



Retrofitting towards climate neutrality

D2.3 Second Report: Work Procedure or Best Practice Methods for Retrofitting

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Nomenclature/Symbols

API	Application Programming Interface
CanBus	Controller Area Network bus
C&E	Cause and Effect
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COSHH	Control of Substances Hazardous to Health
DAQ	Data Acquisition
ECU	Engine Control Unit
FAT	Factory Acceptance Test
GMIS	Green Marine Integrated System
HAZID	Hazard identification
HAZOP	Hazard and Operability
HVAC	Heating, Ventilation and Air Condition
IEC	International Electrotechnical Commission
IoT	Internet of Things
IP65	Ingress Protection rating 65
LR	Lloyd's Register
MAP	Manifold Absolute Pressure
MCA	Maritime and Coast Guard Agency, U.K
Modbus	Modbus communication protocol
NO _x	Nitrogen Oxides

PAT	Portable Appliance Testing
PML	Petronav Shipmanagement Limited
PPE	Personal Protective Equipment
RAMS	Risk Assessment Method Statement
RH	Relative Humidity
SME	Small and Medium Enterprise
SOP	Standard Operating Procedure
TEE	Thermoelectric Element
UV	Ultraviolet
λ	Lambda / Air–fuel ratio

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EXECUTIVE SUMMARY

This document is deliverable “D2.3 – Second report on work procedure or best practice methods for retrofitting” of the European Union project “Retrofitting towards climate neutrality” (herein referred to as “**Green Marine**”), with **Grant Agreement** No. 101096522.

Deliverable D2.3 updates and expands upon Deliverable D2.2, First report: work procedure or best practice methods for retrofitting, submitted in M24. As part of WP2 – Land-Based Testing and Integration of Solutions, this document presents the outcomes of Task 2.1 and provides updated best practices for retrofitting compression-ignition engines for land-based test-bed operation. The deliverable covers the installation of additional sensors to the engine, and bypass system modifications, updated retrofitting protocols, and the safety regulations established by PML, risk assessment matrix, exhaust pipe extension, CO monitoring with alarm system, emergency preparedness measures, fire protection equipment, and mandatory use of personal protective equipment all supporting safe operation and compliance with Lloyd’s Register and other relevant regulatory requirements. It also summarises the key retrofit-related developments introduced by the technology providers and the practical lessons learned from land-based testing activities. These lessons show that successful retrofit planning must consider not only physical integration with the marine genset exhaust system, but also back pressure limits, heat rejection, pressure drop, exhaust leakage, material compatibility, sensor reliability, flue-gas measurement under humid and contaminated conditions, control logic, emergency bypass operation, compact skid-based installation, simplified electrical interfaces, access for inspection and maintenance, and safety provisions such as secondary containment and leak prevention. Overall, this document serves as a reference for Green Marine technology developers, supporting the successful integration of their technologies with the marine genset exhaust system during land-based testing at the initial stages, where onboard scenarios are replicated under controlled conditions, and during the final onboard demonstration phase.

1. INTRODUCTION

The main objective of Green Marine is to significantly accelerate the climate neutrality of waterborne transport through the retrofitting of existing fleets with cost-effective emission-control, carbon-capture, air-treatment and energy-saving solutions. To support decision makers, the project develops retrofit protocols and a software tool catalogue that captures the knowledge generated from design, simulation, testing, integration and demonstration activities. The Green Marine solutions include carbon capture and mineralisation, membrane-based carbon and water capture, air-treatment technologies for improved air reuse and energy savings in HVAC systems, flue-gas pre-treatment, and waste-heat recovery. These technologies are developed and assessed to support practical retrofit pathways for existing vessels and to contribute to wider replication across the maritime sector.

All Green Marine solutions were first assessed through land-based testing using the marine genset setup at the Petronav facility. These tests replicated onboard scenarios under controlled conditions as far as practicable and provided the basis for evaluating integration requirements, exhaust routing, bypass operation, back pressure behaviour, safety measures, monitoring arrangements and technology-specific retrofit needs. The results and lessons learned from the completed land-based testing activities support the refinement of retrofit procedures and provide the technical basis for selecting and preparing the most suitable solutions for future onboard demonstration.

Deliverable D2.3 updates and expands the first retrofit report, D2.2, submitted in M24. While D2.2 presented the initial retrofit procedures and early integration approach for the land-based genset, this second report captures the work completed since then. The updates include additional sensor installation, upgraded IoT and DAQ arrangements, exhaust back pressure monitoring, bypass system modifications, fail-safe and emergency functions, safety improvements, regulatory inputs, and practical lessons learned from the technology providers. This helps align the reader with the progress achieved between the first and second retrofit deliverables and shows how the retrofit methodology has matured through practical testing, partner feedback and regulatory review.

The objectives of WP2 are to create support for the Green Marine solutions through land-based testing, considering regulations, classification requirements, engine manufacturer limits and shipowner needs; to support performance testing of the retrofitting solutions; and to provide inputs for CAPEX and OPEX estimations. In this context, D2.3 provides updated best-practice guidance for retrofitting compression-ignition marine engines and associated exhaust systems, with the aim of reducing technical, operational, safety and regulatory uncertainty before onboard deployment.

1.1 PURPOSE OF THE DOCUMENT

This deliverable provides an updated overview of best practices and recommendations for retrofits to the land-based genset from D2.2, which could eventually be adopted for on-board demonstrations. The land-based tests are intended to mimic the onboard scenarios and test various technologies under controlled conditions. These procedures must comply with PML's protocols wherever applicable. The current document is not a SOP or installation manual. Instead, it provides

a recommended methodology and stepwise decision pathway that can support the preparation of technology-specific and vessel-specific work procedures at a later stage, in accordance with manufacturer instructions, vessel owner/class/flag requirements, and site-specific safety constraints. Table 1 summarises the stepwise retrofit pathway, showing how best-practice guidance progresses from system assessment to vessel-specific procedure development.

Table 1: Retrofit workflow and key outputs

Step	Retrofit workflow stage	Main output
1	Baseline system assessment	Engine / exhaust / HVAC / vessel data
2	Technology applicability screening	Selected retrofit concept
3	Integration and interface review	Layout, utilities, space claim, connection points
4	Safety and regulatory review	HAZID / HAZOP / class / flag / site requirements
5	Land-based validation	Performance, operability, lessons learned
6	Retrofit readiness assessment	Risks, constraints, required modifications
7	Vessel-specific procedure development	Detailed RAMS / installation / commissioning procedure

1.2 DOCUMENT STRUCTURE

Section 2 describes the updated sensor installation and calibration arrangements adopted for the land-based genset, including the additional instrumentation and monitoring equipment used to support reliable data collection during testing. Section 3 presents the exhaust back pressure requirements for the turbocharged marine engine and explains the measurement and monitoring approach used to verify that the exhaust arrangement remains within the manufacturer's recommended operating range.

Section 4 provides the main updates since Deliverable D2.2, with contributions from CMMI and the Green Marine technology providers (SINTEF, CCM, and WPS/SMP). It covers the upgraded IoT and bypass control arrangements, safety compliance measures, regulatory requirements, and the retrofit-related developments and lessons learned for the Green Marine technologies, including air and flue-gas treatment, waste-heat recovery, membrane-based CO₂ capture and carbon capture integration. Section 5 presents the report's conclusions, summarising the key best-practice recommendations and the main considerations for transferring the land-based retrofit experience to future onboard demonstration.

2. SENSOR INSTALLATION AND CALIBRATION.

The instrumentation architecture of the land-based genset comprised pressure, airflow, fuel-flow measurement, and other performance-monitoring sensors, integrated into the upgraded CMMI IoT/DAQ platform. The air-flow meter was installed on the modified intake-air manifold downstream of the air filter, while the fuel-flow meter was installed on the fuel line downstream of the fuel filter in accordance with the manufacturer's installation requirements. A dedicated pressure sensor was incorporated into the exhaust bypass arrangement to enable continuous monitoring of exhaust back pressure during engine operation. This instrumentation provided a robust basis for the reliable acquisition of the principal operating parameters throughout the land-based testing campaign. All measurement and monitoring systems were calibrated in accordance with the manufacturer's standard test protocols. Detailed description and their properties related to the monitoring equipment are available in Deliverable D2.1 "Preliminary report on results of land-based testing" submitted on M17 for the land-based testing

Figure 1 illustrates the updated sensor layout and arrangement adopted on the land-based genset. As shown, the configuration includes the air-flow meter (S1), fuel-flow meter (S2), pressure sensor (S3), temperature sensors (S4 and S6), thermal camera (S5) and gas analyser (S7). In the latest configuration, the monitoring setup was further complemented by a MAP sensor, a lambda (λ /NO_x) sensor and thermocouple instrumentation, all interfaced with the upgraded IoT system. The inclusion of the abovementioned sensors is essential to obtain a comprehensive understanding of in-cylinder conditions and overall combustion behaviour. The MAP sensor provides intake manifold pressure data, which is critical for estimating air charge and indirectly assessing cylinder loading, while the lambda sensor measures the air-fuel ratio, enabling evaluation of combustion efficiency and emissions formation. Thermocouples, particularly when placed within the cylinder/exhaust path, provide temperature measurements that are indicative of in-cylinder thermal conditions. Together, these sensors enable accurate correlation between pressure, mixture composition, and temperature, which is necessary for reliable estimation and validation of in-cylinder temperature and combustion performance. The updated configurations support continuous real-time monitoring and integrated performance assessment of the genset in a comprehensive manner.



