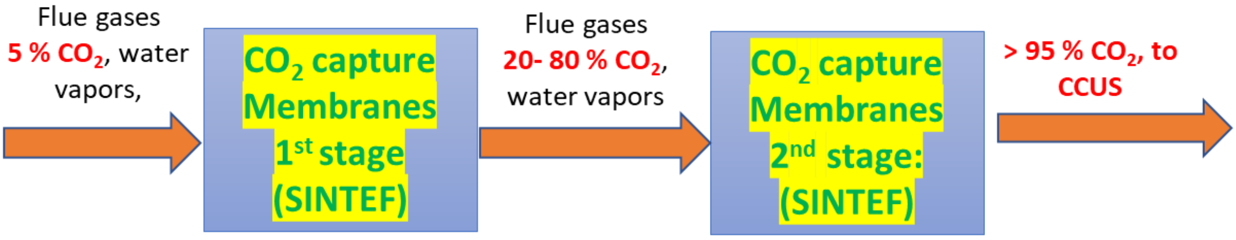


Figure 4. Conceptual use of two-stage CO_2 capture membranes. The number of stages to be determined in later versions of this report and WP3 activities (i.e. depends on WP3 test results and discussions with suppliers). Expected CO_2 capture efficiencies are shown (expected KPIs).

For the pilot tests (land-based and demonstrations) only one stage will be used. Then the performance data from testing together with process simulations will be used to estimate the performance of the 2-stage system. Therefore, the number of stages will be determined in future versions of this report and WP3 activities. This will help the decision on the number of stages at the commercial level. The final decision will depend on CAPEX, OPEX, RoI and CO_2 stream purity (aiming for >95% as per Figure 4).

The pilot unit tests both land-based test and onshore application which will consist of at least two skid-mounted units can be described by the following functional units:

- Flue gas conditioning – for cooling of engine exhaust, removal of water condensate and feeding of conditioned flue gas to the membrane unit. Consist of water cooler, and freshwater circulation pump with connecting pipes.
- The membrane-based CO_2 capture unit produces CO_2-enriched flue gas for storage while CO_2-depleted flue gas is released to the exhaust stack. Since the pilot is only intended to demonstrate CO_2 capture also the CO_2 enriched flue gas will be released to the exhaust stack, after analysis. It consists of membrane-based CO_2 capture unit skid, and a membrane module. Vacuum pump, pressure control valve, and associated piping and instrumentation.
- The flue gas fan is a separate unit connecting the two skids.

The pilot is connected to the "land-based test facilities/ship infrastructure" which provides access to exhaust from the ship engines, access to the exhaust stack for disposal of treated exhaust gas, access to seawater for cooling and finally storage of condensate water from the treated exhaust gas. In addition, sensor information is provided characterising the amount and quality of the available exhaust gas. The pilot is designed to ensure no interference with the operation of the ship engine. It is a requirement that the CO_2 capture process will not create an increase in back pressure in the exhaust channel and that the CO_2 capture unit can be shut down or malfunction without affecting the operation of the ship engine.

2.6.1 Flue gas conditioning

Hot flue gas will be available from the existing engine exhaust pipeline leading to the stack. Flue gas for the pilot will be sucked from the existing engine exhaust pipeline by the "Flue gas fan" in the pilot. Flue gas cooling will take place in the "FG cooler" which is a compact plate heat exchanger operated with a fresh water/glycol mixture as cooling media in a closed loop cooling circuit. The closed loop freshwater circuit will be heat exchanged in the "Water cooler", a gasket plate heat exchanger, which uses seawater as cooling media in an open-loop cooling circuit. This will lead to the discharge of sea water which has been heated by less than 10 ℃ in the "Water cooler". The cooled flue gas exiting from the "FG cooler" will be passed through a water condensate trap to remove condensed water at a maximum rate of 10 kg/h. The flue gas will continue to the "Flue gas fan" which will deliver the flue gas at a slightly elevated pressure (< 30 kPa gauge) to the membrane separation unit.

2.6.2 Membrane-based CO2 capture unit

A single-stage membrane-based CO_2 capture unit will be used to demonstrate the project objective demonstrating 35 % CO_2 capture from a ship engine producing. The CO_2 purity from a single-stage unit will not be suitable for CO_2 liquefaction (< 90 vol% CO_2) but will be sufficient to demonstrate the applicability of the selected membranes. Experimental results from the single stage pilot unit will be used in process simulations to document the performance of a two-stage membrane system which will be able to deliver > 95vol% CO_2 purity with > 35 % CO_2 capture rate.

The membrane unit consists of one hollow fibre membrane module. For the land-based testing, a module with a membrane area between $1m^2$ and $10m^2$ will be used, while for the ship-based testing, modules with a 10 m^2 membrane area will be installed. A backpressure control valve will be installed on the CO_2-depleted retentate stream to maintain the slight overpressure on the feed side over the membrane which is provided by the "Flue gas fan". The pressure difference across the dense polymer membrane will be provided by the permeate "Vacuum pump". A water condensate trap will be installed upstream of the "Vacuum pump" to protect the vacuum pump from water condensate. This will only be operated manually prior to start-up and will be normally closed during operation as no water is expected to form during operation. The vacuum pump will operate with an absolute suction pressure of down to 5 kPa. Suction pressure will be varied between 50 and 5 Kpa through testing. A water condensate trap2 will be installed downstream of the "Vacuum pump" to gather any condensate prior to the flue gas analysis sensor (QT-CO_2) to be installed in the CO_2 product line.

2.6.3 Pilot control strategies

The membrane pilot will be equipped with instrumentation. The instrumentation, as indicated in § 2.5 in D2.1—Preliminary Report on Results of Land-Based Testing also includes signals from on-shore and ship infrastructure. Some additional components used for demonstrations are piping, valves, connectors between components, fresh and sea water circulating pump, FG condensed water trap VP condensed water trap, and waste water storage.

All relevant signals will be linked to a dedicated PLC (programable logic computer) which will be part of the membrane pilot. The PLC will implement the necessary process control logic, including a software-based emergency shutdown system. Storage and retrieval of process data will also be linked to the PLC. The ambition is to provide remote access to process data and potentially a link to a digital twin solution. In addition, control loops will be installed for securing a stable operation of the pilot unit.

2.6.4 Operational method

The pilot will be designed for operation in two modes.

1. Dynamic mode:

The CO_2 capture process follows the engine duty and processes available engine exhaust up to the pilot's maximum capacity.

Data generated will help validate the performance of the CO_2 capture process during the transient/normal operation of the engine. Dynamic mode time series of data may also be valuable for the digital twin activity in WP5.

This mode of operation is most relevant for ship testing but can be tested also during land-based testing.

2. Campaign mode:

The CO_2 capture process operates with a constant set point for Conditioned flue gas flow rate, preferably with constant engine load to avoid variations in CO_2 concentrations. Campaign mode is suitable for validation of membrane module performance, capture rates and separation characteristics during steady state operation.

This mode of operation is most relevant for land-based testing.

In both modes the control loops for flue gas temperature downstream the FG cooler”, the membrane permeate and retentate pressures will be set at predetermined set-points.

2.7. SYNGAS AS A DUAL FUEL

Syngas has been evaluated in D2.1 “Preliminary report on results of land-based testing” and due to technical difficulties for on-board syngas production as well an overall negative energy balance from production and consumption of syngas on-board. Therefore, syngas retrofits for reinjection will not be further examined.

