Demonstration of ship-based carbon capture on LNG fuelled ships

Final report

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1 Identification of the project and report

Project title	Demonstration of ship-based carbon capture on LNG fuelled ships (EverLoNG)
Project ID	327332
Coordinator	TNO (Marco Linders)
Project website	https://everlongccus.eu/
Reporting date	18st April 2025

Participants

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2 Executive summary

The maritime sector aims to reduce CO_2 emissions from international shipping, reaching net zero emissions by 2050. Ship-Based Carbon Capture (SBCC) or onboard carbon capture (OCC) is proposed as a low-cost alternative to decarbonize the maritime sector, as compared to zero-emission fuels (ammonia, hydrogen). The Objective of the EverLoNG project was to accelerate the implementation of Ship Based Carbon Capture (SBCC) technology by:
(i) demonstrating OCC on-board of two LNG-fuelled ships (WP1)
(ii) facilitating the development of OCC-based full CCUS chains (WP2)
(iii) optimising OCC integration to the existing ship infrastructure (WP3)
(iv) perform life cycle assessment and techno-economic evaluation: to show the impact of this technology, both from an economic viewpoint as from an environmental viewpoint (WP4)
(v) facilitating the regulatory framework for the technology (WP5)

The main conclusions of the EverLoNG project to achieve and contribute to these objectives are:

- WP1 – OCC was successfully demonstrated onboard two vessels. Both campaigns were performed using the benchmark post-combustion capture technology based on chemical absorption of CO_2 by an aqueous solution of monoethanolamine (MEA). The first campaign, onboard a LNG carrier (Seapeak Arwa, chartered by TotalEnergies), demonstrated the capture technology and reached capture rates up to 80%. The second campaign, onboard the semi-submersible crane (Sleipnir, owned by Heerema), included both capture and liquefaction of CO_2. The campaigns allowed us to evaluate the system's performance, particularly regarding amine and ammonia (an amine degradation product) to the atmosphere, and the solvent degradation rate. The MEA emissions during the LNG carrier campaign were low, easily controlled by the standard water wash system included in the CO_2 capture pilot. On the other hand, MEA emissions during the Sleipnir were high, caused by aerosols present in the exhaust gas. The origin of such aerosols is not yet clear, and should be investigated in future onboard campaigns. Solvent degradation was relatively high during the LNG carrier campaign, due to the relatively high NO_2 content in the exhaust gas. During the Sleipnir campaign, NO_2 was removed from the exhaust gas before entering the absorber, and this allowed to control degradation to relatively low levels. These learnings are important to de-risk future implementation of OCC.
- WP2 – For a large-scale development of OCC, port infrastructure is essential. Developing ports with CO_2 handling infrastructure is one of the major steps to ramp up this technology. Low CO_2 volumes per ship and potential long time between a ship arrival to port are two of the main challenges and what increases the costs. Minimizing the extra time needed at port to offload CO_2 is also an important consideration for the shipping industry. Through several workshops and webinars with relevant stakeholders and industry representatives, knowledge of challenges and solutions for integrating OCC into the marine industry have been exchanged.
- WP3 – The work done in this work package provided insight in relations between performance parameters of OCC systems, such as CO_2 capture rate and avoidance, fuel penalty, and impact of the OCC systems on the ships and their systems. This allowed the design of fuel efficient OCC systems for the two cases, achieving >70% onboard CO_2 emission reductions. More

importantly, the gained insights and developed methodologies can be applied more broadly to assess the feasibility of OCC for other ships and ship types, and enable the design of efficient OCC systems for these ships. Possibilities for further improvement of the OCC technology have been identified.

- WP4 – The environmental reduction target of >70% CO_2 reduction during operation (tank-to-wake) was validated using LCA, with 72% CO_2 reduction for the Sleipnir and 82% for the LNG carrier. Considering the entire life cycle, including fuel provision and subsequent CO_2 geological storage as well as other greenhouse gases like methane, the impact on climate change can be reduced by 39% CO2-eq and 44% CO2-eq, respectively. However, the cost targets were too ambitious and were not reached. TEA showed that a newly designed full-scale system can come close to the targets while retrofitting is much more expensive.
- WP5 – For the technologies used in Ship-Based Carbon Capture (SBCC) systems Regulatory and Class Rules frameworks exist that allow for their safe implementation onboard. Where prescriptive Rules and Regulations are missing, the alternative design assessment pathways are suitable and available. The risks associated with SBCC installations are credible but well understood. The EverLoNG project delivered a solid set of generic recommendations and safeguards, based on well-established design principles, which should accelerate the relevant approval processes.
- WP6 – Apart from establishing a successful project website with appropriate maritime-themed branding, which contains a 'Ship's Log' section with 25 individual news items, vlogs and videos, three public webinars have also been organized. These webinars were very well attended, each reaching 100+ attendants. The website proved very popular, pulling in an average over 300 monthly users with four discernible peaks of 1,050+ monthly users aligned with the start and end of the 1st and 2nd capture demonstration campaigns.

3 Role and contributions of each project partner

The role and contributions of all project partners are described below:

- TNO: is the coordinator of EverLoNG and Dutch national point of contact; TNO has led WP1 and WP6. TNO performed a campaign with its mobile CO_2 capture plant, assisted with the prototype operations during the demonstration campaigns, performed exhaust gas characterization measurements onboard, performed the conceptual design of the prototype and full scale use-cases, participated on the life cycle assessments (LCA), lead the techno-economic assessments (TEA), and participated on the HAZIDs.
- Conoship: lead of WP3. Conoship coordinated and performed the research and established optimal arrangements for the full scale SBCC system integration components onboard, regarding integration with the existing ship infrastructure and evaluated the impacts on ship stability and other naval architectural subjects. Conoship also advised on the best integration of the prototype for the demonstration campaigns, provided input for and participated in the HAZIDs, and provided input for the LCAs and TEAs.

- Carbotreat: engineered, procured and constructed the prototype unit, engineered and implemented the electrical, instrumentation, control and automation systems of the prototype unit, guided a HAZOP session, was involved in the commissioning campaign, and assisted with the demonstration campaigns. Carbotreat participated on the conceptual design of the full-scale systems, provided P&IDs, designed the heat integration systems and the standardized SBCC system. Finally, Carbotreat contributed with the LCAs, TEAs, HAZIDs.
- VDL: contributed to the design of the SBCC prototype, contributed to the prototype HAZOP session and full-scale HAZIDs, researched and advised on optimal integration of the prototype and full-scale systems on-board, lead the task on the prototype realization, participated on the commissioning, provided training to crew members who operated the prototype, and provided a crew member that sailed several weeks on the Sleipnir to operate the capture unit. VDL also lead the task on standardizing the SBCC prototype. Finally, VDL contributed with the LCAs and TEAs.
- Anthony Veder: was an advisor in the CO_2 Shipping Interoperability Industry Group (CSIIG), contributed to develop offloading strategies and connection to planned storage infrastructure, helped elaborating a roadmap towards a European off-loading network, provided advice on the design of the CO_2 storage units, and contributed to the HAZIDs.
- Heerema: hosted the small-scale CO_2 capture system and the SBCC prototype on-board of the Sleipnir. Heerema made the arrangements necessary for the prototyping campaign, including any required tie-ins to the ship. Heerema also contributed to the LCAs, TEAs and safety studies concerning its ship.
- Forschungszentrum Jülich (FZJ): German national point of contact. FZJ lead WP4 where environmental impacts were evaluated using Life Cycle Assessment (LCA). It conducted the LCA for the different SBCC full chains and provided the results of the CO_{2eq} reduction target evaluation.
- MAN: advised the experimental program, supported in providing engine technical specification for MAN built engines and performed measurements on the exhaust gas composition. MAN gave recommendations about cold recovery equipment and advised on the liquefaction system design. MAN lead the task of analysis of heat integration between SBCC system and ship's systems. MAN provided research on alternative mitigation technologies.
- SINTEF was the Norwegian national point of contact and also the WP2 leader, directly involved in all tasks of this WP. SINTEF was also engaged in activities related to Techno-Economic Analysis in WP 4, CO_2 specifications, CO_2 offloading strategies and the development of a Roadmap for CO_2 offloading network.
- TotalEnergies is a major O&G operator with experience from the Northern Lights Project and added experience to the project across WPs both as ship owners, CO_2 capturing and transport technology experts and knowledge within the area of permanent storage of CO_2. A ship chartered by TotalEnergies hosted the SBCC prototype system, which was integrated with the ship systems. About a 6 month test campaign has been performed onboard.
- The Class societies Bureau Veritas (BV) and Det Norske Veritas (DNV), in close collaboration with Lloyd's Register (LR), technology developers and end users, covered the regulatory and safety assessment work in WP5, aiming to de-risk installation of SBCC systems onboard ships. In particular, BV led the identification of applicable safety and environmental standards and codes associated to SBCC and the risk assessment (HAZID) of the preliminary full-scale design of SBCC on

board the LNG carrier. DNV led the categorization of new technology and the identification of safeguards from the risk assessment.

- AKP has valuable connections to the maritime environment particularly in the north West of Norway including ports. They supported the offloading strategy work and the development of a CO_2 offloading network.
- SCCS is the national consortium for CCS in Scotland and has a track record in analysing CO_2 shipping for CCS projects and acted as the UK lead as well as leading a task in WP2, developed the CSIIG, and was responsible for dissemination and knowledge exchange workshops, and contributed to the development of the port readiness tool; SCCS also participated in WP6 delivering the communication and dissemination activities for the project outputs and findings, including arranged the EverLoNG website.
- Lloyds Register EMEA (LR) is part of the Lloyd's Register Group, a global independent risk management and safety assurance organization that works to enhance safety and to approve assets and systems at sea, on land and in the air. LR lead the WP5 on the regulatory framework for ship-based carbon capture (SBCC) systems in collaboration with the other class societies BV and DNV, technology developers and end users. The Class societies aimed to de-risk installation of SBCC systems onboard ships and endeavored to disseminate among international regulatory regimes.
- LANL provided analytical support for quantifying solvent degradation rates and developed an overall solvent management strategy (WP1). LANL analysed samples supplied from the pilot plants and provide input into the design of the solvent reclaiming process for the CO_2 offloading facilities. LANL was also responsible for coordination and over-seeing the work performed by Nexant under WPs 2 and 4.
- NEXANT, subcontracted by LANL, designed the CO_2 off-loading facilities and on-shore CO_2 purification and conditioning plants (WP2). The onshore plants included solvent reclaiming facilities, which were also designed by Nexant (WP2), based on the campaign results and advices from LANL. Moreover, Nexant provided support for the technoeconomic analysis of the full CCUS chain (WP4).