Figure 1: Latest land-based test setup with sensor location.

3. BACK PRESSURE REQUIREMENTS FOR A TURBOCHARGED MARINE ENGINE

For the land-based testing, the exhaust back pressure was monitored using a dedicated gauge-pressure transmitter installed on the exhaust line of the bypass system, upstream of the point where the flue gas stream is divided between discharge to atmosphere and supply to the Green Marine technologies. This location was selected to provide a representative measurement of the back pressure experienced by the turbocharged engine before any downstream flow-splitting effects, thereby allowing the influence of the bypass arrangement and connected technologies on turbocharger operation to be assessed. The pressure transmitter was mechanically integrated into the exhaust pipework through its threaded process connection and electrically connected to the upgraded IoT/DAQ system using its 4–20 mA output signal, which was scaled in the data acquisition system to the sensor measurement range of 0–4 bar gauge. The selected transmitter has an accuracy of $\pm 0.5\%$ full scale, stainless-steel wetted parts, IP65 protection, and is suitable for industrial pressure monitoring applications, making it appropriate for continuous back pressure measurement in the genset exhaust monitoring arrangement. This integration ensured that the measured exhaust back pressure could be continuously compared against the manufacturer's recommended operating range of 5.0–10.1 kPa(g) [1], confirming that the turbocharger and overall engine performance were not adversely affected during operation. Figure 2 provides the location of the pressure sensor on the bypass system.

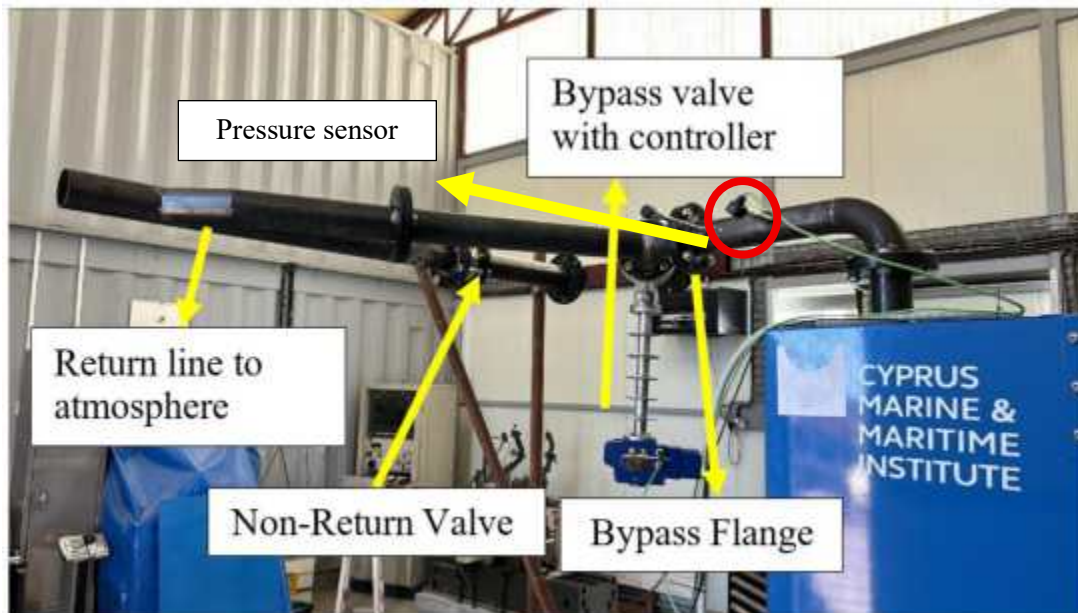


Figure 2: Pressure sensor on the bypass system.

4 UPDATES FROM D2.2 REPORT

The following sections provide updates from each technology provider on the progress achieved since the submission of Deliverable D2.2 in M24 with regard to the best practices on retrofitting activity of the genset. Accordingly, the content focuses only on new developments, modifications, integration activities, testing preparations, lessons learned from regulatory requirements, and the corresponding outcome after D2.2.

4.1 CMMI

4.1.1 *IoT platform to enable real-time continuous monitoring*

The IoT platform underwent a significant upgrade from its initial version to improve functionality, reliability, and operational flexibility during the land-based testing campaign. The platform was upgraded from its basic configuration into an integrated monitoring, configuration, and control system. A dedicated sensor configuration page was added, allowing users to configure individual sensor parameters and modify communication settings, including the IP address required for Modbus communication. The system was also made expandable to support additional sensors and actuators through CanBus, Modbus, and API-based communication. As part of this upgrade, the newly added hardware, including the exhaust back pressure sensor, MAP sensor, lambda sensor, thermocouples, air-flow meter, and fuel-flow meter, was integrated into the IoT/DAQ architecture to enable continuous data acquisition, monitoring, and logging (see Figure 3).

In addition, a dedicated exhaust bypass system tab was incorporated into the IoT platform to enable control and monitoring of the bypass valve. This upgrade allows the valve opening and closing to be performed through the IoT interface, enabling controlled routing of the exhaust gases either

towards the Green Marine technologies or directly to atmosphere. The bypass system also includes emergency functionality, with provision for a hard-wired emergency button which may be located in the captain's/bridge area, allowing the Green Marine system to be bypassed independently of software control (see Figure 4). This emergency function is intended to disconnect power to the Green Marine system and reroute the exhaust flow in case of abnormal operating conditions. In addition, the IoT has a live stream configuration to visualise the thermal images/video from thermal camera (See Figure 5). In the event of a general power failure, the valve system operates in a fail-safe manner, with the bypass arrangement diverting the exhaust gases away from the Green Marine technologies while all subsystems are halted. The emergency bypass function is hard-wired and independent of the IoT/control system, ensuring safe operation even in the absence of electrical power. The IoT platform, which is not part of the safety layer and is powered independently (e.g. via shore power), may remain operational if power is available, but its availability is not required for emergency system response.



Figure 3: Engine monitoring dashboard from IoT.

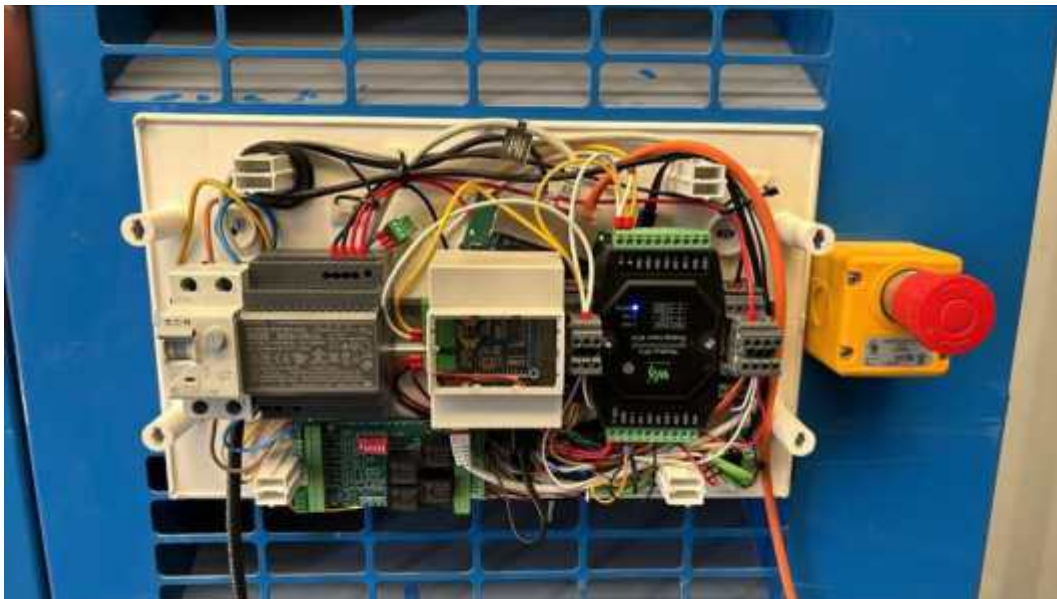


Figure 4: Installation of IoT systems on the Engine's ECU with emergency stop button.