3. LAND BASED ENGINE TESTS LINKED TO WP2

WP2 activities entail the retrofitting of a land-based engine with the carbon and capture technologies (that includes SINTEF's membranes, CCM's technology and the SepaRaptor and Thermoelectric Element; TEE by SMP). The genset will be first mapped and tested with emissions measuring equipment provided by CMMI and the electric energy gain by the TEE. The land-based activities include:

- Engine to be tested for approximately for up to 250 hrs (exact duration to be determined in following reports)
- Support the installation of the carbon capture machine by CCM, CO_2 capture membranes by SINTEF and SepaRaptor by SMP/WPS
- Verification and compatibility of genset with technology providers (CCM, SINTEF, WPS & SMP)

3.1 DUTIES OF ENVIRONMENT, HEALTH & SAFETY OFFICER FOR LAND BASED TESTING

The duties and responsibilities of the Environment, Health & Safety (EHS) officer for land-based testing (WP2) have been defined in the Project Management Handbook (D7.2). The allocated EHS manager for WP2 activities is Mr Angelos Ktoris (CMMI). Revision of the site inspections after receiving feedback from the allocated subcontractor:

WP2 Land based site inspections

The EHS WP2 officer together with the allocated subcontractor's internal EHS will:

1. check the allocated subcontractors site health, safety and any other relevant policies and procedures and if needed align them with **Green Marine** land-based testing activities. This also includes information-related documents (manuals, specifications, TDS, MSDS, etc) for all equipment and any chemicals to be kept at the allocated subcontractor's facilities and are going to be used for Green Marine. The information will be incorporated within the subcontractor's Health & Safety Manual for safety handling and maintenance purposes;
2. evaluate land-based site inspection procedures (§5.1) included in "D2.1 - Preliminary report on results of land-based testing" submitted on M17;
3. collect feedback from all technology providers to produce health & safety guidance and guidelines for appropriate use based on operational requirements during testing and validations;
4. consolidate the **Green Marine** technologies with the subcontractor's guidelines and procedures (points 2 and 3) in the form of a checklist for on-site enforcement;
5. oversee the use of protective Personal Equipment (PPE), such as the use of protective helmets, overalls, goggles, gloves, masks, eye protection, etc. which is the responsibility of the technology provider;
6. ensure during site inspections that the proposed experimental methodology is adhered to and if needed adjustments to be carried out on-site with the collaboration of the WP2 leader, technology providers and the allocated subcontractor;

7. offer training on health and safety and disseminate health and safety brochures at the first site visit before the commencement of testing activities (induction course).

3.2 LAND BASED TESTING OF DEVELOPED SOLUTIONS

3.2.1. Genset engine specifications & operation

Genset specifications are provided in **Table *2*** below.

Table 2. Genset engine specs to be used for WP2 land-based tests at the Port of Limassol.

Engine Model	**Cummins 6CTA8.3-GM155**
Model year	2024
Displacement	8.3 lt
Compression ratio	17.3:1
Bore x Stroke	114 mm x 135 mm
Number of cylinders	6
Configuration	Turbocharged & Aftercooled
Rating power	155 kW_m @1500 rpm
Nominal fuel consumption @75% power	116 kW_m @1500 rpm
Approximate flue gas flow rate	640 - 660 kg/hr and at the exhaust temperature range of 350 – 450 °C. The anticipated CO_2 concentration in the exhaust gases is 7-9% vol/vol (depending on engine load). In accordance with the Description of Work 50-150 Nm^3/hr will be provided for testing for various Green Marine technologies.
Exhaust gas temperatures	The exhaust gas temperature at the turbine out 600°C, anticipated exhaust temperatures at lower engine loads are 450°C.
Backpressure range (as per manufacturer instructions)	Max: 10.1 kPa Min: 5.0 kPa
Exhaust pipe diameter	75 mm
Class approval	Approved by CCS

Figure 5: Marine genset for land-based testing.

The engine will be connected to a resistive load bank. Power resistors are used in resistive load banks to transform electrical energy into heat, which is subsequently released by forced air cooling. For the current study, the AC400V-200kW Automatic load bank has 9 different types of loading inputs. The load bank has a control panel where the user can control the start-stop of the fan, set power values, control the load circuit on and off and read the data by the measuring meter, Emergency stop switch, and protection buttons. Figure 6 depicts the load bank to be used for the land-based tests.

Figure 6: Portable load bank for land-based tests.

The engine will be fully mapped in the land-based testing prior to testing the Green Marine technologies as described in D2.1 “Preliminary report on results of land-based testing”.

3.2.2. Specifications of measuring equipment

3.2.2.1. Gas analysers

The flue gas analyser is Lancom 4 from Land Ametek. Lancom 4 is a portable analyser designed to measure flue gas emissions [5]. Up to nine flue gases, flue gas temperature and pressure can be measured.

- Temperature units: ^{o}C, K
- Gas concentration units: mg/Nm^3, ppm
- Pressure units: in H_2O, hPa
- Hydrocarbon concentration units: %, ppm

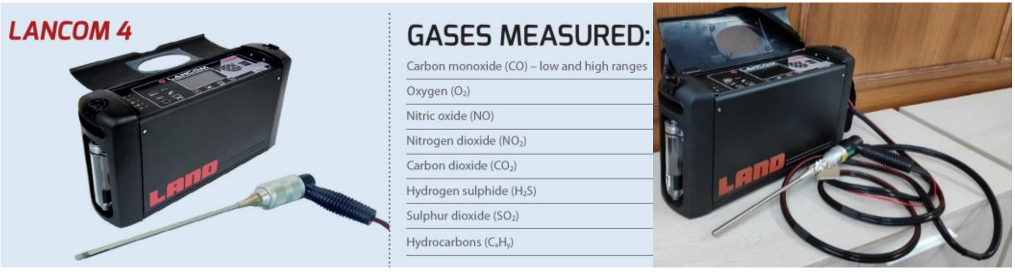


Figure 7. Lancom 4 Gas analyzer *[5]*

In addition, VARIOluxx [6], which is a portable syngas analyser for long-term measurements of special gases (see Figure 8), will be used to measure the syngas composition at the exhaust outlet. The analyzer extracts a partial volume of the flue gas from the combustion channel and analyses it for its components by means of sensors. The analyser can measure O_2, CO, CO_2, CH_4, H_2 and H_2S gases. The syngas analyser will enable measurements for syngas reinjection as a dual fuel.

Figure 8. Gas emission analyzer *[6]*.

3.2.2.3. Fuel flow meter

To be procured

3.2.2.4. Air (thermal mass) flow meter

Figure 9. Air (thermal mass) flow meter

The S401 is a flow sensor which is designed to measure the consumption of compressed air and gases within the permissible operating parameters (Figure 9). The S401 can measure the following values:

- Volumetric flow of the compressed air or gas.
- Total consumption of compressed air or gas
- Accuracy: 1.5% of reading + 0.3% full scale
- Repeatability: 0.25% of reading
- Sampling rate: >10 samples/sec
- Reference conditions: Can be set by use. Standard conditions are Ps = 0.1MPa, Ts = 20°C
- Medium Conditions: -30 – 140 °C / relative humidity <90% no condensation
- Transport temperature: -30 – 70 °C
- Operating temperature: -30 – 140 °C fluid temperature, -30 – 70 °C casing with display
- Analogue output: signal 4 – 20mA, isolated
- Modbus output: isolated RS-485 with Modbus/RTU protocol
  Power supply: 15 – 30 VDC / 200mA

3.2.2.5. Pressure and temperature sensors

To be procured – to monitor backpressure and temperature at the exhaust.