4 Short description of activities and final results

WP1: Demonstration of SBCC

The work in WP1 started with the design of the carbon capture prototype. The prototype is designed to capture and liquefy up to 250 kg of CO_2 per day. TNO has performed simulations to propose a conceptual design of the prototype. The design was also informed by the results of the tests performed with TNO's mobile capture plant operating with exhaust gas of one of the Sleipnir engines. Based on the conceptual design, Carbotreat has performed the engineering design of the prototype. Process Flow Diagrams (PFDs) and Process and Instrumentation Diagrams (P&IDs) were generated, as well as a Basis of Design document. Having the PFDs and P&IDs as basis, HAZOP sessions were performed, led by Lloyds Register, in which all the partners in WP1 reviewed the design. The feedback from these sessions was compiled in a report, and used by Carbotreat to update and finalize the prototype design.

The prototype consists of 3 main modules, each housed in a 20 feet container, as seen in Figure 1. The first container includes the Carbon Capture system. The bottom part of the columns is inside the container, together with all other equipment (heat exchangers, pumps, etc.). The remainder of the columns are assembled in a skid (light blue frame), which can be disconnected from the top of the container to facilitate transportation. The second container is the liquefaction system, consisting of 4 main process steps: compression and partial water removal from the wet CO_2 gas after the capture system; drying of the CO_2 gas; liquefaction of the dry CO_2 gas by cooling down the gaseous CO_2, and finally, non-condensable gases are removed from the liquid CO_2 by a stripping column equipped with a reboiler. The third container is a CO_2 storage tank with capacity for ca. 20 m^3 , where liquid CO_2 is stored at 15 bar(g) and -27°C.

Figure 1. EverLoNG SBCC prototype pictures showing the CO_2 capture and liquefaction containers, as well as the liquid CO_2 storage tank.

The design phase was followed by procuring, installing and commissioning of the prototype. Subsequently, the prototype has been placed and integrated on board two ships: the Seapeak Arwa, an LNG carrier chartered by TotalEnergies and the Sleipnir semisubmersible crane vessel from Heerema. Measurement campaigns were performed on each of these ships, about 6 months on the Seapeak Arwa and about two months on the Sleipnir. Next, the main findings of the campaigns are discussed. The main learnings of EverLoNG, which are relevant for the scale-up of OCC are related to solvent losses due to emissions and degradation, therefore these topics are discussed in more detail.

- Campaign TotalEnergies

During the TotalEnergies campaign, only the capture part of the prototype was operational. The campaign lasted for 2475 hours. The pilot was operational for 1539 hours, and offline for 936 hours. The time offline was caused by either the operation of the ship (e.g. engine maintenance, in port, sailing with Diesel) or problems with the equipment in the pilot (e.g. equipment failure, triggered alarm). The campaign was executed in 3 different phases, starting with lower MEA concentration (5-7 wt%), then intermediate MEA concentration (16-18 wt%) and finally a third phase with 30 wt% MEA, which was the initially intended concentration. In the phase with low solvent concentration, the average capture rate was 23.1% (std 6.6%); with the intermediate solvent concentration, it increased to 54.0% (std 8.6%); and with more concentrated solvent, the average capture rate was 79.3% (std 5.9%).

- Campaign Sleipnir

During the Sleipnir campaign, the prototype was fully operational, and the captured CO_2 was liquified and temporarily stored in the liquid CO_2 tank. The total campaign duration was 1133 hours. The pilot was operational for 418 hours, and offline for 715 hours. The time offline was caused by either the operation of the ship (e.g. engine maintenance, in port, sailing with Diesel) or problems with the equipment in the pilot (e.g. equipment failure, triggered alarm). Due to issues with the gas blower, the exhaust gas flow entering the pilot was significantly lower than was the design value. This caused the capture rate to be quite high, averaging ca. 98%. Around 4200 kg of CO_2 were capture and liquified during the campaign.

- Solvent losses due to emissions

Amines are volatile components. The EverLoNG prototype is equipped with a single water wash column, and during the TotalEnergies campaign this was sufficient to control MEA emissions, which were often near the detection limit of the FTIR equipment, estimated around 1 mg/Nm^3. There were some isolated events with increased MEA emissions, with the highest MEA emissions of the campaign reaching up to 600 mg/Nm^3 for a short period. These are believed to be aerosol-based emissions. The causes of aerosol emissions are not fully understood, but some of the events are linked with incomplete combustion.

To further investigate the nature and reasons of aerosol-based emissions, the Sleipnir campaign included measurement of fine particles (with diameter below 1 µm), which are known to lead to aerosol-based emissions. In this campaign, the average MEA emissions were much higher, averaging 62 mg/Nm^3 (std. 93 mg/Nm^3). High peaks, with emissions up to 854 mg/Nm^3 (std. 92.86 mg/Nm^3) were observed. High emissions were correlated with sub-micron particle concentrations in the range of 10^6 to 10^7 particles per cm^3 of gas. This confirms that the observed emissions are aerosol-based.

Future demonstration and implementation projects of OCC should carefully consider the engines' operational profiles, and preferably perform sub-particle measurements onboard prior to the OCC plant design. When the potential for aerosol-based emissions is identified, measures to mitigate these emissions should be incorporated. Such technologies are commercially available, and are expected to add limited costs to CO_2 capture.

- Solvent losses due to degradation

Amines degrade either thermally or oxidatively. Thermal degradation happens mostly in the stripper side, when temperatures are between 100-120°C, whereas oxidative degradation is caused by reactions of the amine with oxygen or NO_2, which are absorbed from the exhaust gas. To evaluate the MEA degradation rate, the MEA content in the solvent as well as the concentration of some degradation products were measured by analysing solvent samples. The MEA losses were compared against the losses of a reference pilot campaign, performed at the Test Center Mongstad (TCM) using flue gases from a refinery and CHP plant.

In both EverLoNG campaigns, thermal degradation was significantly higher than in the TCM reference campaign. This is due to a design choice of the pilot: heat from the exhaust gas is recovered in a coil heater submerged in the reboiler sump. This leads to high skin temperatures, and increases the solvent thermal degradation. This can easily be circumvented in future OCC projects by using an intermediate heating media (e.g., steam) with controlled temperature.

The oxidative degradation observed in the TotalEnergies campaign was relatively high, as compared to the TCM campaign. The MEA loss in this first EverLoNG campaign was estimated at 3.8 kg/ton CO_2, while TCM reported MEA losses of 1.5 kg/ton CO_2[1]. This is mainly attributed to the higher concentration of NO_2 in the exhaust gas. NO_2 emissions were mostly between 100 and 150 mg/Nm^3, with high emission instances (coinciding with low engine loads) reaching around 400 mg/Nm^3. This is considerably higher than what is normally observed for land-based post-combustion carbon capture systems, including the TCM pilot, where NO_2 concentrations between 1-5 mg/Nm^3 are more common[2]. In the second EverLoNG campaign, onboard the Sleipnir, the NO_2 was removed from the exhaust gas prior to the absorber inlet. This led to controlled oxidative degradation rate, with the rate of degradation products accumulation in the solvent similar to that observed at the reference TCM campaign.

It is concluded that the NO_2 content of marine engine exhaust gases will lead to relatively high solvent losses. This can be controlled by removing NO_2 from the exhaust gas, with commercially available technologies such as selective catalytic reduction (SCR). However, this would lead to additional costs, and may pose retrofitting challenges. This option needs to be evaluated against the economic impact of higher solvent losses. Another important point of attention is the accumulation of nitrosamines, which are carcinogenic degradation products formed due to amines reactions with NO_2. Within EverLoNG, nitrosamines were not monitored, and this should be addressed in future projects.

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[1] A. K. Morken *et al.*, "Degradation and Emission Results of Amine Plant Operations from MEA Testing at the CO2 Technology Centre Mongstad," *Energy Procedia*, vol. 114, pp. 1245–1262, Jul. 2017, doi: 10.1016/j.egypro.2017.03.1379.

[2] M. Campbell, S. Akhter, A. Knarvik, Z. Muhammad, and A. Wakaa, "CESAR1 Solvent Degradation and Thermal Reclaiming Results from TCM Testing," *SSRN Electron. J.*, 2022, doi: 10.2139/ssrn.4286150.

P. Moser, G. Wiechers, S. Schmidt, R. Veronezi Figueiredo, E. Skylogianni, and J. Garcia Moretz-Sohn Monteiro, "Conclusions from 3 Years of Continuous Capture Plant Operation Without Exchange of the Amp/Pz-Based Solvent at Niederaussem – Insights into Solvent Degradation Management," *SSRN Electron. J.*, 2022, doi: 10.2139/ssrn.4274015.

WP2: Full CCUS chain integration

The focus in WP2 has been to:

- Develop off-loading strategies that clarify the post-capture treatment required onboard, as well as the infrastructure necessary on the port side.
- Develop a port readiness tool and establish a maritime industry group focusing on the infrastructure needed to develop OCC.
- Evaluate the design and cases of off-loading, transport and storage (or utilization) of CO_2 in different CCUS chains.
- Formulating a roadmap towards a European off-loading network.

A CO_2 Shipping Interoperability Group (CSIIG) with experts and stakeholders was established to give valuable input to our work and up to now have focused on CO_2 handling and port integration. When a ship equipped with onboard carbon capture completes a journey and reaches a port, it needs to off-load the captured CO_2. This means that the port needs to have the sufficient infrastructure, and be connected to a CO_2 transport network, to take the CO_2 to a geological storage site or to utilization. A key challenge is to develop a common off-loading strategy between ports. To this end, CSIIG has evaluating ports' CCUS readiness levels and their interest in developing a CO_2 handling business.

These offloading options has been evaluated in the project:

- Offloading at a port and transport through a pipeline to a storage injection site or utilization site
- Offloading at an intermediate port and uploading to another ship for onward transport

The work in WP2 has showed that there are several challenges that must be addressed to enable OCC to be implemented in a large scale. Port infrastructure remains a critical bottleneck, with current facilities often unable to accommodate the specific requirements of CO_2 offloading and further transport. The relatively low volumes of CO_2 captured per ship, combined with long intervals between offloading and unpredictable volumes due to short-term contracts, add logistical complexity to the process. To overcome these challenges, initial efforts should focus on large ports with existing or potential infrastructure for CO_2 handling and transport. Additionally, the development of flexible offloading systems capable of accommodating various ship types and sizes is essential to ensure seamless integration of OCC into port operations. These steps are critical to realizing the potential of OCC as a key component of maritime decarbonization efforts.