Figure 5: Thermal camera live stream from IoT.

4.1.2 Safety compliance

Several safety features were added to the land-based testing setup to ensure safe operation of the marine genset, protect personnel, and reduce risks associated with exhaust gases, high temperatures, electrical systems, and emergency operation. These include LR recommendations from HAZID workshops.

Carbon monoxide (CO) monitoring: A mobile CO monitor (see Figure 6) was procured for the hangar room to continuously measure CO levels during testing. This was important because any exhaust leakage or incomplete combustion could lead to CO accumulation, which is hazardous to personnel. The monitor provides an early warning if CO concentration approaches unsafe levels, allowing testing to be stopped and personnel to evacuate before exposure becomes dangerous.



Figure 6: CO monitor.

Exhaust pipe extension: The exhaust line was extended to discharge exhaust gases outside the hangar where the engine was located within the Petronav campus (see Figure 7). This reduced the possibility of exhaust gases accumulating inside the test area and helped maintain a safer working environment during engine operation. The extension was particularly important because the Green Marine technologies and bypass system were connected to the exhaust line, increasing the need to control the exhaust routing and avoid leakage into the workspace.



Figure 7: Extension of bypass pipeline outside the hangar.

Safety audits and risk assessments: Safety reviews were conducted by the technology providers together with Petronav and the project team before and during the land-based testing campaign. These checks covered the test arrangement, equipment interfaces, operating procedures, documentation, and emergency measures. Their purpose was to confirm that each technology could be operated safely within the test environment and that risks related to exhaust flow, pressure, temperature, electrical supply, and personnel access were properly identified and mitigated. A floor plan of the testing facility was available in the engine room (Figure 8). All project partners were informed of emergency exits and the designated assembly point in the event of an emergency. Three fire extinguishers were available and accessible within the testing room. In addition, BX conducted audits together with UPM on the technologies of SINTEF, CMMI and CCM. The audits reports are annex 1.



Figure 8: Floor plan and Fire extinguishers at PML campus

Use of personal protective equipment: All personnel involved in the testing activities were mandated to wear appropriate PPE, including safety shoes, high-visibility vests, and safety helmets (see Figure 9). This was necessary because the testing area included operating machinery, hot surfaces, exhaust pipework, electrical systems, and lifting or installation activities. PPE provided a basic but essential layer of protection against impact, slips, burns, and general engine-room hazards.



Figure 9: Use of PPEs by the personnel during the land-based testing.

Thermal barrier gaskets: Rubber gaskets capable of withstanding elevated exhaust temperatures were added to the exhaust and bypass connections to act as thermal barriers and reduce the risk of flue gas leakage. Their use was important for maintaining a sealed exhaust system, preventing hot gas escape, and reducing thermal exposure at connection points. This also helped protect nearby components and personnel while supporting stable operation of the bypass system.

Power supply modification for the IoT system: The initial IoT system was designed to draw power from the engine battery. Following Lloyd's Register and CalMac recommendations, this was changed to shore power. This modification improved electrical safety and reliability by separating the monitoring and control system from the engine starting and auxiliary battery system. It also reduced the risk of battery drain, avoided interference with engine operation, and provided a more stable power source for continuous monitoring and data logging. Figure 10 and Figure 11 depicts the initial and final versions of the power supply line for the IoT system, respectively.

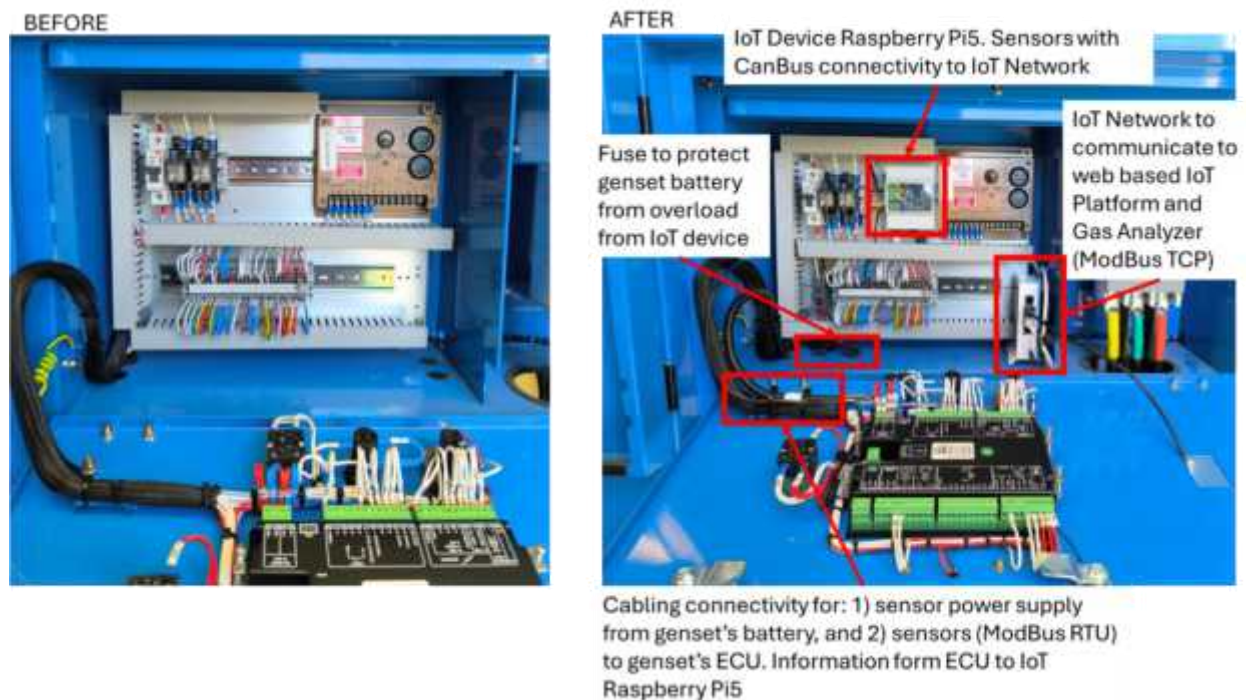


Figure 10: System Configurations before modification.



Figure 11: System Configurations after modification

Emergency stop and bypass function: An emergency stop function was incorporated to allow the Green Marine system to be isolated quickly in the event of any emergency.

Type-approved fail-safe bypass valve: In general, all materials/products/systems must be type-approved for maritime applications. This is mandated by regulatory bodies for safety requirements in operating scenarios. LR recommended that the bypass valve be treated as a safety-critical component within the bypass system and that it be certified, self-closing, and fail-safe. To increase the system's reliability, two valves in tandem were mandated with a self-closing/fail-safe mechanism. This is required to ensure that, in the event of power loss, shutdown, or control failure, the valve moves to a safe condition and prevents hot exhaust gases from continuing to enter the Green Marine system. Additionally, LR mandated that valves should close automatically in case of any failure in the green marine systems.

Replication of onboard bypass configuration: The land-based bypass arrangement should replicate the intended onboard configuration as closely as possible, including valve type, exhaust routing, control logic, emergency shutdown, pressure monitoring, pipework, flanges and gaskets. Replicating the onboard scenario allows the project to assess back pressure behaviour, turbocharger impact, valve response, heat transfer, leakage risk and emergency isolation under realistic operating conditions and provide representative evidence of how the system will behave onboard MV Coruisk. This reduces uncertainty before vessel installation and supports the LR approval process.

4.1.3 Regulatory requirements

The technology providers along with UoS and CalMac participated in four Lloyd's Register and two MCA workshops, for the Green Marine land-based and future onboard integration focused on the regulatory requirements ensuring that the exhaust bypass arrangement and connected technologies could be operated without compromising engine safety, vessel safety, or personnel safety. LR required a structured risk-based approach supported by HAZID outcomes, updated process flow diagrams, equipment specifications, operating procedures, and defined safeguards for abnormal conditions. Particular emphasis was placed on maintaining acceptable exhaust back pressure, providing reliable pressure monitoring, preventing flue gas leakage, ensuring suitable thermal barriers and material compatibility, ensuring fire safety, conducting structural assessment, and enabling the safe isolation of the Green Marine technologies in an emergency. The workshops also highlighted the need for a robust emergency shutdown and bypass function, including power disconnection and exhaust rerouting, as well as independent/manual intervention capability where required. In addition, LR recommendations led to improvements in the electrical supply arrangement, with the IoT/control system moved from engine battery supply to shore power to improve reliability and avoid interference with engine operation. Five recommendations have already been fully implemented, while the remaining thirty-six continue to be addressed during the onboard preparation phase (refer to D1.2).