3.2.2.6. Energy meter sensor

To be procured – energy meter at load bank to monitor power consumption.

3.2.3. Process Flow Diagram

Figure 10 illustrates preliminary the overall combined solution in the form of a Process Flow Diagram of the various technologies (namely the TEE, SepaRaptor, CO_2 capture membranes and CCM).

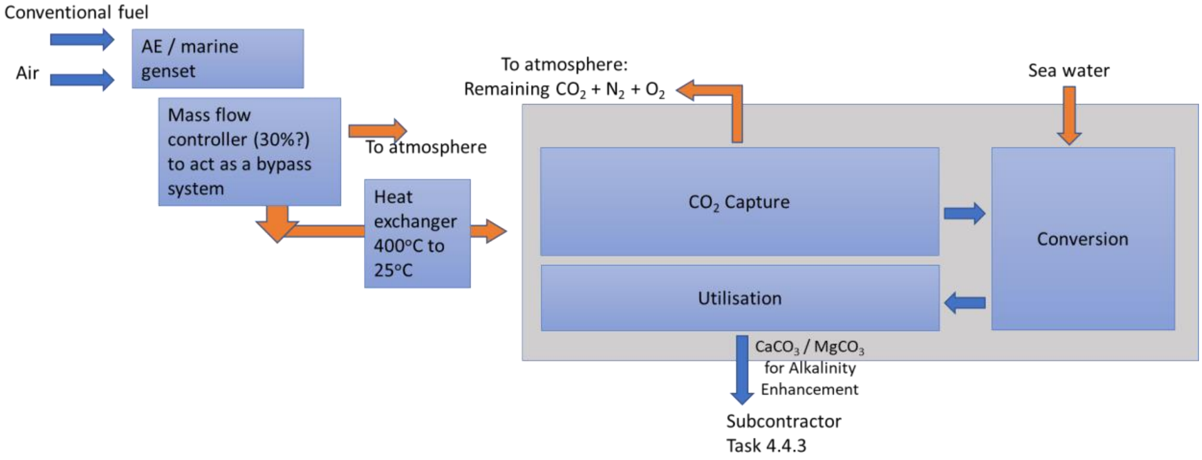


Figure 10. Process Flow Diagram for carbon capture with chemical absorption for land-based testing

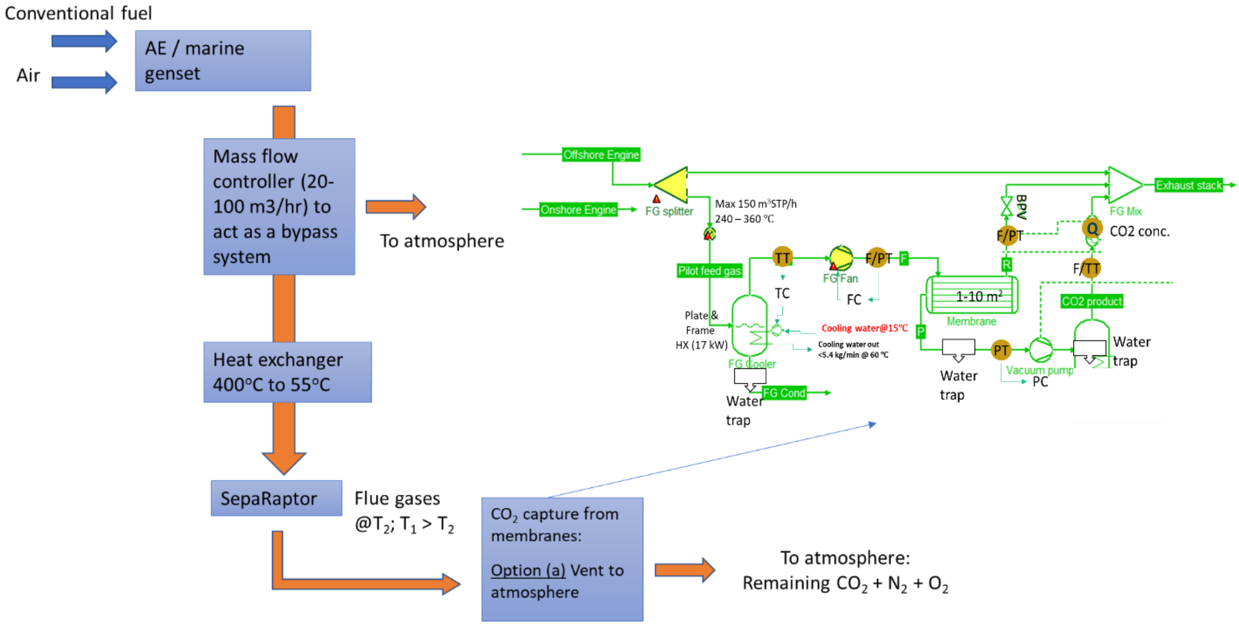


Figure 11. Process Flow Diagram for carbon capture with membranes and SepaRaptor for land-based testing. On the right side preliminary simulations with Cape Open to Cape Open (COCO) simulation environment *[7]*.

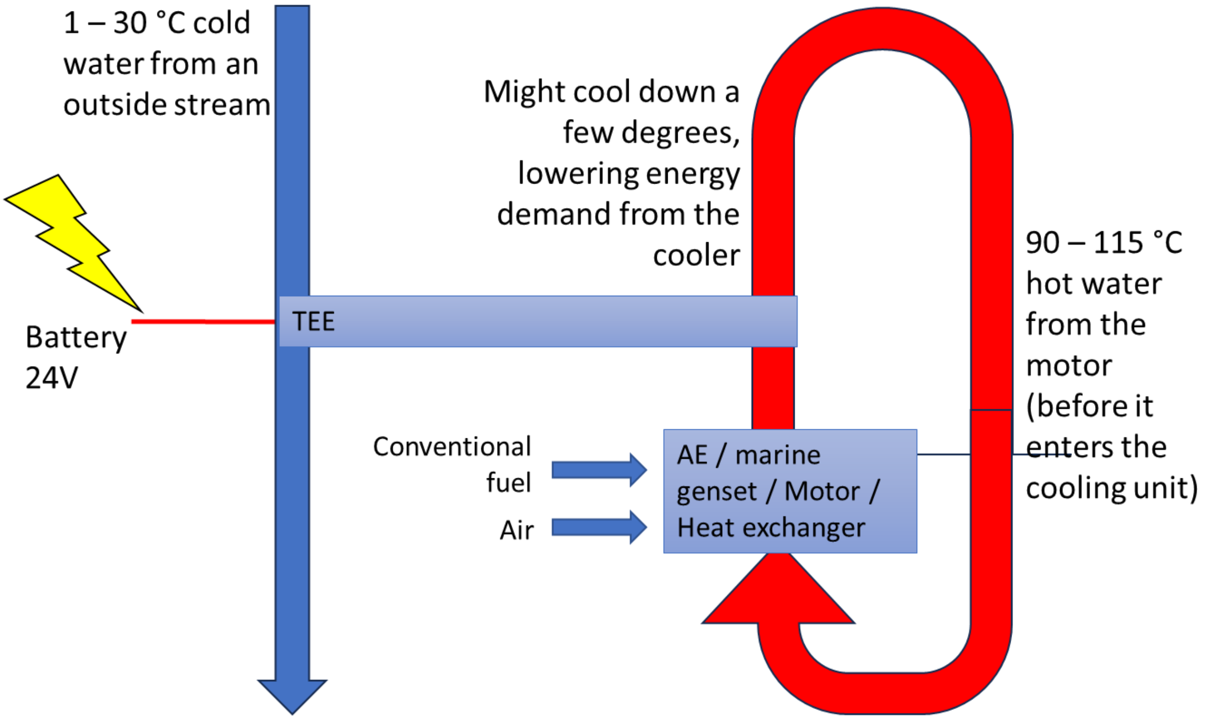


Figure 12. Process Flow Diagram for ThermoElectric Element for land-based testing.