In order to assess 'port readiness', EverLoNG has produced a Port Readiness Tool for CO_2 (PRT-CO_2) tool which will help ports to assess how ready they are to be part of the CO_2 transport and storage market. It will be important for large-scale deployment of carbon capture and storage (CCS) to have a network of participating ports and interoperability between ports and ships for many reasons:

- back-up storage: if one storage site is not operating then CO_2 may need to go to another site possibly in another region via an alternative port
- market growth: enabling alternative storage options and avoiding lock-in to one storage site or storage monopoly

- opportunity cost: enabling ships and ports to import CO_2 from capture projects to competitive storage sites in different regions
- international equity: ultimately storage sites should be accessible by all, especially those who have no storage of their own
- decarbonisation of shipping: onboard capture of CO_2 means that ships may need a number of alternative ports to offload CO_2 for storage or utilisation.

A roadmap for expansion of OCC in the shipping industry has been developed. The roadmap has been based on forecasts and goals from IMO and DNV and is highly related to the progress of fossil- free fuels. Some major, key ports have been identified as relevant start up ports, and an indicative development of OCC has been suggested. A figure of the roadmap is presented below:

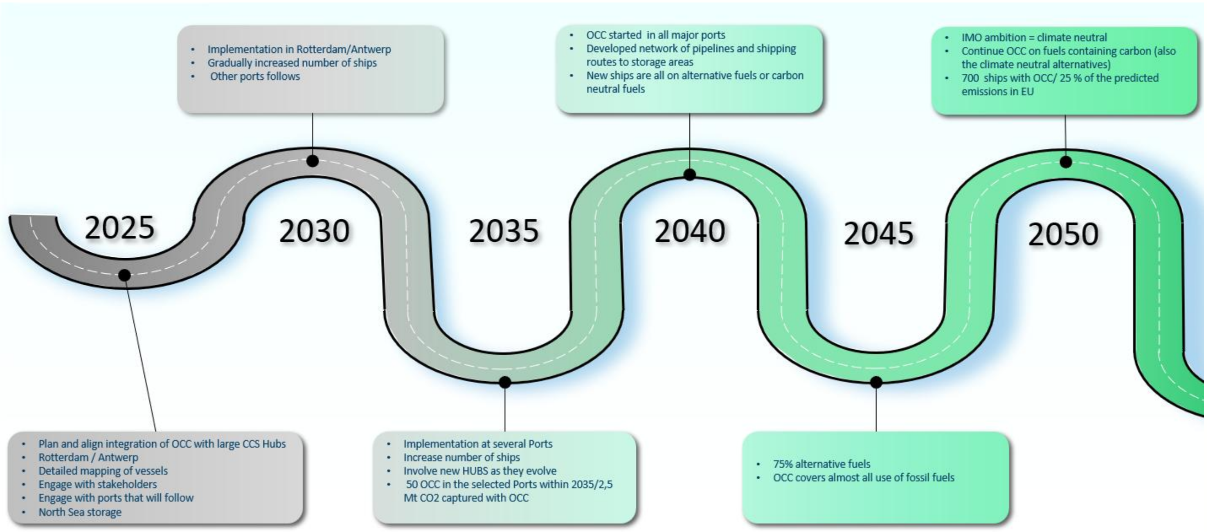


Figure 2. Suggested roadmap for OCC to 2050.

WP3: Impact of full scale SBCC on existing ships infrastructure

The main objectives of WP3 were:

- To investigate and optimize the integration of a full-scale SBCC system including CO_2 capture, liquefaction and temporary onboard storage installations, on the Sleipnir and the LNG carrier.
- To research the impact of the full-scale SBCC system on trim- and stability characteristics of the ships, on related risks and on cargo carrying capacity.
- To research required capabilities and producibility criteria for standardized, cost-effective SBCC systems to enable application and integration on a wider range of ships.

For the Sleipnir, an extensive analysis was performed of two years of operational data of all 12 of Sleipnir's engines, providing insight in, amongst others, overall emissions, ratio between gas operation and diesel operation, distribution of engine loads. These insights were combined with correlations for the fuel consumption and exhaust gas composition, temperatures, flow, and recoverable heat, which were based on the Sleipnir engines' technical files. This enabled a detailed analysis of the potential emission reduction as a function of the OCC system size, allowing an optimal sizing of the capture system which is not larger than necessary, which is important for limiting the CAPEX, while still achieving the target of >70% CO_2 emission reduction. The resulting design is able to capture and liquefy 8 tonnes of CO_2 per hour. All heat required for the capture system is recovered from the exhaust gas of the four-stroke engines, so no external heat needs to be added.

For the onboard integration of the technology the most important design criterion was that the function of SSCV Sleipnir as a crane vessel should not be compromised. This meant that the negative effect on lift capacity and workability should be minimized, sufficient deck space should remain available. As a modification to an existing vessel, it should be possible to retrofit the components, limiting the design freedom. One of the main challenges was to accommodate the 4000 m^3 CO_2 storage capacity without having a severe impact on the lift capacity. Eventually, a design was proposed with the CO_2 tanks accommodated in a hull extension at the stern, resulting in an increase in deck space and a limited impact on lift capacity on some draughts.

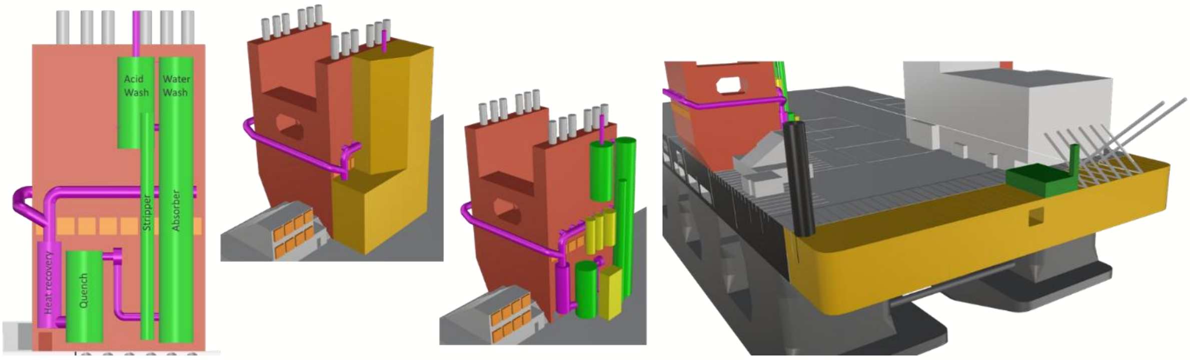


Figure WP3.1. Impression of the OCC systems and their integration onboard Sleipnir.

For the LNG carrier, a similar analysis of the operational profile was performed as for Sleipnir. As this was a newbuild scenario, the optimization work was not limited to adapting the OCC system to an existing situation. There was some degree of freedom to optimize the LNG carrier and capture system to work together efficiently. A thorough analysis was done of the suitability for OCC of different engine types. Several two-stroke engine types were considered, as well as a four stroke dual fuel diesel electric setup. Auxiliary engines were included in the analysis. A methodology was developed to combine all these analyses with the operational profile into a single performance curve, plotting CO_2 avoidance against fuel penalty, making it easier to compare the performance of the different engine setups. The results show that the engine type and configuration can have a big impact on the efficiency when combined with an OCC system, mainly due to differences in exhaust gas heat availability. For CO_2 avoidance rates of 70 to 90% over the entire operational profile, the fuel penalty of the best performing engine setups was approximately 50% of the worst performing setup considered. The four-stroke engine setup showed high potential with respect to exhaust gas heat availability, but would need addressing of its higher methane slip compared to the two-stroke setups. The final resulting combination of 2-stroke engine and OCC system showed an approximate 75% CO_2 avoidance against a fuel penalty of less than 16% over the entire operational profile.

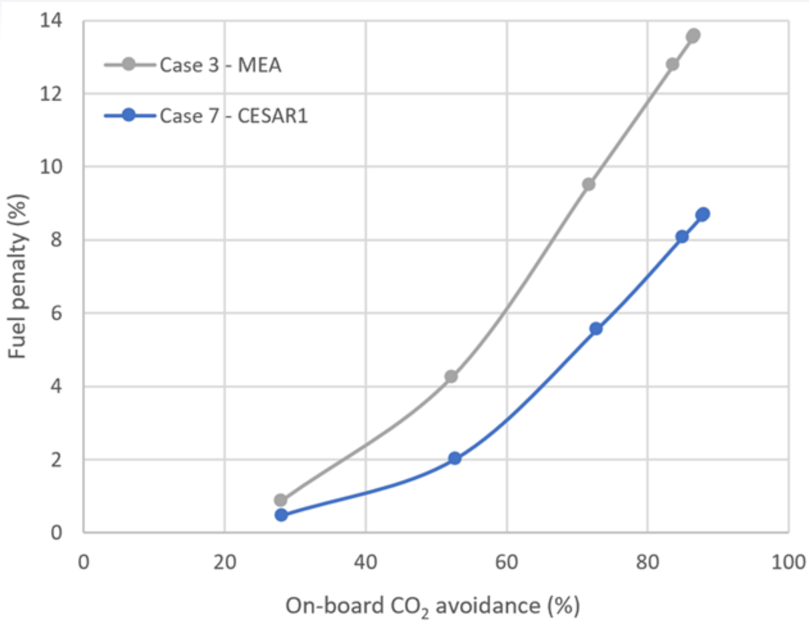


Figure WP3.2. Example of a performance curve, in this case comparing two different solvents (MEA and CESAR1) for the OCC system.

Designs for the onboard integration of the 7200 kg/h OCC system was made for the LNG carrier, with a 3000 m^3 CO_2 storage capacity. Apart from this, several opportunities to further optimize the integration design were identified. Because these optimization opportunities touch on many aspects of the basic design of an LNG carrier, further exploring them was out of scope for this project. The perspective they offer for further optimization of an LNG carrier fitted with OCC, is however promising.

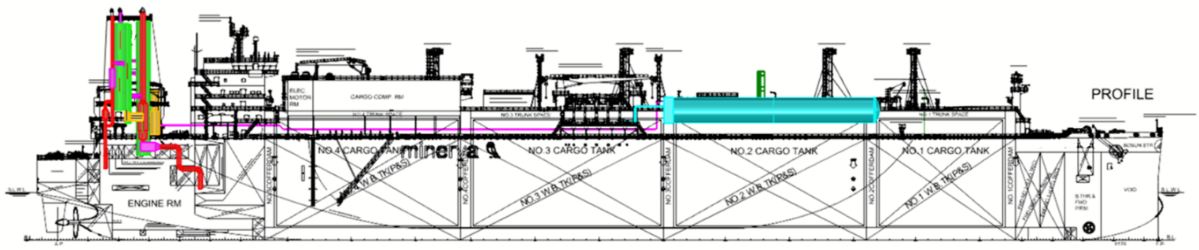


Figure WP3.3. Sideview of the LNG carrier fitted with the OCC systems.