4.2 SMP/WPS

SMP/WPS contributed to the development of retrofit procedures in three principal areas: design and development of SepaRaptor system for air cleaning and flue-gas pre-treatment, and waste-heat recovery system (thermoelectric elements).

4.2.1 *SepaRaptor (Air treatment)*

SepaRaptor units (air) were deployed primarily as stand-alone devices in crew spaces and on the bridge, with 29 of 40 units installed in these areas, while ceiling-mounted variants were assessed as non-feasible. Their placement was determined on the basis of practical retrofit considerations, namely desk availability, access to electrical power sockets, and minimisation of tripping hazards. To support participation, WPS/SMP, with the aid of CMMI and CalMac, prepared a short information brochure for crew members, while the SepaRaptor with UV technology is reported as already CE certified. Two ceiling-mounted alternatives were also developed, but these were found to be non-feasible because they required additional retrofit effort, offered lower benefits for air circulation, and, in one case, would have required a further CE certification route.

In addition to onboard retrofitting, SepaRaptor units were also taken home by crew members during the trial period from October 2024 to May 2025. A feedback survey was conducted, and the results indicate that 67% of respondents reported a reduction in cold frequency during the trial period.

For vessels equipped with compatible HVAC recirculation systems, the SepaRaptor unit (see Figure 12) was developed as an in-line retrofit solution for direct integration into existing HVAC ducts (refer to deliverable D2.2). These are modular types that require minimal duct modifications. The unit can be inserted into the airflow path by sliding it into the HVAC filter holder, with or without an accompanying filter element. The unit operates on a 110–230 V, 50/60 Hz power supply and has a nominal power consumption of 18 W. This configuration supports air-reuse management in passenger cabins and is intended to improve air-treatment efficiency compared to stand-alone deployment.

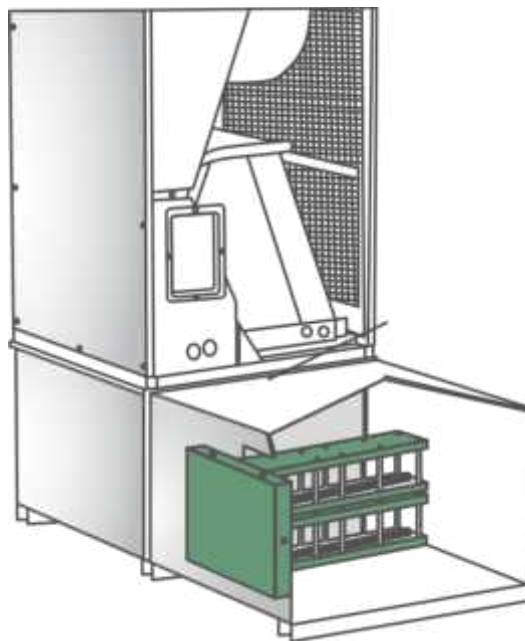


Figure 12: Illustration of HVAC system.

4.2.2 *SepaRaptor (flue gas treatment)*

For flue-gas applications, SMP/WPS developed the SepaRaptor as a pre-treatment unit upstream of the membrane capture system. The RP2 report documents an iterative design progression from an initial acrylic prototype to enclosed metallic housings and, subsequently, to a fully enclosed configuration intended to reduce leakage points and better support class-oriented design development. Validation and design refinement were carried out over an airflow range of approximately 20–180 m³/h. These results indicate that retrofit-oriented flue-gas pre-treatment systems should be designed from the outset around enclosed housings, standardized interfaces, minimized leakage paths, and low pressure-drop operation, particularly where subsequent classification review and onboard integration are anticipated.

4.2.3 *TEE system*

TEE retrofit was implemented as a compact, modular waste-heat recovery system interfaced with the existing engine through externally mounted double-walled exhaust piping, which simplified installation and supports future regulatory approval. The land-based testing in Cyprus followed a staged best-practice approach: inspection for transport damage on arrival, initial commissioning in an open and accessible configuration to improve inspection, continuous monitoring of temperatures, pressures, flow rates and electrical output, active adjustment of the hot- and cold-loop flow rates to maximise efficiency, use of thermal imaging for verification, and testing under defined engine-load steps before applying thermal insulation to emulate onboard conditions and improve heat transfer. The TEE remained connected to the cooling system via a bypass system, with voltage and current monitoring, and with the possibility of safe isolation for maintenance.

4.2.4 Feedback and lessons learnt

A key lesson learnt from the air-reuse activities is that the SepaRaptor solution must be designed on a vessel-specific basis and compatible with the existing HVAC recirculation system, which was absent in the current scenario. In addition, any retrofit must comply with Classification Society and Flag State requirements and be aligned with the retrofit procedures of the vessel operator. Also, it is critical to identify the location for these units for efficient air inflow. Therefore, as part of Task 5.2.1 of WP5, CFD-based airflow analysis on MV Coruisk was conducted to identify the most suitable positions for these units, particularly in the passenger and ticket-sales areas.

For the flue-gas pre-treatment system, the design must not induce additional back pressure, ensure downstream membrane protection, and provide a class-compliant enclosure. During development, the unit progressed from early prototypes to enclosed metallic housings and finally to a fully enclosed configuration, because multiple joints and bolts created potential leakage points, and any leakage in operation would involve flue gas. At the same time, the separator was intended to agglomerate fine particles and protect the downstream membrane system without relying on HEPA filtration, since this would increase back pressure and could adversely affect engine performance.

With regards to TEE, the retrofitting is technically viable and can deliver positive net electrical output, but performance depends more on thermal-loop design and auxiliary losses than on the thermoelectric modules. The maximum measured temperature gradient was 66 °C and an operational output was about 0.997 kW, while net power above 800 W was achieved at higher loads after subtracting auxiliary demand. At the same time, the added hydraulic resistance of the loops, heat exchangers and internal TEE channels increased pump's power consumption and reduced net benefit. The future retrofits should prioritise reduction of the temperature differences, minimisation of pressure drop and pump demand, compact modular integration, and class and flag compliance, insulation and safety systems.

Note: All tasks, which could be done without involving NA/marine consultants, were completed by SMP/WPS. (Refer to D1.2 Report on Retrofitting submitted in M42 for additional information)

4.3 SINTEF

The preparations for pilot testing of the membrane-based CO₂ capture technology followed a standard sequence as illustrated in Figure 13. The first three stages of pilot design and construction were largely completed by month 24 of the project. The subsequent HAZOP evaluations carried out together with LR Registry (external consultant) revealed several design changes which needed to be introduced in the pilot design. The changes were mainly related to flue gas conditioning (cooling) and required a redesign of the pilot, including changes to already constructed parts of the pilot.



Figure 13. Overview of the workflow for developing membrane pilot for demonstrating CO₂ capture using polymer membranes from a ship engine.

The changes led to a 6-month delay in the land-based testing campaigns. The land-based testing campaigns were still completed, and the pilot rig successfully allowed for integration with the other technology providers test set-ups. Unfortunately, the duration of the individual test periods at the land-based test facility was too short (only seven hours daytime operation) to achieve stable operating conditions for the membrane process. Thus, the value of the land-based testing was limited, and it was only possible to demonstrate the expected purity of the product, whereas operational stability and CO₂ recovery were not documented to a satisfactory degree during the land-based testing.

4.3.1 Membrane-based CO₂ capture unit

The main layout of the membrane-based CO₂ capture unit is shown in Figure 14 and a picture of the freshwater/glycol cooling circuit is shown in Figure 15.



Figure 14. Main equipment skid, flue gas conditioning, HX-1; flue gas fan, P-2; Separaptor unit, SEP-1, Membrane unit Mem-1 (yellow), Permeate vacuum pump P-3; and control cabinets. Flanges at the top of the skid show hot flue gas feed entering to the right and to the left is the return flange for the mixture of CO₂-depleted retentate and CO₂-enriched permeate from the membrane module.



Figure 15. Fresh water/glycol circulation loop.

Table 2 provides preliminary information on the weight and dimensions of the main equipment in the integrated Green Marine system.

Table 2. Preliminary information on weight and dimensions for the main equipment in the integrated system

Skid / Unit	Weight (empty / filled)	Dimensions (L x W x H)
<i>Membrane-based CO₂ capture (separate skid)</i>	<i>191 kg / 196 kg</i>	<i>1200 x 840 x ~2200 mm</i>
Flue gas fan, P-3	53 kg	
FG cooler, HX-1	16 kg / 21 kg	
Membrane module, MEM-1	10 kg	<1000 x 150 x 150 mm
Vacuum pump, P-4	17 kg	
Separaptor unit, SEP-1	20 kg	
Instrumentation and cabinet + frame	75 kg	
<i>Fresh water/glycol circulation loop (separate skid)</i>	<i>63 kg / 70 kg</i>	<i>800 x 600 x 600 mm</i>
Expansion tank V-1	10 kg / 15 kg	
Water cooler, HX-2	33 kg / 35 kg	
Fresh water Circulation pump, P-1	20 kg	
<i>Exhaust Bypass system and IoT platform</i>	<i>162 kg</i>	
<i>Thermo-electric element unit - TEE (separate skid)</i>	<i>105 kg dry</i>	<i>781 x 509 x 1160mm</i>
	<i>140 kg wet</i>	
Total:	521 kg / 568 kg	

Figure 16 shows the 3D illustration of the connection between the membrane-based CO₂ capture unit and the exhaust bypass arrangement.