3.3 LAND BASED TESTING KPIS

KPIs and some system requirements for overall land-based solution:

- Marine Genset at CMMI
    - Up to 100% load; resistive load bank is used to change the engine load – will test load conditions up to 80% as per discussion in D2.1 "Preliminary report on results of land-based testing"
    - Fuel: MDO
    - 4-stroke diesel engine
    - Rating: 155kW
- CalMac engine specifications (see §5.4.1. for additional details):
    - 65-85% load
    - Fuel: MDO
    - 4-stroke diesel engine
    - Rating: 164 kW
- Operating temperatures:
    - Membranes: 25 – 60°C
    - SepaRaptor: 25 – 60°C
    - CCM: 25 – 30°C
    - Typical exhaust temp. 360°C – 450°C, thus the exhaust gases will need to be cooled down to the required operating temperatures of membranes, SepaRaptor and CCM.
- 35% GHG reduction as per WP1

Preliminary test matrix for land-based testing (reiterated from D2.1 “Preliminary report on results of land-based testing”).

Table 3: Testing matrix during to test the Green Marine Technologies as per D2.1 “Preliminary report on results of land-based testing”.

Fuel type	**Test Type**	**Load conditions (kW), Engine power: 155 kW**	**Engine (rpm)**
Marine Diesel Oil	No technology	25kW until max nominated power with increments of 20kW	1500
	Carbon Capture Machines	To be determined during measurements per technology	1500
	Membrane		
	Thermoelectric element (TEE)		
	SepaRaptor	With and without membrane	

4. GREEN MARINE LIFE CYCLE ASSESSMENTS LINKED TO WP4

No changes from previous report D4.2 “Second report: End System Requirements & KPI’s”, but reiterated for completeness.

4.1. LCA FRAMEWORK

As per Task 4.3, LCA will be carried out according to ISO 14040. which include the following phases (see Figure 13):

1. Goal and scope definition for the system to be assessed.
2. Inventory analysis, requiring the compilation of data on all the inputs and outputs of the system that occur within the system boundary.
3. Impact assessment, in which the output of the inventory is manipulated to extract data on the magnitude and significance of the potential environmental impacts.
4. Interpretation, involving the evaluation of the findings from either the inventory stage or impact assessment stage (or both) based on methodology defined in the scope to reach a set of conclusions.

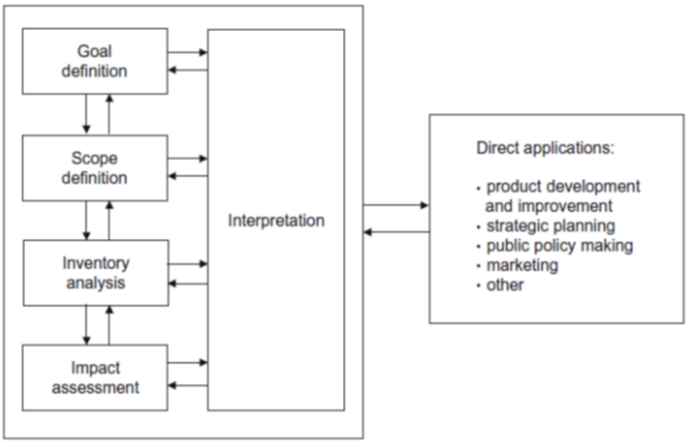


Figure 13. LCA in accordance with ISO 14040

The LCA will be performed on a per technology basis, and these require information about:

1. Boundary conditions
2. Control volume
3. Mass and energy balances
4. Inventory creation:
    a. **input** of resources, materials, semi-products and products;
    b. **emissions**;
    c. **output** of waste and valuable products for the product system, according to the definition of goal and scope.

Note that the inventory analysis considers all the processes belonging to the product system, and the flows are scaled according to the reference flow of product that is determined from the functional unit.

Preliminary KPIs of LCA analyses are:

- Global Warming (kg CO_2 eq)
- Stratospheric Ozone Depletion (kg CFC11 eq)
- Terrestrial Acidification (Kg SO_2 eq)
- Marine Eutrophication (kg N eq)
- Terrestrial Ecotoxicity (kg 1,4-DCB)
- Freshwater Ecotoxicity (kg 1,4-DCB)
- Marine Ecotoxicity (kg 1,4-DCB)
- Human Carcinogenic Toxicity (kg 1,4-DCB)
- Mineral Resource Scarcity (kg Cu eq)
- Fossil Resources Scarcity (kg oil eq)

Specific LCA use cases will be determined in future versions of this report after finalization of WP3 activities.

5. SOFTWARE TOOL CATALOGUE LINKED TO WP5

As per the Grant Agreement, general KPIs regarding the software tool are:

- Number of software tool users = 20
- User engagement survey feedback = satisfactory engagement of 500 users

Ability to integrate a new module within a timeframe to be defined in later versions of the report. Figure 14 illustrates the Green Marine software catalogue tool with different "software modules" or "Service Provider Layers". Figure 14 provides the high-level visual understanding of data flow to be used within the Green Marine software platform.

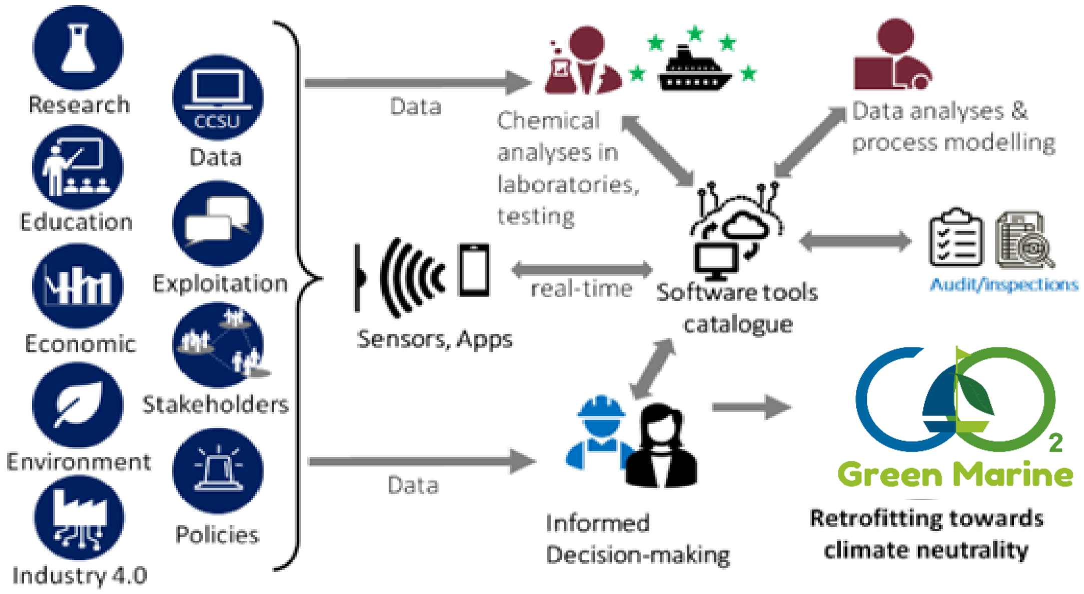


Figure 14. As per the Grant Agreement; the envisioned Green Marine software decision tool catalogue