For both cases, design documents were provided for the HAZIDs performed as part of WP5, in which relevant risks were identified. The results of the HAZIDs were used as guidance to improve the design of the integrated OCC systems. One major risk item specifically related to LNG fueled ships is that in the OCC system exhaust gases from different engines are combined. Hence, when the OCC system is in operation, the engines have a common exhaust system, which is typically not allowed for gas fueled engines due to the risk of explosion of unburnt fuel in the exhaust. After analysis and discussions on this subject it was concluded that, with the right precautions, it is possible to safely combine the exhaust gases in one common OCC system. This conclusion allows significant CAPEX reduction of OCC systems for LNG fueled ships, because otherwise each engine needs a separate economizer, quench, and absorption system.

Apart from heat recovery from the exhaust gas, further heat integration with the vessels was studied on the CO_2 liquefaction side. A cold recovery system was proposed and analyzed, utilizing the vaporization of LNG feed to the engines for cooling of the captured CO_2. Although it was concluded that this type of cold recovery system was not feasible for the Sleipnir (because of the complexity of retrofitting such a system) and for the LNG carrier (because the boil-off produced from the cargo makes active LNG vaporization redundant), the results of the analysis show that a cold recovery system can be a viable option for other (newbuild) LNG-fueled ships, further increasing the energy efficiency of the OCC system. Moreover, a different cold recovery system was proposed for the LNG carrier, utilizing the sensible heat of the cargo boil-off gas.

Although work on standardization was somewhat limited compared to the original work plan due the regrettable bankruptcy of partner VDL AEC Maritime, the developed methodologies can be applied broadly to many ship types, not only LNG-fueled, and the lessons learned from the cases provide valuable insight in the possibilities for standardization to achieve cost reduction. The main takeaway here is that the development of cost-effective standardized OCC systems is challenging for the high CO_2 avoidance rates targeted in this project (>70%). For less ambitious avoidance rates however, standardization of OCC systems is less challenging because lower design capture rates enable the systems to be designed for more constant and predictable loads. This is especially relevant since there is a large amount of existing ships for which OCC is one of the few available options for emission reduction. For these ships, lower CO_2 avoidance rates can be sufficient for the remaining lifetime of the ship. Through standardization, reduction of CAPEX of OCC systems can be achieved, which proves to be the dominant factor in the cost of OCC, as also pointed out in WP4.

WP4: Life cycle assessment and techno-economic evaluation of SBCC

For technically feasible SBCC systems identified in the WPs 1-3 the related environmental impacts and costs were assessed using Life Cycle Assessment (LCA) and Techno-economic Assessment (TEA) approaches in WP4. The EverLoNG project set two targets:

- Reducing CO_2 emissions of ship operation by at least 70%, taking the same ship running on LNG without capture as benchmark case
- Achieving CO_2 capture and on-board storage costs below 100 €/ton (1st of a kind) and 50 €/ton (nth of a kind)

Basis for the assessment of environmental impacts and costs was a framework document defining the investigated systems for the Sleipnir and the LNG carrier in detail. Both ships were described in their operation profile, the capture systems installed on board, the port facilities receiving the captured CO_2 and spent solvent as well as the subsequent transport systems to final geological storage. The descriptions are supported by the results obtained in the other WPs.

The two ships provide different functions. The crane operations of the Sleipnir are the relevant function, supplemented by shipping to and from operation site and necessary idle times. Thus, an average 6-week operational profile including all these operation types was determined to be the functional unit of the Sleipnir for the LCA. Delivering LNG is the determining function of the LNG carrier. It was assessed for a specific delivery route from Port Arthur (US Gulf Coast) to the Port of Rotterdam (NL), including a ballast trip back (with 5% heel still in tank). The functional unit for the LNG carrier is therefore 1 metric ton LNG delivered. In total, 16.45 days of ship operation were considered for the trip to Rotterdam and the same duration back, including necessary idle times (3.29 days). While the Sleipnir was assessed as-is, being retrofitted for CO_2 capture, the design and operation of the LNG carrier was considered using a new engine type, more suited for SBCC. For the subsequent CO_2 treatment, offloading of CO_2 and spent solvent at the Port of Rotterdam and sending the CO_2 to the Northern Lights storage project was assumed. For the LNG carrier, additionally, the CO_2 captured on the ballast trip back to the US was sent to a nearby enhanced oil recovery via pipeline. Both systems are shown in Figure WP4.1.

a) Sleipnir b) LNG carrier

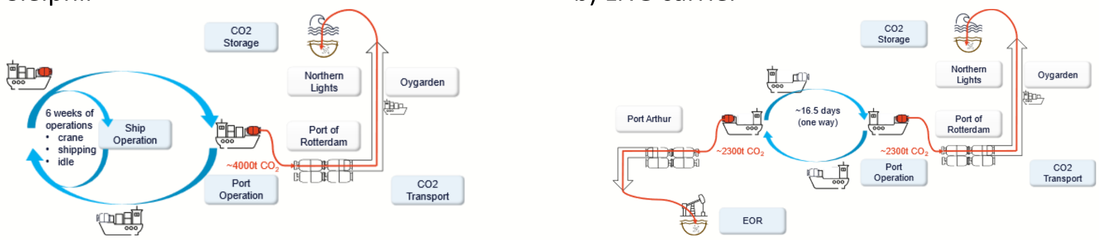


Figure WP4.1 Systems considered for LCA and TEA; a) Sleipnir, b) LNG carrier

Assessment of environmental impacts using LCA

For the LCA the material and energy inputs and outputs are assigned to environmental impacts, following the Environmental Footprint method version 3.1 (EF3.1) described by the European Commission and in line with the guidelines on life cycle GHG intensity of marine fuels by IMO's Marine Environment Protection Committee (MEPC). Strong focus was given to the impact on climate change considering various greenhouse gases (GHG), mainly CO_2 and methane. Additionally, other environmental impacts were investigated, following EF3.1.

The GHG reduction potentials were evaluated for the on-board (tank-to-wake (TtW)) system alone and for the entire life cycle (well-to-wake (WtW) plus handling and storing of CO_2). The ship benchmark operation shows distinct features of the Sleipnir and LNG carrier operational profiles and engine properties. Figure WP4.2 shows the GHG reduction potential on-board (TtW) for the Sleipnir. In Figure WP4.3 the reduction effects for the LNG carrier are presented.

a) CO_2 emissions b) climate change impacts

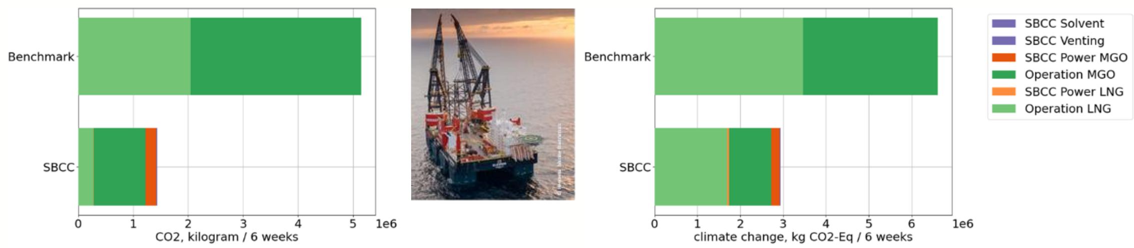


Figure WP4.2 Sleipnir -on-board- a) CO2 emissions, b) climate change impact per functional unit

a) CO_2 emissions b) climate change impacts

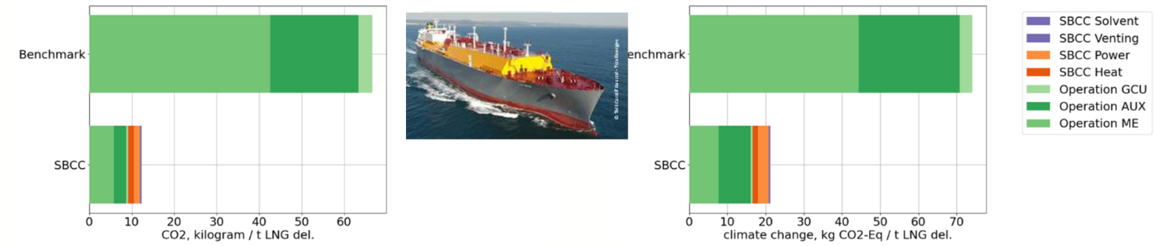


Figure WP4.3 LNG carrier -on-board- a) CO2 emissions, b) climate change impact per functional unit

Running the capture unit reduces the TtW CO2 emissions by 72% over the complete operational profile for the Sleipnir and 82% for the LNG carrier. This surpasses the goal of >70% on-board CO2 capture set within the project. The effects of methane slip, which cannot be captured by the capture unit but even slightly increases due to additional fuel necessary, are visible in the climate change impact (CO2-Eq emissions). Climate change impacts reduce by 55% for the Sleipnir and 71% for the LNG carrier. While the Sleipnir shows some increase in the methane emissions from the main engines, the LNG carrier methane emission increase is driven by the auxiliary engine used for the capture system power.

The full system includes fuel supply, capture system production, operation and CO2 handling. Figure WP4.4 depicts the climate change impacts for the full life cycle for both ships.

a) Sleipnir b) LNG carrier

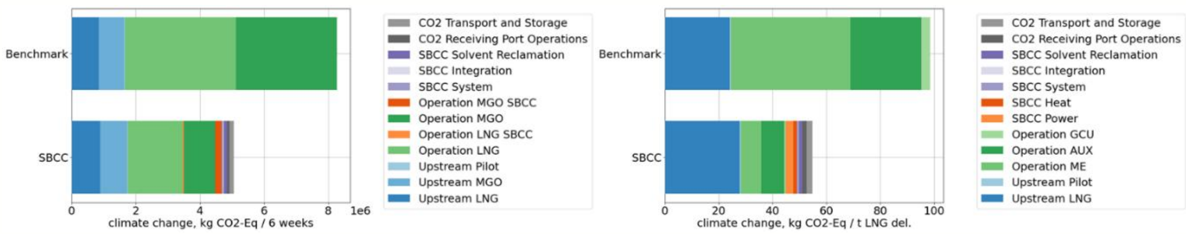


Figure WP4.4 Full life cycle- climate change impact per functional unit a) Sleipnir, b) LNG carrier

The overall reduction of climate change impacts lies by 39% and 44% CO2-Eq for the Sleipnir and LNG carrier, respectively. The main drivers against further reduction of climate impacts are found in the fuel production stages and the on-board methane slip. Higher reduction could be obtained by reducing fuel consumption of the capture operation with further improved heat integration or explicitly by choosing fuel from suppliers guaranteeing lower upstream fuel emissions. A general handling of the methane slip provides additional improvement potential which is independent from CO2 capture.