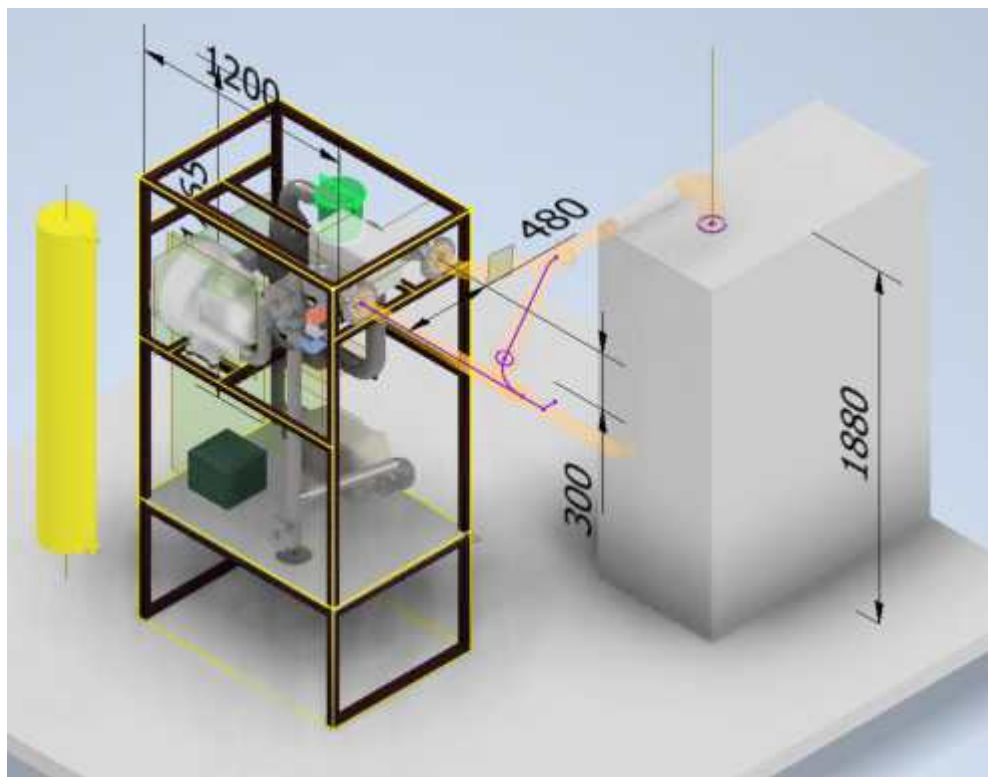


Figure 16. The updated bypass design was integrated with the engine at the CMMI site.

4.3.2 Off-shore testing at MV Coruisk

Entrance for equipment to the engine room will be through a hatch with a rectangular opening of 1210 mm x 840 mm. Figure 17 indicates the suggested location for the integrated system equipment within the engine room, where the location of the flue gas inlet/outlet from the system matches the flue gas duct from the land-based testing at CMML. However, it will be possible to install the integrated system at different locations (e.g., option 2) in the engine room, provided that the necessary adaptations are made to the exhaust bypass arrangement on the ship.

Details on connection to the sea water-based cooling system, as well as the connection between the TEE unit and the engine cooling circuit, need to be designed in detail.

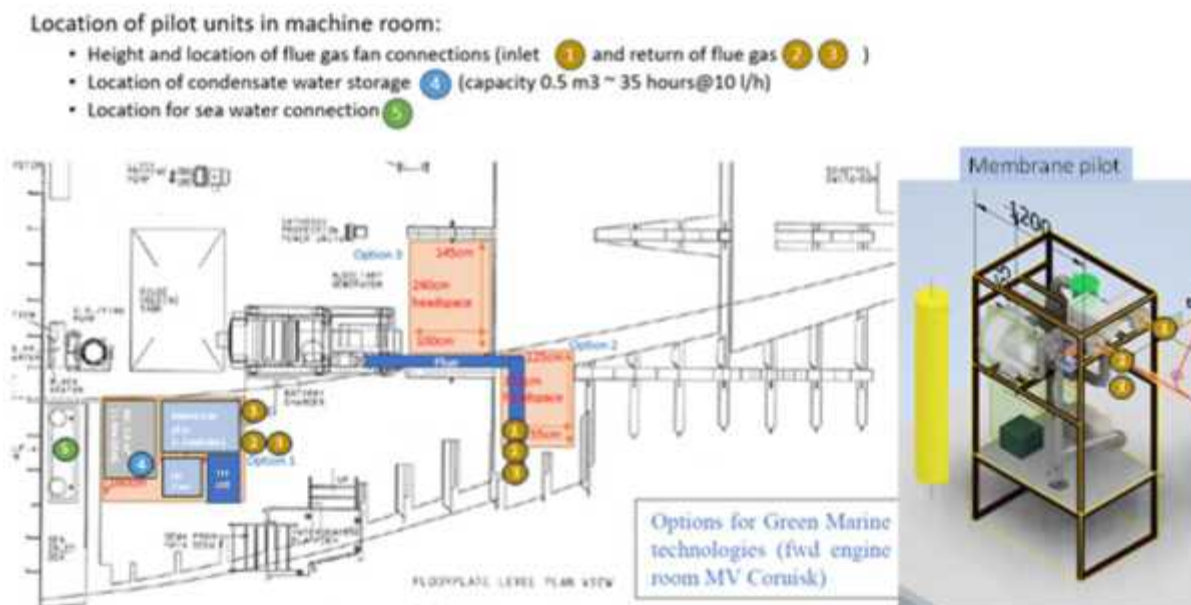


Figure 17. Tentative location of the integrated system in the Engine room of MV Coruisk.

4.3.3 Lessons learned

- Competence with a good overview of the CLASS and FLAG requirements for installation on board a ship should be involved already at the early design stage to guide design decisions.
- More than one land-based testing campaign is to be expected for a new process concept which has not been tested offshore. Pilot testing always triggers design changes.
- The vessel selected for offshore testing should be selected so as to minimize risk and consequences caused by any disturbance due to installation of pilot equipment.
- The land-based test facility needs to provide test periods with sufficient length (24/7 operation) and stable conditions to ensure that the process can be adjusted and performance evaluated at steady state for sufficient time periods. These requirements may vary depending on type of technology to be tested.

4.4 CCM

The Carbon Capture system which was built and delivered to Limassol for the January 2026 testing campaign (Figure 18) and intended to be installed onboard the MV Coruisk represents a significant technical advancement for CCM from this project. The original demonstration system built and evaluated in Aberdeen for the XPrize competition, though effective to prove feasibility of the technology and validated by Southern Research Institute, was ultimately the result of multiple design compromises which rendered this system incompatible with the technical requirements of the Green Marine project. Consequently, it was determined that a clean slate redesign was necessary to allow for the Carbon Capture Machine technology to be successfully adapted to a marine environment, beginning with the selection of materials of construction.

The original CCM design emphasized usage of low-cost, highly available plastics such as HDPE or PVC as the materials of construction for the majority of the process components. However, in consideration of the mobile maritime environment as well as the risk of UV damage with sunlight exposure depending on the siting of the equipment, it was decided to change the materials of construction for all major process components to metal. Additionally, metal materials of construction were preferred due to the ability to operate at higher temperature ranges than plastics such as HDPE or PVC, mitigating potential overheating which may come from heat transfer from the engine.

Considering the risk of corrosion due to environmental and process factors, the specific material of construction selected was 316L. Whenever possible, components were selected to consist of 316L stainless steel. For auxiliary components such as gaskets, or flexible hoses, fluorinated polymers such as FEP or PTFE were selected. These are more expensive and have more severe environmental impacts than other polymers, but the performance improvements justify the costs because they expand the window of operation by tolerating higher temperatures, are more durable materials, and the overall quantity used in these applications is relatively low.