5.1 APIS AND INDIVIDUAL SOFTWARE MODULES

The following KPIs and end system requirements for Task 5.1 are expected (or defined if not yet known). As per the Grant Agreement these are:

- Exact definition of API interfaces to allow 3rd parties to connect to the platform with their tools or software apps
- GUI definition (see §5.2.2)
- Data security
- User engagement (see §5)
- Quality and validation of data for benchmarking/model development
- Stakeholder acceptance and engagement

5.2 SOFTWARE PLATFORM

The software platform will integrate independent physical models of the different technological solutions and addresses the lack of integrated environment for complex distributed simulations and lack of data validation (see §5.2.1) that are needed to feed the models to be developed.

Thus, the requirement of the software platform is to provide a fully integrated CCUS platform by using the state-of-the-art tools.

5.2.1 Tailor existing AI technologies – Digital twining of solutions

AI technologies to facilitate predictive performance of the technologies and retrofits. The AI algorithms will "learn" from the land-based test data (WP2) and demonstration data (WP1). Thus, predictions and recommendations for GHG avoidance measures based on ship operations, engine type etc.

Thus, preliminary KPIs and end system requirements regarding the AI technologies are:

- Creation of repository data / models that can be used by researchers in a privacy-preserving way ensuring collaboration without sharing of proprietary data (using federated learning techniques by not sharing raw data)
- Reliable algorithms that do not lead to Floating Point Exceptions or any other issue; quality assurance to filter out bugs
- Optimised algorithms in terms of performance depending on techniques for digital mimic (up to x10 speed-up of current GPU architectures with usual federated learning techniques of the current state of the art)
- Accurate algorithms; up to 10% variation with land-based and demonstration data
- Genset monitoring: Rate of data sampling from IoT platform (to be developed for the land-based genset): 1 sample per second (depending on installed sensors to be procured). We will ensure data synchronization for effective assessments. Hence large data samples with good granularity (1 sample per second) to train the deep neural networks (DNN) such as Long-Short Term Memory (LSTM)
    - This requires the duration of the tests to be long enough for a statistical acceptable sample
    - If this is not achievable, closure models will be needed
    - Sensors are mentioned in §3.2
- Green Marine technologies: KPIs on sampling rate and sensors per technology to be provided in future version of this report once design has been finalised in WP3.

5.2.2 Software framework

As per the Grant Agreement, for easy processing of all results can be visually presented, including different circularity scenario options – computers do not make decisions on a set of parameters, people do so, based on their understanding. Therefore, also "gamification" of the tool is envisaged, where the user interacts with the platform to try a circular scenario.

Thus, preliminary KPIs and end system requirements regarding the software framework are:

- Opensource user friendly GUI with multiple visual interfaces (for example Graphana). KPI: Approval rate from end user feedback > 80%
- Development of a high-quality technical documentation that is openly available. KPI: Technical Operational & user-Manual available by M43 (D5.5). Approval rate from end user feedback > 80%. Instructions Handbook available by M43 (D5.6). Approval rate from end user feedback > 80%. Measurement of users ability to perform tasks after reading the documentation > 70%

- Advanced navigation and visualisation interface to simplify information access and usage (effective information management) KPI: Time spent on site by end users before finishing a task and Number of clicks by end users before finishing a task. See following table:

Table 4. Time spent on site and Number of clicks by end users per visit

Visit	Average Time	Average clicks
3	<10m	<30
5	< 5m	<20
10	< 2m	<15

- Organisation management configuration & administration features. KPI: Approval rate from Organisation Administrators configuration and features from user feedback > 80% KPI: Usage of functionalities regarding Organisation management configuration & administration by Organisation Administrators >70%. Platform downtime after entering production as per following table:

Table 5. Targeted uptime per month

Month	Target Uptime
37-39	90%
40-48	95%

- APIs for data visualization
- Independent reference modules for calculation decisions
- Facilitate gamification user experience
- Facilitate logistics process
- Seamless interaction and coordination of modules
- Number of simulations executed as per following table:

Table 6. Simulations per month during project implementation

Month	Simulations per month
37-39	60
40-42	120
43-48	200

5.2.3 Use case definition

Preliminary KPIs for use case definition are:

- Minimum 50 user stories
- Minimum 100 technical requirements

5.3 COMPUTATIONAL FLUID DYNAMICS SIMULATIONS

CFD simulations will provide physical models which will iterate to be part of the software framework. However, CFD activities are planned in WP3, WP4 and WP5.

5.3.1 Activities related to Task 3.1 "Tailor (Develop) aerosol control solutions"

CFD simulations will optimise the flow streams passing through the membranes of the SepaRaptor and UV system. The following requirements are needed for successful CFD simulations:

- Selection of a CFD software package & estimation of computational power and estimated CPU time
- Definition of boundary and initial conditions (definition of inlet velocities, temperatures, species composition, pressure etc)
- Definition of physical models, such as membrane porosity and appropriate numerical schemes to be used
- Provision of CAD model (SepaRaptor + UV system)
- Generation of a suitable mesh

KPIs of CFD simulations for Task 3.1 "Tailor (Develop) aerosol control solutions" are:

- Verification/validation with available experimental data as generated by WP2 activities and open access literature, and any deviation of results to be within 10% of experimental data.
- Optimisation of system, once verified, through various simulations to mitigate back-pressures and improve overall efficiencies of the system.
- Scale up of overall system via optimised flow streams.

5.3.2 Activities related to Subtask 4.4.1 "Process modelling"

As needed in Subtask 4.4.1 "Process modelling", to determine the back-pressures of the overall system (genset + CCM + membranes as set by the WP2 setup), the following requirements are needed for successful process modelling:

- Use of COCO simulator [7] to setup process modelling
- COCO simulations to be used per technology as described in the Process Flow Diagrams of section 3.2.3 of this report.
- CFD simulations will be used to determine the backpressure in the exhaust of MV Coruisk. Appropriate location will be estimated to have a minimum impact on backpressure and thus the performance of the genset on-board.

5.3.3 Activities related to Task 5.2 "Air circulation"

MV Coruisk has an open HVAC system (i.e. natural ventilation), hence there is no air recirculation. In addition, the cabins on MV Coruisk are not pressurised. Note, there is no HEPA filter on MV Coruisk's ventilation system, the only filter used is Euro 4 dust/dirt filter to prevent outdoor foreign contaminants (such as leaves/dust/dirt) from outside entering the ventilation system. The filter must remain on the system preventing dirt/contaminant build up through the ducting. As such the SepaRaptor wth UV will not be integrated within the ventilation system of the vessel but instead be tested through the use of standalone units within the crew cabin. Therefore, CFD simulations will be used to determine the air circulation patterns inside a staff cabin and/or bridge to determine appropriate position and number of standalone SepaRaptor wth UV units. These simulations will pave the way for optimising the SepaRaptor and UV system for vessels with pressurised cabins and HVAC systems with air-recicrulation, such as cruise-ships.