The higher fuel demand due to capture causes an increase in all other environmental impacts for the LNG carrier. For the Sleipnir this increase is compensated by lower NOx emissions, due to an optimized combustion regime especially for low engine loads. Therefore, effects strongly impacted by NOx emissions, such as acidification, eutrophication or photochemical ozone depletion potentials stay in the same range as operation without capture for the Sleipnir. For acidification, terrestrial eutrophication and particulate matter, the impact of ammonia emissions as degradation product from the capture process become visible for both ships, though to a much lesser extend then NOx emissions.

Cost assessment using TEA

In the TEA, the costs were determined again at both levels: on-board costs and full chain costs. The evaluated total costs consist of the CAPEX, fixed OPEX and variable OPEX of the SBCC system and the subsequent CO_2 treatment (port to geological storage) plus engineering costs and project/process contingencies using the annualization method. For this method, the CAPEX was annualized, using mostly a discount rate of 6% and a lifetime of 25 years. Class 4 accuracy (-30% to 50%) was considered, since this project considers a feasibility study. The CAPEX consists of the material and installation costs of the equipment (bare equipment costs) and the engineering costs. OPEX can be split up between fixed (e.g. labour, maintenance, insurance) and variable (e.g. utilities, consumables) OPEX. They vary heavily between the two ships and different sections of the full chain. Figure WP4.5 presents the total costs for the on-board section for the Sleipnir, figure WP4.6 for the LNG carrier.

a) Total costs b) Bare equipment costs

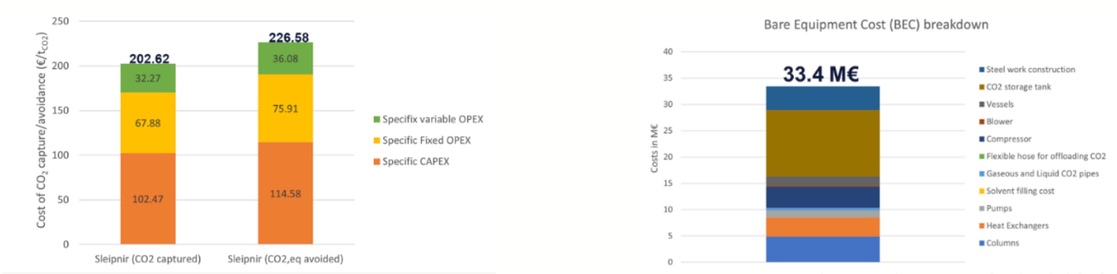


Figure WP4.5 Sleipnir - on-board- a) total costs, b) bare equipment costs

a) Total costs b) Bare equipment costs

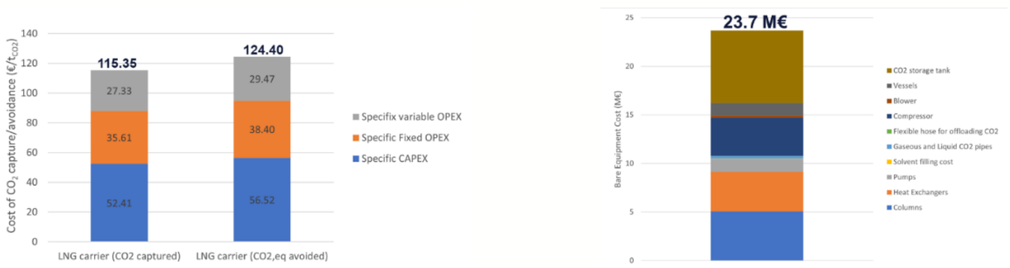


Figure WP4.6 LNG carrier - on-board- a) total costs, b) bare equipment costs

For both ships the total costs are determined by the CAPEX costs. Here, the CO2 storage tank costs are the major equipment cost driver. For the Sleipnir additional cost for steel work construction (13%) was considered, due to the retrofitting approach, while this was not necessary for the new-built case assumed for the LNG carrier. This and the 40% lower costs of the CO2 storage tanks for the LNG carrier, are the two main drivers for the difference of CAPEX. As the specific fixed OPEX costs of the systems are calculated in relation to the CAPEX, the Sleipnir shows higher values here as well. Overall, the higher capture system capacity factor for the LNG carrier and the advantage of optimization option for designing and placing the system, lowers its specific total costs compared to the Sleipnir where the design options are limited to fit with the existing equipment. Hence, the estimated on-board total costs for the newly designed LNG carrier lie close to the targeted range of 100 €/ton (1st of a kind), while the costs for the retrofitted Sleipnir is twice as high.

For the total costs of the full chain, costs for the receiving facility, the transport and the final storage were evaluated and added to the on-board costs. Table WP4.1 gives the total costs for the different stages of the full chain. As geological storage facility the Aramis storage project (NL) was assumed.

Table WP4.1 Total costs for the full chain for both ships

Full chain segment	**EUR/t CO2 captured**	
	Sleipnir	**LNG carrier**
On-board carbon capture	200	115
Receiving facility	20	
Transport pipeline	20	
Storage	40	
"Total cost full chain"	**280**	**195**

Costs for transport and storage are also not negligible. It shows the need for sharing receiving facilities between ships. Overall, the current emissions penalties/subsidies are not sufficient to incentivize onboard capture, new financial structures would be required.

WP5: Regulatory framework for SBCC

Whilst the technologies for land-based and Ship-Based Carbon Capture (SBCC) project are close to identical, the regulatory frameworks in which they operate, as well as the safety principles applied, can differ substantially. Where land-based installations typically adhere to local regulations that govern licensing, safety and disposal, the majority of ships are engaged in international trade, which requires routine border crossings and adherence to international Rules *(Classification)* and Regulations *(Flag, Port States and IMO)*. To accelerate the uptake of SBCC in a safe and credible manner, WP5 reviewed and summarised the regulatory framework, identifying pathways for compliance and thereby highlighting the various incentives *(EEDI, EEXI, EU ETS)*, challenges *(London Protocol)* and safety considerations associated with SBCC.

The nature of shipping implies that SBCC installations will be subjected to dynamic loads, green seas, vibrations, humidity and the presence of chlorides. In addition, the potential for collisions and groundings and the consequences thereof all require design considerations typically not seen in land-based applications.

Due to the relatively limited space on board, commonly applied safety distances and segregation from hazards such as fires, cargo handling, and ship operations cannot be maintained. Furthermore, a ship at sea must manage emergencies with limited options for escape for the people onboard. These special circumstances necessitate appropriate preventive and mitigating safety barriers, which is why marine regulations sometimes have stricter requirements than those governing installations on land.

To identify the applicable safety and environmental standards and codes, WP5 systematically risk assessed the risks of the demonstrator onboard the Seapeak Arwa *(chartered by TotalEnergies)* and Heerema Marine Contractor's (HMC) SSCV Sleipnir, as well as the full-scale concept designs for a new build TotalEnergies LNG Carrier and the SSCV Sleipnir developed in WP3.

A review of the generic hazards against existing regulations and standards indicated that, at this stage, not all aspects of a SBCC system are covered by prescriptive regulations or standards. Where these are missing, alternative design assessment pathways were considered suitable and available. While the technology status of equipment in SBCC was considered proven, the application on board ships of CO_2 recovery, solvent regeneration and large volume CO_2 offloading on other than CO_2 tankers were considered new. The risks associated with SBCC installations were deemed credible but well understood, with well-established safeguards and design principles available from other parts of the marine industry, like LNG-fuelled vessels.

The main safety hazards associated with an SBCC installation pertain to loss of containment in the chemical systems *(amines, caustic soda, ammonia, thermal oil, LNG)* used during the CO_2 capturing process and the hazards linked to loss of containment in systems employed for processing, storing, and off-loading captured CO_2. No matter how good systems are designed, build and maintained, there remains a residual risk of equipment and pipework failure, which in turn could lead to a releases of process liquids and gases. A good design accounts for all probable leakage scenarios and implements appropriate safeguards to prevent or mitigate their associated consequences.

The chemicals employed in the capture process may possess toxic, flammable, and corrosive properties that the crew could be exposed to during replenishing work, maintenance, or system leaks. CO_2 is an asphyxiating/toxic gas processed under pressure and utilises storage systems with high potential energy, which could be released in a damaging scenario.

Having a good handle on what to expect, in terms of risks, at the start of a design allows for better and inherently safer designs to be created and reduces the risk of costly last-minute design changes required to meet the required levels of safety. Noting the large quantities of CO_2 needed to be captured and stored onboard, designers will need to consider a vast array of release scenarios. To deliver to designers, as well as reviewers, order of magnitude estimates for a wide range of CO_2 release scenarios WP5 generated easy-to-use engineering diagrams covering a wide range of release conditions.

To draw global attention to the EverLoNG project at the highest regulatory level, the WP5 partners delivered an afternoon presentation to delegates attending the 9th session of the Sub-Committee on Carriage of Cargoes and Containers (CCC) of the International Maritime Organisation (IMO). The audience showed great interest in the project and were particular interested in the Techno-Economical Assessments (TEA) of WP4. Subsequently, EverLoNG was invited to present to the IMO's *"Correspondence Group (CG) on Regulatory Framework for Ships Using New Technologies and Alternative Fuels"*, which reported its findings to the Marine Safety Committee (MSC) 108. The presentation was attended by 59 delegations from various Member States and Non-Governmental Organizations (NGO).

The Classification Society partners in WP5 *(LR, BV, DNV)* are also connected to the International Association of Classification Societies (IACS). IACS publishes Unified Requirements (UR) for various technologies and has started work developing an UR for SBCC. This will set the minimum standards to which the equipment needs to comply to achieve Class approval. Although Classification Societies can opt for additional requirements based on their own experience and Rules, an SBCC system that complies with the UR stands a very good chance on being approved for use onboard. The knowledge acquired in the EverLoNG project has indirectly impacted the UR for SBCC via the partner's their participation in both.

Overall, WP5 concluded that SBCC is the most mature technology available today to make a direct impact on the CO_2 emitted by shipping, which can not only be applied to newbuilds, but can also be retrofitted to existing vessels, therefore considerably increasing the potential CO_2 reduction. In addition, SBCC in combination with LNG fuel was considered a credible long-term solution that can assist with achieving net zero faster. Experience with LNG fuel is considered a steppingstone for the implementation of future fuels, for they require levels of risk management that exceed those on LNG vessels and chemical tankers. Hence, future fuels not only require a change in equipment, but overall company management and culture, which takes time, training and dedication.

Brand ID and Logo

The EverLoNG brand ID and website were developed in tandem, starting with the project logo. An initial draft idea was suggested by one of the project partners, from which additional concepts were designed.