The proper selection and layout of sensors is important for consistent unit operation. For example, as carbon capture retrofit projects would seek to add equipment to an already existing ship with a developed and mature propulsion system, it may be an intuitive design choice to rely on the upstream measurements of air flow, temperature, pressure, composition. However, in the attempt to effectively integrate disparate components, we find that the potential cost-savings are outweighed by the added complexity. First, as each engine room is unique, integration with the existing sensors such as thermocouples and tachometers may lead to consistency problems due to fine differences in device construction. Additionally, there may exist incompatibilities in communications protocols between the devices and modification of the engine or its subcomponents to accommodate the carbon capture systems may void warranty. Considering the relatively low cost of most sensors, independent measurement of process conditions within the Carbon Capture subsystem is the best approach because it allows for repeatable operation by consistent data collection protocols across multiple deployments. Rather than be used for control, we believe that the upstream measurements are best used to cross-reference unusual readouts and confirm calibration accuracy of sensors within the Carbon Capture subsystems.

Among the multiple types of sensors used, the flowmeters and gas analyzers are the most crucial instruments to quantify CO₂ capture and control the system in response to changing inputs, but both sets of equipment face unique requirements when applied to capture of carbon dioxide from flue gases. Flue gas is known to contain a significant amount of condensable moisture as well as acid gases which dissolve in the condensate. Flowmeters can be damaged by exposure to entrained water droplets which will cause inaccurate readings leading to eventual failure. The solution to this problem within the Green Marine project was to place the flowmeter downstream of a cooling heat exchanger and condensate knockout unit, which was effective for the purposes of the project. A more elegant solution could be to use a hot-wire anemometer or other thermal flowmeter intended for use in humid environments, because it would be more able to withstand moisture and potentially eliminate the need for a knockout, which must be routinely drained at least once per day.

Gas analyzers are used to measure the concentration of CO₂ in the inlet and outlet streams. There are many types of CO₂ analyzers, typically developed for specific applications – outside of the intended application, depending on the sensor, the accuracy may be adversely impacted. In addition to the condensation problem also faced by flowmeters, these analyzers may be susceptible to reading drift or be easily fouled by contaminants. For example, most commercial sensors for measurement of CO₂ in flue gas do not directly measure the CO₂; rather the O₂ concentration is measured, and an estimate for CO₂ is generated based on the amount of consumed oxygen versus ambient air (21%). If CO₂ is removed from the exhaust gas after combustion without consuming O₂, these sensors will simply not perform as intended. Electrochemical sensors are also common but highly susceptible to moisture and may be impacted by the many contaminants in engine flue gas. Instead, a sensor which can directly measure the CO₂ concentration but which does not directly contact the gas is required.

We have found that nondispersive infrared (NDIR) sensors fit these criteria well. These differ from traditional Fourier transform infrared spectrometers (FTIR) in that the light is not monochromatized prior to the analysis, which significantly reduces the cost and complexity but limits each sensor to analysis of just one or two gas species whereas FTIR can simultaneously determine the concentration of all IR-active molecules. Gas molecules contain bonds (e.g., O-H or C=O) which have unique energy levels. When light contacts these molecules, the photons corresponding to the energy levels of the bonds are absorbed and the energy converted to heat. This is the same fundamental mechanism as the Greenhouse effect which is the primary driver of anthropogenic climate change from CO₂ emissions. Thus, light absorption at specific wavelengths (4.26 μm for CO₂) is a highly reliable method to determine concentrations. Additionally, optically transparent windows may be used to protect the sensors and light sources from the process gas. We have found the Quantek 906 NDIR CO₂ analyzer to be an accurate and economical device, which has been implemented into the system developed for this project. For the most consistent measurements, the same model analyzer was used to analyze the gas composition at both the inlet and outlet of the CCM.

Though effective and robust, the Quantek 906 analyzer does have drawbacks. Most significantly, the NDIR analysis chamber is located within the tabletop unit, meaning the instrument relies on

an air pump which samples a gas stream for analysis before venting. The need to physically transport the gas inside of the analyzer increases response times; but because both the gas flowrate (<1 L/min), and concentrations of toxic species like NO_x (ppm's) in flue gas are also low, there is no serious safety risk. The most significant risk for our Carbon Capture Machine is that there can be a failure mode in which scrubber liquid enters the gas sampling lines and creates a blockage. In line (*in situ*) gas analyzers solve these problems by bringing the analysis chamber inside of the gas line, avoiding the need for sampling lines entirely. These devices are also commercially available (e.g., Mettler Toledo GPro 500, Vaisala GMP251) but were not selected for the Green Marine project due to cost and lead time considerations.

Besides CO₂, understanding of the other combustion products (CO, NO_x, SO_x, soot, hydrocarbons) is key to technological advancement of marine carbon capture systems, because these species can corrode, foul or have other unintended reactions with process components. Also important to understand is the effect of an ostensible carbon capture system on the concentration of these other contaminants, which would give an entire emissions profile when combined. Different engines will have different emissions profiles; the engine tested in Limassol for this project had no emissions control devices (e.g., catalytic converter, diesel particulate filter, soot oxidation) installed. Other factors which impact the engine emissions are the air-fuel ratio, exhaust gas recirculation and combustion chamber designs. Advanced combustion analyzers can measure all these components found in combustion exhaust, but such devices are significantly more expensive and require more overhead than NDIR; an analyzer provided by CMMI was installed into the bypass system to support this aim.

Another key learning from the Green Marine project is the importance of heat and pressure management to system design. While engine manufacturers specify a maximum back pressure, typically 100 mbar, the requirements for effective operation, in our experience, are much more stringent. When installed into a bypass configuration without a throttle, gas must be actively drawn into the carbon capture systems by a fan, otherwise the path of least resistance will be through the bypass. Higher resistance to flows means that more energy is required to power the fan for exhaust extraction to effectively compete with the bypass. The original Aberdeen CCM sourced gases from air compressors and CO₂ cylinders, meaning gas was easily available under ideal conditions for carbon capture, namely low temperatures and high pressures. In this setting, refrigeration as low as 5°C was available to help drive the CO₂ capture. The operating pressure or resistance to flow of the system was not relevant because the pressure budget (>2 bar) was very high owing to the nature of the gas sources. In contrast, flue gas aboard the MV Coruisk is available at low pressure and high temperature; the heat must be rejected prior to capture and only outside air can be used as a heat sink. Refrigeration below ambient temperature is not available. Consequently, successfully deploying CCM technology to a marine context necessitates a system capable of operating at higher temperatures and with a minimal pressure drop. Rather than re-use the existing architecture, a scrubber was designed from the ground up with the aid of process simulation software to meet these new stringent requirements. Additionally, the operating conditions of the system were reoptimized experimentally to fit the new requirements. Where the original carbon capture machine used 3-4 scrubber units to remove CO₂ at ambient to subambient temperatures,

the updated design just requires one unit and can operate up to 60°C with lower overall flow resistance.

The available space and utilities aboard a vessel influence the feasibility of a carbon capture retrofit. The CCM system contains multiple pumps, fans and sensors, each of which consumes electricity for operation and has its own size footprint. While each device must be installed, wired and configured, it is best to separate this from the act of retrofitting. Each vessel will have unique layouts and amenities, so it is imperative to simplify system facility requirements to the greatest extent possible to minimize risk of incompatibility based on electrical or footprint mismatch. To that end, rather than assemble and wire a system together on-site, every major CCM process component was packaged into a single 1.0 x 1.5 m skid within CCM's facilities. This approach also allowed for the proper functioning of the as-built system to be verified prior to the integrated land-based testing. All power draws were routed to a single 440 V, 32 A, 5 pin, 3 phase plug selected to match the existing receptacles in the Limassol testing site, meaning only one electrical connection was needed to complete setup.

When retrofitting ships with carbon capture, appropriate siting is key to minimization of cost and complexity. If carbon capture equipment is to be installed in a hazardous combustible environment, such as the engine room of a ship, it may be a requirement for the equipment to have relevant safety certifications (e.g., Class 1 Division 2). Neither flue gas nor any CCM components are flammable – the risk comes from proximity to fuel-handling components in the engine room. Removing the carbon capture unit operations from the hazardous area is a much more cost-effective approach to safety. The obvious failure mode of incomplete combustion in the engine leading to flammable mixtures downstream can be easily mitigated by engineering controls such as a simple combustible gas sensor and interlock. An additional safety measure is to increase design margins. For example, even though the carbon capture system is intended to operate below 100 mbar and has no mechanisms to reach higher pressure than 300 mbar under the worst-case scenario, the vessel used was rated to 8 bar (8000 mbar), which helps to inspire confidence with shipowners. Additionally, secondary containment is an extremely effective mitigation in the event of a leak; appropriately designed systems should be able to contain a leak 10% larger than the maximum possible from a single point of failure. From this perspective, it is safer to store liquids across multiple smaller tanks as opposed to a single larger tank. An additional safeguard which may be taken to minimize risk of leakage would be to seal unions by welding rather than by using a flange and gasket or compression fittings.