5.4 DIGITAL MIMIC OF CRITICAL PARTS/TECHNOLOGIES OF VESSEL

Under Task 5.3, the KPIs and end system requirements will be defined in future versions/updates of this report.

All necessary information for developing digital models of the three technologies that are planned for retrofitting will be provided by the technology providers once they become available. Whenever possible, these models will be defined using mathematical equations and integrated with the sensors that are scheduled for onboard installation. These sensors aim to continuously assess the effectiveness and performance of these technologies throughout their service life.

If a mathematical approach is not viable, experimental data and laboratory tests carried out by technology providers will be used as a baseline. These data will support the use of artificial intelligence techniques for modelling while considering the onboard sensors that will bridge the physical and digital components of the system.

Subsequently, these models will be validated with data collected from land-based tests. KPIs and end system requirements will be specified once the digital models and their physical counterparts are established, allowing for the setting of realistic targets.

5.5 RETROFIT DESIGN CATALOGUE TOOLS

Under Task 5.5, the KPIs and end system requirements will be defined in future versions/updates of this report.

6. DEMONSTRATIONS LINKED TO WP1

6.1 DUTIES OF HEALTH AND SAFETY ADVISOR DURING DEMONSTRATIONS

Procedures will be documented, especially in regard to risk & eventual approval (under Lloyds Register) by the Health & Safety Advisor. The specific role to be allocated to CalMac to deliver obligations, through CalMac's internal "HSQE department". The department has the relevant competencies and skills to ensure Health and Safety during the WP1 demonstrations.

Briefly these roles and scope of work in relation to **Green Marine**:

- Head of Safety and Security; responsible for providing professional support to vessel and shore-based operations for all relevant safety and security matters.
- Environmental Manager; responsible for providing professional support to vessel and shore-based operations for all relevant environmental matters.
- Health and Safety Manager; responsible for providing professional support to shore-based operations for all relevant safety and security matters.
- Marine Safety Advisors; responsible for providing professional support to vessel operations for all relevant safety and security matters.

In Appendix B of D4.2, the safety protocols expected from CalMac's contractors, also known as Managing Contractors Process, is presented. This document will form the basis of the safety protocols in the WP1 demonstrations.

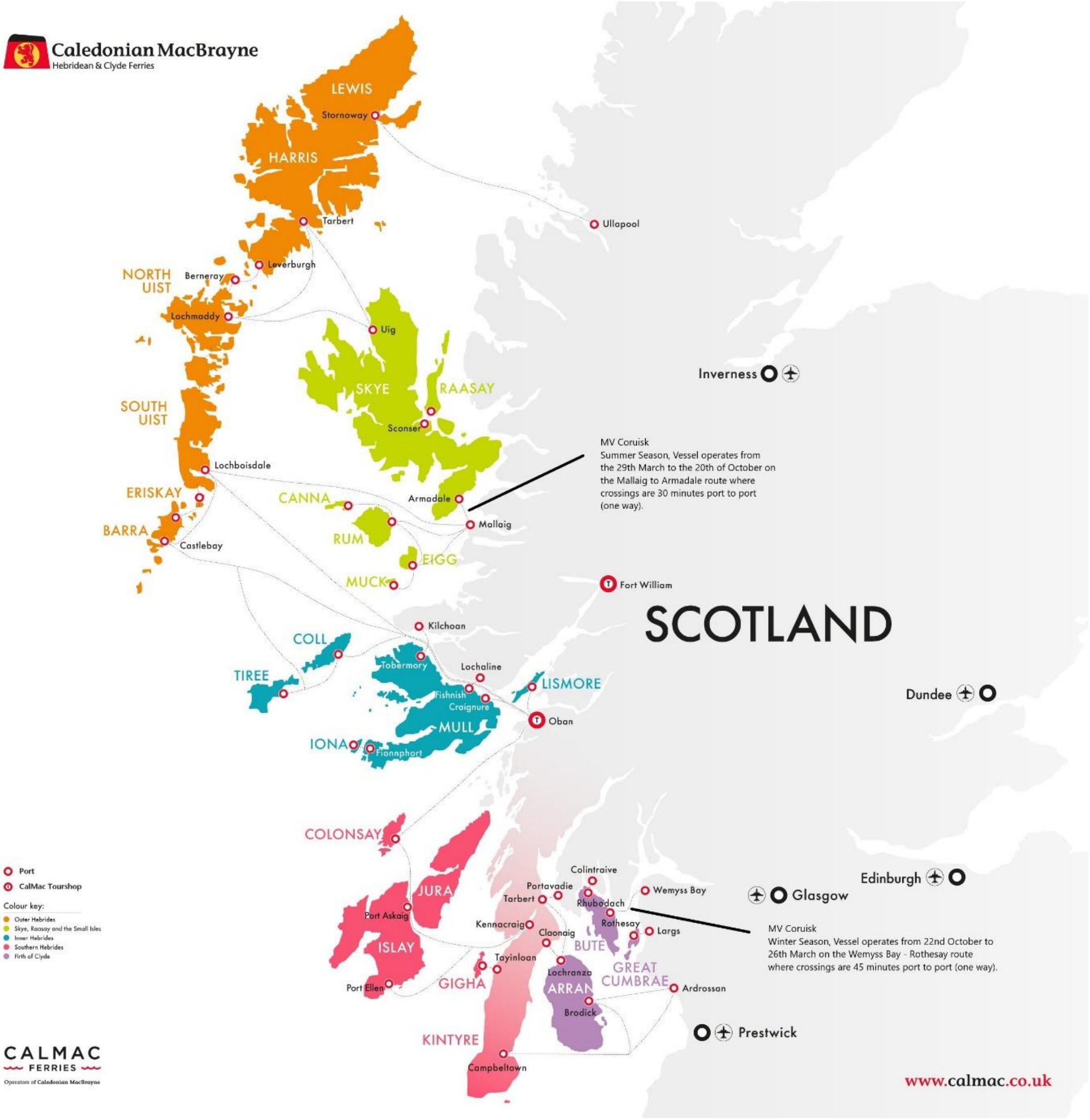
As per the D7.2 "Project Management Handbook and draft Data Management Plan", the vessel demonstrations site inspections check list is defined.

WP1 Vessel demonstrations site inspections

The EHS WP1 officer will follow CalMac's procedures as described in the internal document "*Vessel Operations Manual; Vessel Inspection, Maintenance & Overhaul – Control of Contractors (Procedure VOM 06.03)*". The procedure includes quality records on (1) Contractor Risk Assessments, (2) Contractor Method Statements, (3) Purchase Orders, (4) Job Instruction Sheets, (5) Planned Maintenance Records, (6) Contractor Insurance Certificates, (7) Permits to Work, (8) Safety Induction Records, (9) Near Miss Reports, (10) Accident Reports, and (11) Hours of Work Records, which are all relevant to **Green Marine** WP1 demonstrations. Note that for **Green Marine** WP1 demonstrations the term "*Contractors*" refers to **Green Marine** researchers/scientists needed to install the various technologies on-board CalMac vessels.