Initial draft:

Concept options:

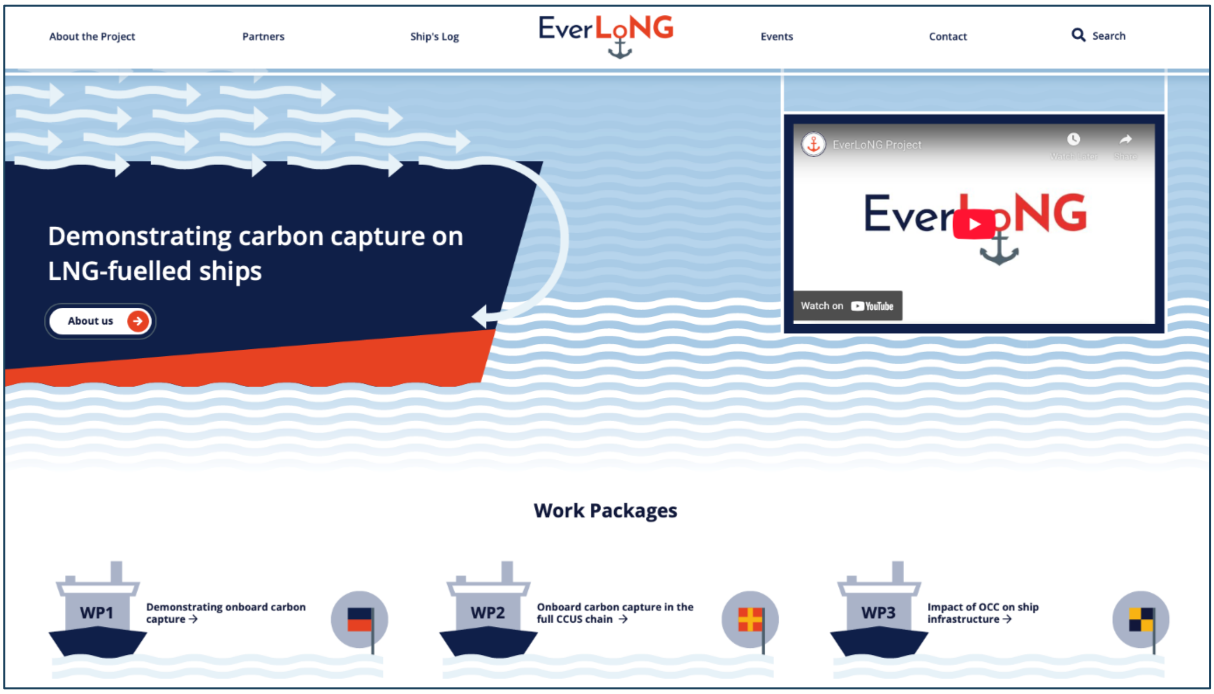
Option 1	Option 2	Option 3
Full form logo	Full Form Logo	Full Form Logo
Logo Icon	Logo Icon	Logo Icon

The three options were put to a vote amongst project partners, and Option 3 was selected. This unique concept was produced for the project, to be used on all communication and dissemination outputs, from website and social media channels to presentations and posters. The logo was made available in different formats for flexibility of use and a 'Branding guidelines' document was produced to ensure consistency of usage. The recognisable "brand" was further developed with maritime themes for the website, and included a tagline and colour palette. A set of templates (for document reports, presentations, and posters) were also created using the brand ID and logo, and made available to the partners. Furthermore, graphics were designed to show the OCC schematic for WP1 and a Portside schematic for WP2. Finally, a 2-page project briefing document was made available for print, and linked to in the 'About Us' page of the project website.

Website

The project website launched on 06 April 2022 at www.everlongccus.eu. The website will be available throughout the project duration, and beyond — until September 2027. In addition to the home page, containing an overview of the project and links to social media accounts, the website consists of the following pages:

- About the project page, with subpages to show objectives and outcomes, details from each work package, funding acknowledgements, public results, and useful links.
- Partners page, with subpages dedicated to consortium project partners, and advisory board members.
- Ship's Log, a section with 25 individual news items including 17 articles, 3 blogs, 1 vlog and 4 project videos. Highlights included two videos of the carbon capture demonstration campaigns aboard the SEAPEAK ARWA, and the SSCV Sleipnir, both with over 1,000 views.
- Event page.
- Contact page.



The website also contains mailing list sign up form, for subscribers to keep up to date with project news. The mailing list gained 189 subscribers.

Analytics were gathered tracking website traffic and activities from December 2022. In the 28-month period between December 2022 and February 2025, the website averaged over 300 monthly users, with four discernible peaks of 1,050+ monthly users aligned with the start and end of the 1st and 2nd capture demonstration campaigns.

Editorial Board

A bi-monthly Editorial Board (EB) was established to help generate news items for the project. Attendance was voluntary and open to all project partners. The EB forum was responsible for 16 individual news items, some of which were specifically designed to keep the project visible until WP results materialised.

Webinars

Three project webinars were organised covering project updates from all work packages, results from the first EverLoNG capture demonstration campaign, and final project results, in May 2023, June 2024, and March 2025, respectively. Webinars well well-attended, each one having over 100 attendees. Details of each webinar, including agenda, presentation slides, and a recording of proceedings is available in the Events page of the project website.

Social media

Social media accounts were setup at the start of the project on LinkedIn (691 followers) and X (Twitter) (38 followers). A YouTube channel (24 subscribers) was also created to host all project videos, and webinar recordings.

The table below presents an overview of financial results per partner and per work package. Further financial details can be found in Appendix 1.

Partner		WP 1	WP 2	WP 3	WP 4	WP 5	WP 6	Total	Comments / Spesifications
TNO	The Netherlands	532.904	40.601	169.492	87.856	34.784	256.424	**1.122.061**	
Conoship International BV	The Netherlands	6.897	1.438	128.114	5.158	6.171	20.091	**167.869**	
Carbotreat	The Netherlands	1.738.260		55.304		4.452		**1.798.016**	
VDL AEC Maritime	The Netherlands	97.907		129.800	10.200	16.200		**254.107**	
Heerema Marine Contractors SE	The Netherlands	203.795	4.800	4.800	4.800			**218.195**	
MAN Energy Solution SE	Germany	124.849		84.608	50.000			**259.457**	
Forschungszentrum Juelich GmbH	Germany				374.848		22.365	**397.213**	
Total EP Norge	Norway	308.863	55.963	15.125	15.125	5.294		**400.369**	
SINTEF AS	Norway		505.000		148.000		25.000	**678.000**	
Bureau Veritas Norway AS	Norway					59.740		**59.740**	
ÅKP AS	Norway		16.296	13.105	10.421			**39.822**	
University of Edinburgh (SCCS)	United Kingdom		75.039				142.262	**217.301**	
Lloyd's Register	United Kingdom	3.884	0	155	220	55.225	15.619	**75.102**	(GBP)
Los Alamos National Laboratory	United States of America	210.700	179.300		107.100			**497.100**	(US Dollar)
DNV GL	Norway	4.900		4.900		44.100	4.900	**58.800**	
Anthony Veder LNG Shipping B.V.	The Netherlands		23.400	31.200		15.600	8.000	**78.200**	
Total		**3.232.959**	**901.836**	**636.604**	**813.728**	**241.565**	**494.660**	**6.321.352**	

5 Project impact

- **Contribution to the facilitation of the emergence of CCUS**

Specifically WP5 has contributed to facilitate the emergence of CCUS in addressing the following aspects: 1) Identifying applicable safety and environmental standards and codes; 2) Major hazard of CO_2 loss of containment; and 3) Assessment of technology novelty. The main conclusion from this activity is that the regulatory framework exists and is currently being expanded for the implementation of ship-based carbon capture (SBCC). The risks associated with SBCC installations are credible but well understood, with well-established safeguards and design principles available from other parts of the marine industry, like LNG-fuelled vessels. Please note that this work has been made public.

An important policy development that will help the emergence of CCUS is related to the EU's Emission Trading System (EU ETS). The EU's legislative bodies have reached an agreement on including shipping in its Emission Trading System (EU ETS). The EU ETS is an emission cap-and-trade system where a limited amount of emission allowances – the cap – is put on the market and can be traded. The cap is reduced each year, ensuring that the EU's emission target by 2030 of 55% reduction, relative to 1990, can be met while becoming climate-neutral by 2050. The ETS provides an incentive for CCS deployment. According to the EU legal framework, CO_2 that is captured and safely stored is considered as "not emitted" under the ETS.

On a technology development level, the demonstration campaigns onboard will bring SBCC to TRL7 (WP1). The results from the campaigns confirm the technical viability of the solution. When starting the project, one of the main concerns for the marinization of CO_2 capture was the impact of ship motion on the CO_2 capture efficiency. While onboard the Seapeak Arwa, the prototype experienced very significant motion, and no measurable loss of efficiency was observed. One important aspect investigated was the loss of solvent due to emissions and degradation. It is identified that factors such as incomplete combustion, for instance due to operating at low engine loads, can lead to aerosol-based emissions. Sub-micron particle measurements on the targeted engines' exhaust gases are advised prior to design and implementation of OCC. When needed, mitigation technologies for aerosol emissions are available and must be included in the OCC design. Moreover, a relatively high NO_2 content in marine engines exhaust gases (as compared to industrial flue gases) lead to higher solvent degradation rates. If no measures are taken, solvent losses in the order of 3-5 kg MEA per ton of CO_2 captured can be expected. If NO_2 removal measures are implemented, the losses are expected to be controlled around 1-2 kg MEA/ton CO_2. The solvent accumulates degradation products overtime, and a solvent management strategy is required.

The solvent management strategy envisioned, based on results from task 1.1, considers that the solvent will be exchanged once degradation reaches a pre-established threshold. The degraded solvent will be delivered and treated at the port location. Moreover, the ports will need to be equipped with facilities for CO_2 offloading and temporary storage. Discussions regarding the infrastructure on the port side have been held as part of the CSIIG. Interoperability will facilitate the emergence of CCUS, and particularly SBCC.

In WP2, the CSIIG group facilitated several workshops and webinars, bringing different part of the OCC value chain together to discuss possible pathways and as communication is crucial to move OCC forwards, this work may be a contributor for acceleration of the technology.

In WP3, valuable insights have been gained into the configurations of machinery determining the technical applicability and feasibility of SBCC, enabling both better assessment of feasibility of SBCC for different ship types and optimization of ship machinery for SBCC systems. Making the main conclusions of this work publicly available enables other designers to make use of this knowledge as well, which contributes to the emergence of SBCC.

In WP4, the LCA framework has been established. With that, and the calculations of EEDI and EEXI in line with the new IMO's guidelines on life cycle GHG intensity of marine fuels, the CO_2 avoidance of SBCC will be properly calculated. Together with the findings by the TEA the results support the discussion which role OCC can play in reaching IMO's ambitious GHG Strategiey in combination with additional reduction measures.