Figure 18: CCM's Carbon Capture Setup at the Land-Based Test Site

5 CONCLUSIONS

This deliverable presents the updates on the work procedures first described in D2.2 First Report: Work Procedure or Best Practice Methods for Retrofitting, developed within Green Marine for the retrofitting of the land-based marine genset and the preparation for future onboard implementation. Building on the first retrofit report, the work carried out in this reporting period refined the integration approach for the Green Marine technologies and translated practical testing experience into structured retrofit guidance. The results confirmed that a controlled and instrumented land-based setup is essential for reducing technical uncertainty before onboard installation, particularly where multiple abatement and energy-recovery technologies must interact with an existing turbocharged marine engine.

The report showed that successful retrofitting on the land-based scenario depends not only on the physical integration of sensors, bypass arrangements and technology interfaces, but also on the establishment of clear safety procedures, robust monitoring capability, and close alignment with Classification Society, Flag State and operator requirements. In simple terms, the report highlights the practical issues and solutions identified when applying the technologies developed in the project to an existing engine. The addition of upgraded sensors, IoT-based monitoring, exhaust back pressure measurements, safety barriers, emergency functions and revised power supply arrangements strengthened the testing platform and improved confidence in the retrofit methodology. In parallel, the experience gained through the LR and MCA workshops demonstrated that early regulatory engagement is critical to identify safety-critical components, define safeguard requirements and avoid late-stage redesign.

From the technology-provider perspective, the retrofit lessons confirmed that each solution requires early adaptation to the marine operating environment. CCM highlighted the importance of marine-compatible material selection, independent subsystem monitoring, low pressure-drop design, heat management, suitable CO₂ measurement under humid flue-gas conditions, compact skid packaging and leak-prevention measures. SMP/WPS demonstrated the need for vessel-specific integration of SepaRaptor and TEE systems, with emphasis on low back pressure, modular

installation, thermal-loop optimisation, safe isolation and compatibility with existing HVAC or exhaust arrangements. SINTEF's membrane system experience showed that flue-gas conditioning, cooling, stable operating periods, sufficient space, class/flag input and early HAZOP-driven design updates are essential for reliable onboard CO₂ capture demonstration.

Overall, D2.3 confirms that Green Marine has developed a more mature and realistic retrofit framework for land-based and future onboard applications. The lessons learned in relation to installation, monitoring, safety, control logic, materials selection and regulatory compliance provide a practical basis for the next project phase. These best practices will support the tailoring of the selected solutions for onboard deployment, reduce integration risk, and contribute to the wider objective of accelerating retrofit pathways towards climate-neutral waterborne transport.

REFERENCES

[1] Cummins, *Generator Engine Performance Data, Basic Engine Model: 6CTA8.3-GM155*, Cummins.

ANNEX 1

Annex CMM Audit (Page 1/3)



Environmental Health, Safety and Quality audit checklist

Location:	Limmasol Harbour, Petronav premisses
Date of Check:	27 Jan 2026
Inspection by:	Harsha
Tech evaluated	Carbon Capture Machine
Date of test	23 Jan 2026 (Dry Run-Zero Load), 26 to 27 tests with 80KW engine load.

Name auditor and Signature:

H. Prabhakara

Data collection

Type of data for:	CCM System parameters include Flowrate, CO2 % in in and out flows, dosing rates, pressure and temperature in the packed bed, the conductivity and pH of the of the dosing solution.
Where and how are they registered?	Collected on the laptop data logger.
How is it stored?	On laptop equipped with Data logger.
Who does it? Person Name	CCM: Tomas, John & Michael
Are all KPIs collected?	CCM: Dosing Flow rates, Flue gas flow rates, P, T of the column and CO2%
o Missing KPI's:	KPI's ok. Testing protocol missing with test plan being only shared with CMMI. BX cannot verify if all the tests as planned were done. However, the tests witnessed by BX seems to be logical and technical.
Where are KPI's logged?	On laptop which is equipped with data logger.

Monitoring of KPI's

Which KPI'S	CCM KPI's include CO2 % in in and out flows, dosing rates, pressure and temperature in the packed bed, the conductivity and pH of the of the dosing solution.
Technique (monitor) used for KPI:	CCM: Dosing Flow rates, Flue gas flow rates, P, T of the column and CO2%. Data with CCM.
Where and how is sample taken and monitor used?	On laptop equipped with Data logger. Data with CCM
Technique to evaluate?	
o CO2	Standard Sensors.
o Contaminants?	Depends on CMMI logger. It was not functional during CCM tests.
o Nano-particles	Not applicable
o Energy?...	Packed bed temperature measured using integrated thermocouple.
o NaOH consumption	Monitored by dosing pump and data logged.
Who does it – person name?	Automatic

Product – technology provider / developer

Annex CMM Audit (Page 2/3)

Type of product collected:	CO ₂ ends up in solvent which is then converted into a solid product.
How is purity of product determined?	CO ₂ Sensors used for determining gas purity. The solid product purity to be investigated in lab.
How is amount quantified? (Recovery)	Mass balance to be checked by CCM.
How is contaminant quantified?	Solid products contaminate to be investigated in lab. The gas purity depends on CMMI sensors. CCM can only check CO ₂ concentration.
Who does it and is this person trained, what is the skill set of this person?	Team of 4 persons from CCM: 2 technicians, 1 PhD and CEO visited for observations.

Demo testing conditions

Duration of testing and measurements?	Total Continuous testing of about 3 to 4 hours with load ramping up steadily.
Simulation conditions: e.g. regime's, start-stop, continuous, other	
Engine operating conditions	CMMI to provide data.
○ Type of fuel:	Diesel. CMMI to confirm in deliverable.
○	
○	

Quality of Work & Costs

Is working procedure standardised and if so according to whose requirement?	BX cannot comment on the CCM protocol.
Is analytical procedure standardised? According to whose requirement?	BX cannot comment on the CCM protocol.
Are external variables considered i.e. NOx from port area – vehicles / vessels?	no
How is sampling conducted? Is this checked regularly?	Real time continuous monitoring.
How is analytical equipment calibrated and is this checked?	BX cannot comment on the CCM protocol as it did not share with BX.
Variables included in costs considered if so how:	Not applicable.

Safety to people and environment

Is there a Last Minute Risk Analysis	Yes. CCM assured that the relevant safety measures are in place. CMMI and SINTEF team was present during the Safety explanation.
Is equipment necessary like PBM's, provided?	Yes
If PBM's are provided are they of good quality	Yes
Are their hazards (hot surfaces, CO ₂ , moving parts)	Yes. There were cables on the floor. Engine issue with cooling and therefore

Annex CMM Audit (Page 3/3)

Is the facility sliding door open for ventilation	the safety cabinet was open and personnel had restricted access. Yes
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Environment

Measures taken to prevent harm to marine species?	Not applicable
Disruption to natural environment?	No
Significant emissions to water / Air?	Yes, standard emissions for flue gas
Is there a risk to impact the environment	Minor risk if the solvents are not handled/transported in a safe manner
How is impact to environment evaluated?	Not applicable

Any remarks auditor during inspection:

The CCM system seems to be technically operational and logical. The CCM flowmeter seems to restrict the flue gas flow. The Flowmeter was removed in the last tests to ensure there is high flow through the system (55 to 65 m³/hr). CCM could have gone even higher, but they were limited by Engine issues (Not cooling enough).

The CCM sensor was not functional for about 1 hour during the last day of testing.