6.2 PERMITS AND ACTION PLANS FOR ALL DEMOS

For the effective vessel demonstrations, the relevant sites and permits will be required. Demonstrations will possibly occur where MV Coruisk operates. A demonstration route will be defined at later versions of this report, but indicatively shown in Figure 15.



MV Coruisk
Summer Season, Vessel operates from the 29th March to the 20th of October on the Mallaig to Armadale route where crossings are 30 minutes port to port (one way).

MV Coruisk
Winter Season, Vessel operates from 22nd October to 26th March on the Wemyss Bay - Rothesay route where crossings are 45 minutes port to port (one way).

Figure 15. MV Coruisk winter and summer season operation.

As per Figure 15, MV Coruisk in the summer season, the vessel operates from the 29th March to the 20th October on the Mallaig to Armadale route where crossings are 30 minutes port to port (one way). In the winter season, the vessel operates fom the 22nd October to 26th March on the Wemyss Bay – Rothesay route where crossings are 45 minutes port to port (one way). Note that the vessel is off operation for approximately 1 month over the winter period and there is also a a dry docking period of 3 weeks (see §6.4.4).

The necessary action plans as per the Grant Agreement are:

- GHG emission reduction goals;
- responsible contact person;
- quality reviewer;
- safety and environmental issues;

- test campaigns;
- planning;
- quality monitoring;
- Classification Society/regulatory authority compliance (under an appropriate classification society – the majority of CalMac ferries are registered with Lloyds Register);
- onboard technologies evaluation, certification procedures.

As per the Grant Agreement, the final action plan and test campaign will be authorised by the end users responsible site's Environmental, Health & Safety manager (as defined in §4.1).

6.3 ENGINEERING AND PREPARATIONS FOR RETROFITTING

The mapping of new technology approval process from classification societies is described as part of D1.1 "Report for engineering and preparations for retrofitting" deliverable on M8. The description of risk approval process and approval in-principle certification is examined for the time being as part of the continuous WP1 tasks T1.2-T1.5. At the moment as there are no specific KPIs and end system requirements. However, these. will be defined in detail in future versions/updates of this report.

Preliminary KPIs and end-system requirements are:

- as per technology the technology approval to be aligned with specs (energy efficiencies, mass flow rates, how devices operate);
- approval to be performed in 6 months, depending on available information and overall progress of **Green Marine** – harmonisation of KPIs as per appointed classification society;
- 3 workshops of 10 Green Marine participants and 5-10 experts (class society, tech. providers) from industry providing high-level information and maritime background.
- A preliminary HAZID workshop has been conducted with 9 Green Marine participants including technology providers and stakeholders. The Risk-Based Certification process flow had been discussed for stakeholders and technology providers to be prepared for approval from the appropriate classification society. A follow-up workshop has been planned to take place in M17 with the same participants. This process will be repeated for all the technology providers of the Green Marine project.

6.4 RETROFITTING SHIPS

Based on internal CalMac's Risk Assessment process with input from technology providers the selected vessel is Coruisk as shown in Figure 16. The Risk Assessment will be used by Lloyd's Register, the classification society of the Coruisk vessel. Additionally, UK MCA will be informed and consulted on the Hazid process and results in order to receive further feedback and guidance on the verification of the Risk Based Certification (RBC) process followed in Green Marine WP1 as initially described within the LR certification guidance for carbon capture and new technologies to be installed and tested onboard ships. Therefore, the setup of the land based technologies should be similar to the retrofits on-board. The Coruisk vessel, with IMO/LR No.: 9274836, is a passenger/Ro-Ro Ship with carrying capacity of 40 cars, crew 7 and 250 passengers.

Figure 16. Coruisk vessel to be used for **Green Marine** demonstrations.

6.4.1. Engine specifications and available space of CalMac possible vessels

The auxiliary engine specifications of the Coruisk is detailed below. It should be mentioned that there will most probably be other pieces of machinery and equipment within the same space. Both auxiliary engines operate at fixed engine speed of 1500 rpm (i.e., at 50Hz) and use Marine Gas Oil (MGO) fuel.

Auxiliary engines on-board: Cummins, Engine Builder: Cummins 1 x 6BT5.9-D(M), 4 Stroke 6Cy. 102 x 120, Mcr: 91 kW (Emergency Generator) Design: Cummins, Engine Builder: Cummins 2 x 6CTA8.3-D(M), 4 Stroke 6Cy. 114 x 135, Mcr: 150 kW**.** The engine is operated up to **80% load.**

The auxiliary engine to be utilized is the 6CTA8.3-D(M); Table 7 depicts the engine performance at various loads:

Table 7. Engine performance data as per the manufacturer *[8]*

Output power		**Fuel consumption**	
%	**kW$_m$**	**kg/kWh**	**Lt/hr**
110% (overload)	181	0.216	45.8
Prime Power			
100%	164	0.214	41.3
75%	123	0.212	30.7
50%	82	0.216	20.8
25%	41	0.251	12.1
10%	16	0.300	5.8
Continuous Power			
80%	134	0.211	33.3

Note that the engine is turbocharged, which use the exhaust gas as a driving force to compress the incoming air, and aftercooled. Hence any system retrofitted must not affect back pressure which will therefore impact the turbocharger performance.

In addition, based on the General Arrangment drawings of the engine room (see Figure 17), several options are to be considered for the retrofits.

6.4.2. Ventilation system of Coruisk and relevant demonstrations

There is no HVAC system on-board the vessel but a ventilation systems that heats the air. The ventilation manuals on-board MVCoruisk HVAC is in Ref. [9].

The SepaRaptor+UV system will be a standalone unit operating in a cabin crew or bridge (location and number of standalone units to be determined in future versions of this report). The units must be compliant by a Portable Appliance Testing (PAT) and appropriately has a CE certificate. Note the SepaRaptor+UV system is already CE certified.

KPIs of the SepaRaptor + UV technology are provided in §3.2.4. The specific KPIs of the SepaRaptor are provided in §2.2.