- **Chances for commercializing the technology further**

The chances for commercializing this technology are significant. Change in maritime regulations, both in Europe as well as worldwide, push forward the interest of ship owners in carbon capture as it is a field proven decarbonization technology and relatively easy to implement onboard existing as well as new built vessels. Partner Carbotreat (and previously VDL as well) recognizes an increasing market attractiveness for this technology. They experience an even more interesting market for HFO fueled vessels compared to LNG fueled vessels, LNG being the focus of the EverLoNG project. Carbotreat is highly interested to become a main player commercially offering of capture systems on both LNG as well as HFO fueled ships.

Heerema Marine Contractors: CCS is potentially the cheapest solution for the problem (CO_2 reduction). All other solutions will be, to the least short term, very expensive. Bio- and e-fuels, let alone nuclear, are expected to be more expensive than CCS. There are some technical challenges to be resolved, especially the logistics behind it, but this is the main reason why this technology is to be developed further.

Anthony Veder: recognizing the potential, pulls attention to need for further infrastructure development. Anthony Veder sees the benefit for equipment installed onboard, as described in the point below; however, offloading captured CO_2, as is described in WP 2.3, is part of a ship owner's perspective for investment decisions.

Beyond EverLoNG, we see the OCC interest peaking, and large-scale implementation projects starting to take place. The ship *Clipper Eris* – owned by Solvang ASA – is the first to be installed with a full-scale OCC plant, targeting CO_2 emissions reduction by up to 70 per cent. Moreover, the recently-awarded ME2CC project (led by Value Maritime) plans to install an OCC system on board 2015-built, LNG-fuelled roro vessel *Samskip Kvitbjorn*. With construction start planned to the end of 2025, the system goal will be to capture at least 80% of the ship's CO_2 emissions.

- **Strengthen the competitiveness and growth of European companies**

This relates to the actual implementation of SBCC. Trends observed are the increasingly stringent environmental regulations for shipping in recent years; also, the trend that large companies which make use of global transportation (e.g. Amazon) require their shipping companies to provide sustainable transport. Trends like these boost the chances to commercialize this technology significantly. Once SBCC becomes indeed successfully implemented, more sustainable shipping will be available, and this will strengthen the growth of the global economy. Countries/companies offering decarbonized shipping will experience a competitiveness edge. Partners Heerema, TotalEnergies, and Anthony Veder recognize this opportunity.

Heerema Marine Contractors: As per the previous statement Heerema recognizes the potential value of this technology. Especially as a transition / retrofit technology.

- **Other environmental or socially important impacts, such as public acceptance**

LCA also evaluated other environmental impacts of OCC. It was shown that many other impacts increase due to the higher demand of fuel. For the Sleipnir this increase is compensated by lower NOx emissions, due to an optimized combustion regime especially for low engine loads. Therefore, acidification, eutrophication and photochemical ozone depletion potentials stay in the same range.

SBCC in combination with LNG fuel was considered a credible long-term solution that can assist with achieving net zero faster. Experience with LNG fuel is considered a steppingstone for the implementation of future fuels, for they require levels of risk management that exceed those on LNG vessels and chemical tankers. Hence, future fuels not only require a change in equipment, but also changes in overall company management and culture, which takes time, training and dedication. SBCC can assist companies setting the first steps towards other future fuels.

- **Gender issues**

Accelerating the market implementation of onboard carbon capture is not gender sensitive. Nevertheless, the project, the consortium and the participants' organizations are committed to the promotion of equal opportunities between men and women. In EverLoNG, the leadership of the R&D work packages (three WP's lead by women and three WP's lead by men) and the scientists and technical staff of persons working on the project is very balanced between men and women.

The table below gives an overview of the key expected results/the main technical milestones per work package, in chronological order.

WP	Key expected result	Impact	Status
1	200h campaign finished at the Sleipnir using TNO's small scale capture plant	Bring SBCC to TRL5, de-risking the demonstration phase	Finished and report delivered
2	CSIIG established with at least 5 ports as members	Ensuring strong port participation in the CSIIG is important for achieving the targets of establishing a European off-loading network. This will impact not only SBCC but accelerate the development of CCUS in general.	CSIIG established with 4 regular port members: Rotterdam, Antwerp-Bruges, Hirshals, Aveiro. Three meetings were organized, with 162 attendees from 68 key stakeholder organisations.

1	10 ton of CO_2 captured and liquefied onboard of TOTAL's LNG carrier	This will ensure that CO_2 can be delivered in enough quantity to the utilisation/storage demonstration projects. Also, the quality of CO_2 will be demonstrated.	CO_2 was successfully captured. However, the liquefaction system was not in operation due to malfunction of the compressor, which could not be timely repaired.
2	CO_2 delivered to RWE Niederaussem	Connecting to projects demonstrating CO2 utilisation in Germany could help fast-track the development of SBCC in that country.	CO_2 has not been liquified due to technical problems with the compressor
2	CO_2 delivered to a PTX plant in Germany		
5	Completion of Risk Assessments identifying associated HAZIDs	The recommendations from the HAZID will be incorporated on the SBCC design, making it intrinsically safer	Finished and report delivered
1	2 ton of CO_2 captured and liquefied onboard of the Sleipnir	The quality of CO_2 will be demonstrated/verified. The connection with a greenhouse could help fast-track the development of SBCC in The Netherlands.	About 1.5 tons of CO_2 was liquefied; Unfortunately, the CO_2 was lost (potentially due to a mistakenly open valve) and could not be transferred to WP2
2	CO_2 delivered to a Dutch greenhouse		
4	Verification of CO_2 reduction target (>70% CO_2 reduction)	This proves that SBCC is a technically viable option for reducing the CO_2 emissions in the shipping industry	The CO2 reduction target was verified for both ships
3	Define standardized SBCC sizes	This is an important step in the exploitation plan of SBCC.	Standardized SBCC sizes were defined, see public deliverable D3.4.1
4	Verification of cost targets for SBCC: 100 €/ton CO_2 for FoaK and 50 €/ton CO_2 for NoaK/standardized systems	This proves that SBCC is an economically viable option for reducing the CO_2 emissions in the shipping industry	The cost target was nearly reached for a newly build design. Retrofitting shows nearly double costs. Still, additional incentives are necessary to make OCC attractive
5	Regulatory input to International regulatory regimes	This is an important step in the exploitation plan of SBCC.	This result has become available and publicly reported

About 1.5 tons of CO_2 was liquefied during the Sleipnir campaign. Unfortunately, the CO_2 was lost (potentially due to a mistakenly open valve) and could not be transferred to WP2 for further use. While this mistake impacted the results of this project, this is not expected to be a significant hazard to the CCUS supply chains (whether connected to OCC or not). Transport of liquid CO_2 in storage tanks is a widespread operation, and good operational practices are in place in the gas industry that prevent leakages and losses. It is recommended that such practices are followed in the implementation of OCC.

6 Implementation

Describe the implementation of the project results in relation to the SET plan Implementation Actions (no 9 on CCUS), Mission innovation research priorities and how you have engaged industry in your work.

The SET-Plan TWG9 CCS and CCU Implementation Plan outlines 10 specific targets, required to achieve the ambitious targets for CCS and CCU agreed by the European Commission, SET-Plan countries, and industry. The Implementation Plan also identifies the ongoing actions which will be required to meet the Key Performance Indicators which have been set for 2030.

The project EverLoNG was set completely in line with the intentions of ACT to accelerate the implementation of CCUS and is aligned with the SET plan and the mission innovation goals. In EverLoNG, CO_2 was captured from industrial sources, as CCUS is extended to the maritime sector, which is in line with the SET targets. The project de-risked implementation of CCUS in this relatively unexplored industrial sector for CCUS, and shared the first open pilot campaign results onboard two ships. In this project, for the first time, post-combustion CO_2 capture has been demonstrated, at TRL-7, onboard of ships.

EverLoNG gives a major boost for the maritime industry to achieve its goals of lowering emissions drastically, achieving net-zero by 2050. The lessons learned in EverLoNG should be considering when designing SBCC technology, de-risking and further accelerating the timely and safe implementation of the technology in the maritime sector.

Moreover, EverLoNG can potentially have a high impact on accelerating CCUS:

• Ships require smaller systems as compared to other industries (cement, steel, power); smaller systems are easier to finance and modularize;

• SBCC is feasible using open technology (the benchmark 30wt% MEA was used in EverLoNG), which can be provided by multiple vendors, leading to more competition and a market-driven cost reduction. In fact, the players installing the first large-scale SBCC systems onboard, Wartsila (onboard Solvang's Clipper Eris) and Value Maritime (onboad Samskip's Kvitbjorn) are new players in the CO_2 capture field (which includes SLB Capturi, MHI, Shell Cansolv) and are installing open-art technology;

• SBCC can potentially be applied to hundreds of ships, applying standardised solutions, in the near future;

• Widespread application of SBCC is intertwined with and accelerates the development of full chains. This creates a cascade effect, that accelerates the implementation of CCUS in other industries as well (such as cement, steel, refining, etc.), thus multiplying the impact of EverLoNG.

7 Collaboration and coordination within the Consortium

The management structure of EverLoNG is shown in Figure 7.1.

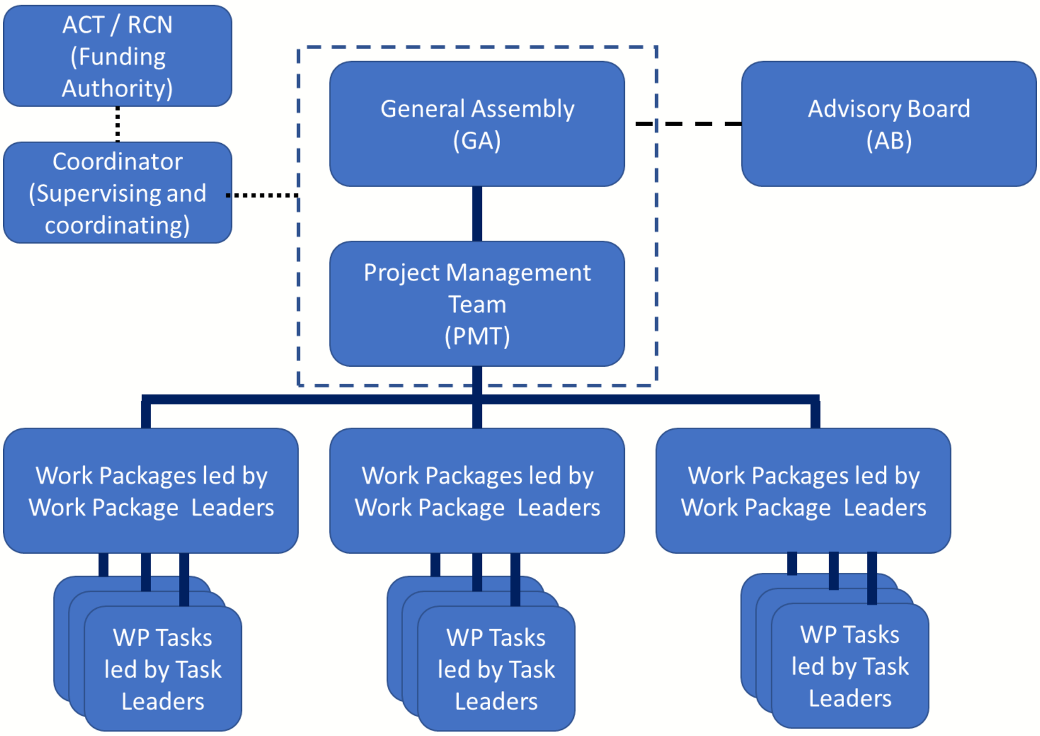


Figure 7.1: Management structure in EverLoNG.