Annex CMMI Audit (Page 1/3)



Environmental Health, Safety and Quality audit checklist

Location:	Limassol Harbour, Petronav, premises	Name auditor and Signature Sara Antomaroni & Ludwin Daal
Date of Check:	15 Jan 2026	
Inspection by:	Sara and Ludwin	
Tech evaluated	Membrane Sintef, bypass and engine	
Date of test	Dry run 14 Jan	

Data collection

Type of data for:	Membrane and Engine parameters. Operational checks for Engine and Sintef pilot together.
Where and how are they registered?	On the pilot system for membrane: SD card, Server Trondheim (via antenna); Logbook of Engine CMMI stores on IoT platform, sensors software (for the latter a usb stick needed to transfer data)
How is it stored?	On server, SD card and laptop, Engine: on
Who does it? Person Name	SINTEF: Lars, Marius, and Stefan, CMMI: Georgia and Pavlos
Are all KPIs collected?	See Deliverable 4.2, SINTEF: flow rates, P, T, CO2 and O2; CMMI: Temperature, CO2, CO, contaminants (NOx)
☐ Missing KPI's:	No KPI's missing, all ok, water condensate may accumulate in pipe
Where are KPI's logged?	Onsite and logged by SD card / server / IoT and by hand

Monitoring of KPI's

Which KPI'S	Tech specific: i.e. CO2 (product) Recovery, CO2 Purity, Efficiency removal, energy consumption, operating pressure
Technique (monitor) used for KPI:	Flow, P,T, CO2, CO data will be stored and included in SharePoint
Where and how is sample taken and monitor used?	Automatic and data will be shared and analysed with real-time control
Technique to evaluate?	
☐ CO2	SINTEF: NDIR online monitor (feed and permeate) and for engine Vario Flux
☐ Contaminants?	SOX handheld Lancom 4 Analyser; Safety sensor on CO
☐ Nano-particles	not applicable
☐ Energy?...	Thermocouples and System measurements
☐ NaOH consumption	Not applicable
Who does it – person name?	Automatic

Product – technology provider / developer

Type of product collected:	CO2 collected
How is purity of product determined?	Measurement online, CO2 sensors, Sintef to followup on the type of sensor (sent to Ludwin)
How is amount quantified? (Recovery)	Flow meter, P,T, measured CO2 and O2

Annex CMMI Audit (2/3)



How is contaminant quantified?	SINTEF (O2, CO2), with Engine (Cmmi) team,
Who does it and is this person trained, what is the skill set of this person?	Team of 3 persons from SINTEF: techs/scientific CMMI: 2 techn/scientists

Demo testing conditions

Duration of testing and measurements?	Continuous - to verify Thiller's performance
Simulation conditions: e.g. regime's, start-stop, continuous, other	
Engine operating conditions	See Deliverable 2.2 as reference. i.e. backpressure and load conditions
○ Type of fuel:	Diesel (to be confirmed with details → diesel similar to fuel a car
○	
○	

Quality of Work & Costs

Is working procedure standardised and if so according to whose requirement?	According to testing protocol. Yes variables have been pre-tested and compared to real-time.
Is analytical procedure standardised? According to whose requirement?	
Are external variables considered i.e. NOx from port area – vehicles / vessels?	no
How is sampling conducted? Is this checked regularly?	Real time parameters monitoring,
How is analytical equipment calibrated and is this checked?	Comparison between manual and automatic measurements before testing
Variables included in costs considered if so how:	

Safety to people and environment

Is there a Last Minute Risk Analysis	Yes, discussed items: automatic valves, emergency stops, hot surfaces (exiting pipe), trip danger, CO sensor
Is equipment necessary like PBM's, provided?	Yes
If PBM's are provided are they of good quality	Yes (helmet)
Are their hazards (hot surfaces, CO2, moving parts)	Yes tripping of cables, hot pipe (not reachable for some ppl).
Is the facility sliding door open for ventilation	Yes

Environment

Measures taken to prevent harm to marine species?	Not applicable
Disruption to natural environment?	No
Significant emissions to water / Air?	Yes, standard emissions for flue gas

Annex CMMI Audit 3/3



Is there a risk to impact the environment
How is impact to environment evaluated?

No

Not applicable

Any remarks auditor during inspection:

..... Piping was fixed by CMMI, risk of CO/CO2 was reduced.

End of day, no water was found in Sintef system. Engine was operating at just 20%.

On final day 16 Jan, engine was operating at about 75% and flow in system was 25-30 Nm3/hour. About 2 liters of water was found by SINTEF team (Nuno Pedrosa gathered the data). The RH meter showed 100% directly after heat exchanger.

Water condensation in system is a risk and regular releases of water is needed to prevent pilot system to be flooded. SINTEF team monitors pressures and this should be picked up relatively quickly if this changes.

Annex SINTEF Audit 1/3

Environmental Health, Safety and Quality audit checklist

Location:	<u>Limnassol Harbour, Petronav</u> <u>premisses</u>	Name auditor and Signature Ludwin <u>Daal</u>
Date of Check:	<u>14 Jan 2026</u>	
Inspection by:	<u>Ludwin Daal</u>	
Tech evaluated	<u>Membrane Sintef and bypass</u> <u>(engine)</u>	
Date of test	<u>Dry run 14 Jan</u>	

Data collection

Type of data for:	Membrane parameters. Operational checks for <u>sintef</u> monitoring test setup
Where and how are they registered?	On the pilot system for membrane: SD card, Server Trondheim (via antenna)
How is it stored?	On server and SD card
Who does it? Person Name	Lars, Marius, and Stefan
Are all KPI's collected?	See Deliverable 4.2 and compare
o Missing KPI's:	No KPI's missing, all ok, water condensate may accumulate in pipe
Where are KPI's logged?	Onsite and logged by SD card / server

Monitoring of KPI's

Which KPI'S	<i>Tech specific: i.e. CO2 (product) Recovery, CO2 Purity, Efficiency removal, energy, operating pressure; For water this can be captured separately and weighed (manually)</i>
Technique (monitor) used for KPI:	CO2 with NDIR (filter, membrane), O2 Transmitter (membrane/package), P, T and flow (meter)
Where and how is sample taken and monitor used?	See drawing and pictures. Permeate, feed and retentate. BX provided RH meter installed at feed (can also be located at retentate)
Technique <u>to evaluate</u> ?	O2 with Sensor containing electrolytes (supplier <u>Southland Sensing</u> www.ssO2.com)
o CO2	NDIR online monitor (feed and permeate, supplier <u>Sensors-inc</u> www.sensors-inc.com from Germany) and for engine Vario Flux
o Contaminants?	NOX and <u>SOx</u> handheld <u>Lancom</u> 4 Analyser
o <u>Nano-particles</u>	No <u>analyzer</u> , not applicable for membrane only
o <u>Energy?</u>	Thermocouples for heat, And energy monitor for entire membrane system
o NaOH consumption	Not applicable
Who does it – person name?	Automatic

Product – technology provider / developer

Type of product collected:	CO2 collected – sent back to flue gas outlet
How is purity of product determined?	Measurement online

Annex SINTEF Audit 2/3



How is amount quantified? (Recovery)	Flow meter, <u>P.T.</u> measured CO2 and O2
How is contaminant quantified?	Not on <u>Sintef</u> system, with Engine (<u>Comm</u>) team, collected water can determine pH and conductivity (acids)
Who does it and is this person trained, what is the skill set of this person?	Team of 3 persons from SINTEF, all well trained and experienced. Experience at Tiller.
Demo testing conditions	
Duration of testing and measurements?	Not running – dry run
Simulation conditions: e.g. regime's: start-stop, continuous, other	Not running – dry run
Engine operating conditions	See Deliverable 2.2 as reference. I.e. backpressure and load conditions
☐ Type of fuel: ☐ ☐	Not running – dry run

Quality of Work & Costs

Is working procedure standardised and if <u>so</u> according to whose requirement?	Not exactly on paper, but yes fixed steps/procedures and discussed daily with project leader SINTEF (by phone). Steps are <u>a.o.</u> Electrical pre-testing, mechanical, cooling, flows, leakage test.
Is analytical procedure standardised? According to whose requirement?	<u>P.T.</u> flow meter all pretested in Tiller <u>Norway</u> . <u>Sintef</u> own requirements, and upon request SINTEF team conducted a BX proposed leakage test. This was conducted on permeate side (100 mbar 3 mbar increase in 1 minute).
Are external variables considered i.e. NOx from port area – vehicles / vessels?	Dry run not evident
How is sampling conducted? Is this checked regularly?	There is a regulated flow meter for CO2 and O2. Calibration on O2. O2 was also checked with ambient value 23 vol.%, 6% at Tiller and CO2 checked on 10 vol.%. (<u>gasbottles</u>) BX's checked logic of all T's, slight differences likely due to sun / hot engine to test setup.
How is analytical equipment calibrated and is this checked?	Flow meter results BX (handheld Testo) did not correspond to flow meter SINTEF. Likely flow meter BX not working properly (age, visual damage/scratches)
Variables included in costs considered if so how:	Energy consumption, flow meter

Safety to people and environment

Is there a <u>Last Minute</u> Risk Analysis	No, not on 1 st day = dry run (2 nd yes, with engine)
Is <u>equipment necessary</u> like PBM's, provided?	Yes
If PBM's are <u>provided</u> are they of good quality	Yes (helmet)

Annex SINTEF Audit 3/3



Are their hazards (hot surfaces, CO2, moving parts)

Yes tripping of wires / hoses

Is the facility sliding door open for ventilation

Yes

Environment

Measures taken to prevent harm to marine species?

Not applicable

Disruption to natural environment?

No

Significant emissions to water / Air?

No

Is there a risk to impact the environment

No

How is impact to environment evaluated?

Not applicable, dry run

Any remarks auditor during inspection:

..... For membrane testing, water can accumulate in hose just after exit of membrane vacuum pump (see pics below – right foto)

Several fixtures (like wrap or with band (see pics)) are likely not according to Lloyds requirements.