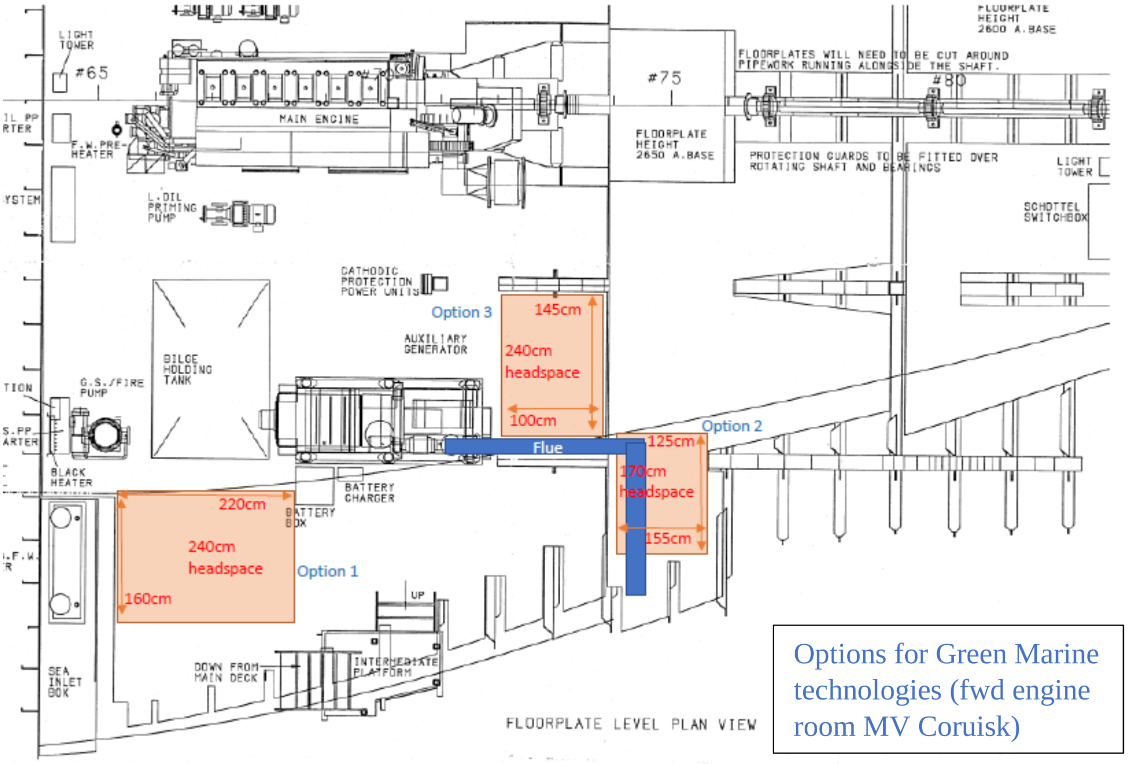
6.4.3 Sea water access on MV Coruisk

Sea water access on-board MV Coruisk through sea water chest, but difficult to have access within the engine room. Therefore, if a technology requires access to sea water, then internal and Class and Flag authority approval is needed.

6.4.4 Dry-docking scheduling

Alignment of **Green Marine** activities in terms of demonstration/installation/retrofitting activities planned for 2026 with dry-docking schedule is needed. Dry-docking is very strict to cover CalMac's vessels. Only one month extension is allowed, hence there is no flexibility.

Therefore, process and installation of technologies on-board the chosen vessel should be ready in Autmn (October-November) 2025. Alignment of classification societies (Lloyd's Register), who will a) supervise the dry-docking sequence, and b) the overseeing of the installation of proposed **Green Marine** technologies. Paperwork from appointed subcontractors will potentially be considered (such as WP2 land-based pre-approval process report).



Options for Green Marine technologies (fwd engine room MV Coruisk)

Figure 17. Options for modifications/retrofits in engine room of Coruisk, indicating available space.

6.4.5 Carbon Capture Machine (CCM) on-board Coruisk

CCM will observe the key considerations of the marine industry for the design of the vessel-based solution. Reference standards include:

- Lloyd's Register – Shipboard Carbon Capture and Storage
  RINA – Guide for Approval in Principle of Novel Technologies
  Effective from 1 January 2014

Other key considerations, reiterated from §2.1. as per CCM's technology:

- Size: Estimated to fit in the volume of a typical 20ft container; but to be designed in a modular framework to use available space at land-based testing and vessel-based demonstrations/integration.
- The CCM 'Green Marine' modules will include:
  - Emission diversion, cooling, treatment
  - CO_2 Capture
  - CO_2 Conversion
  - Carbonate Utilization and Dissemination
- Storage requirements of chemicals – The system will require on-board storage of Sodium Hydroxide (NaOH), and this feedstock will be stored either as a pure solid or as a 47% aqueous dilution to optimize storage space. The size of the storage area and/or tank will be sized in relation to the anticipated test duration.

CCM will work closely with Scottish Association for Marine Science (SAMS) or other research institutes to optimize carbonate production to the specific morphological characteristics required for effective ocean alkalinity enhancement.

These KPIs will be re-evalutated in future versions of this report.

6.4.6 Membrane technology (SINTEF) on-board MV Coruisk

Demonstration of capture rate of CO_2 and its purity at different load conditions under normal vessel operation. Energy consumption KPIs from WP3 (described in §2) are still relevant for on-board demonstrations.

The following set of key performance indicators can be used in evaluating and optimizing the different design solutions which are developed as part of this work:

- CO_2 capture rate:

The aim of the project is the demonstrate a capture rate of > 35% CO_2 using a single stage membrane concept. Recovery rates in the range up to 90% will be explored theoretically using simulation models of multistage systems.

- CO_2 product purity:

The required purity of the captured CO_2 will depend on its end-use [10]. Liquefaction for transport and storage required high purity (>95 %). In combination with capture technologies a moderate CO_2 purity may also be beneficial and will be considered here as short-term on-board storage as compressed CO_2.

- Specific compressor duty, MJ/kg CO_2 captured:

Mechanical energy demand related to compression of gas will be the major operating costs for a membrane-based CO_2 capture system. Thus, the specific compressor duty (including all required mechanical energy input) will be a key OPEX-related KPI. In practice the mechanical energy demand is covered by the ship engine and will as such lead to increased fuel consumption.

- Specific membrane area, m^2*h/kg CO_2 captured:

The installed membrane area will be an important size and cost factor related. Typically, there will be a close to linear tradeoff between the installed membrane area and the feed pressure for a membrane separation stage (and intrinsic membrane permeability, depending on membrane). Thus, related to feed gas compression there is a tradeoff to be expected between specific mechanical energy consumption and the specific membrane.

- Weight and sizing of equipment:

On an offshore installation footprint, height and weight of process equipment is an important cost factor, which is likely to have an impact on CAPEX for the different designs. For retrofit of existing ships there will be practical limitations to consider with respect to weight and sizing of additional process equipment. The relative modularity and simplicity of membrane-based capture may be an advantage compared to other technologies such as chemical sorption.

6.4.7 SepaRaptor and TEE on-board Coruisk

KPIs of SepaRaptor and TEE are already described in §2, but these will be re-evalutated in future versions of this report.

6.5 DEMONSTRATE GHG EMISSION REDUCTION BY >35%

KPIs and end system requirements will be defined in future versions/updates of this report.

6.6 COMMERCIALISATION APPLICATIONS

KPIs and end system requirements will be defined in future versions/updates of this report.

7. CONCLUSIONS

The third version of this report is to document the necessary End System Requirements and KPIs under deliverable D4.3 of WP4 due on M17. This deliverable is a follow up of the second and first versions of D4.1 “First report: End System Requirements & KPI’s” and D4.2 “Second report: End System Requirements & KPI’s”. This document was updated and/or incorporated the requirements needed for:

- WP1 – Demonstrate retrofitting of existing fleets (led by UoS)
- WP2 – Land based testing and integration of solutions (led by CMMI)
- WP3 – Solutions development and scale-up (led by SINTEF)
- WP4 – KPIs, Integration, TEA, SEA, LCA, Risk, Safety (led by UPM)
- WP5 – Software tool catalogue for GHG-emission reduction solutions (led by PDM)

Most importantly and as per §2, the Marine Genset and load bank for land based testing have been included and updated Process Flow Diagrams per technological pathway. In addition, a preliminary test matrix that will map the marine genset (emissions measurements and overall performance) has been provided. The test matrix includes the evaluation of the performance of Green Marine technologies. Other sections of this report are a reiteration of the previous version D4.2.

This report is scheduled to be updated on M36 (interim reports) and M48 (final report). Therefore, this is a “live” document which will be monitored and updated as needed throughout project activities. Note that at this early stage of the report, some KPIs and End System Requirements are qualitive and quantitative.

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