At the kick-off meeting of the project a strong and experienced Project Management Team (PMT) was appointed, which is needed to deliver a successful project. The PMT is constituted of the following people/organisations, see table below.

PMT members EverLoNG.

Function	Person(s) in charge	Organisation
Coordinator Technical coordination	Marco Linders Juliana Monteiro	TNO (NL) TNO (NL)
Dissemination coordination	Richard Stevenson	SCCS (UK)
WP1 leader	Juliana Monteiro	TNO (NL)
WP2 leader	Ragnhild Skagestad	SINTEF (NO)
WP3 leader	Joan van den Akker	Conoship (NL)
WP4 leader	Petra Zapp	Jülich (GE)
WP5 leader	Erik Vroegrijk	Lloyd’s Register (UK)
WP6 leader	Marco Linders	TNO (NL)
USA representative	Prashant Sharan	LANL (USA)

General Assembly

The General Assembly (GA) is the ultimate decision body of the project. Every partner has one representative (one vote) in the general assembly. After the first project year had passed, the first GA meeting was held. This meeting appeared informative, there were no issues raised that needed formal decision. The second GA meeting was dedicated to the rising costs of the carbon capture unit. The required budget to build the prototype capture unit appeared much higher than anticipated at submission of the project, partly due to the rising prices for materials since the start of the war in Ukraine. How to deal with this financial gap and finding solutions, has been discussed amongst the partners in the GA. Ultimately, partner VDL invested in the pilot plant, which solved the financial issue. In the third GA meeting extension of the project was discussed. The project suffered delays and all partners agreed unanimous to ask for extension of 6 months that was granted by ACT.

Meetings

About two to three PMT meetings per year were organized to keep track of the project progress. Technical consortium meetings were organised about every half a year. Since early 2023, it was possible again to organise in-person meetings (after COVID). In person meetings were held at the premises of partner Carbotreat to see the status of the CO_2 capture demonstration unit being built. Another in-person meeting was held at the Sleipnir ship of partner Heerema, where at that moment the capture unit had been installed. A true highlight for the project partners to have this meeting on a ship and see the capture unit installed. The meetings were all very well attended, up to 40 persons, and the discussions were important for the project. The meetings were focussed on informing the consortium as well as people from the funding agencies on the progress achieved in all WP's and the planned activities to come.

Apart from these more official meetings, there have been plenty of inter WP meetings (in particular to transfer information to WP4), inter-WP meetings (with highlight to weekly frequent WP1 meetings during prototype operation) and even meetings on task level. The project closed with a final consortium meeting at location of MAN in Germany, and this meeting ended with a public webinar.

Advisory Board

An Advisory Board (AB) was established for EverLoNG, consisting of 13 members among which several Port Authorities. Two AB meetings were held, one in April 2022 and a second one in June 2023. Apart from these dedicated meetings with AB members, the AB was invited and participated in the CSIIG meetings (CO_2 Shipping Interoperability Industry Group) that were organised as part of WP2, three meetings in total.

Transnational collaboration on CCUS

Maritime CO_2 emissions are not limited to a certain country but are cross border and it is, therefore, evident that international collaboration is essential to meet the goals as specified for EverLoNG. Clearly, where it comes to emission regulations, the regulatory framework around capture systems onboard vessels, as well as the CO_2 off-loading strategies and infrastructure at ports and beyond, international cooperation is essential on a worldwide level. In ACT projects this is possible, and although the contractual side of the cooperation can be difficult, the value of working with top partners in the field from across the world has proven to be a great value for EverLoNG. In EverLoNG, we have demonstrated that CO_2 capture and storage onboard vessels is possible; we have evaluated the impact of the capture system on the ships' infrastructure, stability and safety, to guarantee the technical feasibility of the proposed technology; we have identified the major safety hazards associated with the capture technology and determined safeguards to mitigate those risks; moreover, we have established a CO_2 Shipping Interoperability Industry Group (CSIIG) and have proposed a roadmap towards a European CO_2 off-loading network. Addressing these issues requires fundamental knowledge, operation experience and creativity to think and to develop possible solutions. The EverLoNG consortium has brought this experience together making the project a success.

8 Dissemination activities (including list of publications)

Carbotreat: The EverLoNG project has provided lots of insight in operating a capture unit on a moving ship. Also, the conclusion of the analyzed data, showed points that require more attention and improved designs. This experience has led to further developments and enhancements in the design of next generation onboard capture systems. Working in partnership with the other consortium members, helped understand how we can jointly contribute to sustainable shipping. Achieve goals using our combined views, capabilities and efforts. The project had great visibility throughout the shipping world. The consortium showed that we are at the forefront of onboard carbon capture. This created interest from ship owners from all over the world to decarbonize their ships by means of OCCS.

Heerema Marine Contractors: The results are promising enough to continue the concept design of a SBCC system. The design of such a system integration might affect the core functionality of the vessel and therefore needs to be investigated in further detail. Especially the storage system requires further attention, due its size and CAPEX, but as well due to the logistics behind shipping cryogenic CO_2.

Anthony Veder: Anthony Veder is further investigating the implementation of OCC as part of the consortium LNG-Zero and they received a grant for the follow-up full-scale demonstration project called Blue Horizon, both part of the Dutch Maritime Masterplan.

MAN Energy Solutions: the results can be categorized into 3 clusters:

Emission measurements: the measurements during actual operation on engines supports the competence in making statements towards CO_2 reduction potentials through e.g. CCS.

Competence in propulsion systems: while MAN ES currently does offer CCS systems for ships, cooperating in the project increased the company's competence in the necessary interfaces, dependencies, potential engine configuration and modifications to ideally interface with CCS system. Additionally, WP3 supported a deeper understanding of the cryogenic interface of fuel heating and CO_2 cooling which may be relevant in consulting customer projects.

Customer support: MAN ES receives occasional requests for consulting and also to establish a connection with CCS Marine companies. Due to the still relatively high uncertainty about decarbonization pathways in Marine (Bio/Future Fuels vs CCS), these requests are not too frequent and will require time to develop. But in such case MAN ES can reach out to the EverLoNG partners.

SCCS: The EverLoNG project has garnered significantly high levels of interest and attention from industry, policy and academic actors. Owing to the project's high and very visible public profile, SCCS specifically was invited to develop and contribute to numerous knowledge sharing activities. Mostly listed below in section 8.1, they include: the NECCUS Scotland-Norway Trade Mission; NECCUS DecarbScotland 2024; University of Strathclyde Society of Naval Architecture and Marine Engineering forum 2024; Port of Aberdeen site visit; New Energy World publication article; CCSA Non-Pipeline Transport Working Group; NECCUS Maritime Special Interest Group CO_2 Maritime Opportunity in Scotland White Paper; invitation to present at the upcoming ZEP Technology Committee meeting in May 2025). As a consequence of the above activities, SCCS was approached by Veolia VWS Westgarth and Brittany Ferries, with subsequent introductions being made to other EverLoNG research and industry partners.

8.1 List of publications and dissemination activities

Please find below a list of the publications resulting from the project activities. The list contains the following type of publications: Po = Poster, O = Oral Presentation, Web = Webinar, WS = WorkShop, V = Video, N = newsletter/item, B = Blog, I = Interview, PR = Press Release, Oth = Others.

- Po1. Demonstration of ship-based carbon capture on LNG fuelled ships (EverLoNG); M.J.G. Linders, J. Garcia Moretz-Sohn Monteiro, M. Mælum, J. van den Akker, P. Zapp, E. Vroegrijk, J. Belgaroui, C. Dijkhuizen; 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, October 2022, Lyon, France.
- Po2. Demonstration of ship-based carbon capture on board of two LNG fuelled ships; Juliana Garcia Moretz-Sohn Monteiro, Jasper Ros, Elleke van Doorn, Pierre-Yves Duclos, Cees Dijkhuizen, René Veldman, Joan van den Akker, Vivian Reck, Marco Linders; 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, October 2022, Lyon, France.
- Po3. Ship-based CO_2 capture – Port integration; Michel Mælum, Anette Mathisen, Chameera Jayarathna, Ragnhild Skagestad, Jed Belgaroui; 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, October 2022, Lyon, France.
- PR1. A press release has been issued to announce the EverLoNG project including launch of the project website, 06/04/2022, see http://www.act-ccs.eu/news-1
- V1. Video, Promotional video released to publicise the launch of the project, 05/04/22. Link: https://everlongccus.eu/index.php/ships-log?field_video_category_value%5BVideo%5D=Video&sort_bef_combine=created_DESC#node-content-88
- B1. Blog: EverLoNG researcher Juliana Monteiro of TNO highlights recent momentum to decarbonise global shipping; 15/06/2022, link: Blog: Everlong researcher Juliana Monteiro of TNO highlights recent momentum to decarbonise global shipping | EverLoNG (everlongccus.eu)
- WS1. Workshop initiated by the Research Council of Norway and Gassnova, together with US DOE on the topic of further develop cooperation and financing of such between US/EU stakeholders. EverLoNG project presentation and workshop discussion performed on 30.06.2022 by Ragnhild Skagestad, SINTEF.
- O1. Oral presentation at ACT Knowledge Workshop, Marco Linders (TNO), June 2022, the Netherlands.

- O2. Oral Presentation at CIMAC, Pierre-Yves Duclos (TotalEnergies), 12th October 2022.
- WS2. Workshop, CO2 Shipping Interoperability and Industry Group (CSIIG) established and 1st meeting (CSIIG#1) held, 11 November 2022.
- O3. Oral Presentation of the project at the Climit Summit 2023 by Ragnhild Skagestad (SINTEF) at the 8th of February, Norway.
- I1. Dr. Petra Zapp, CO2-Kreislauftechnologien, 90 Prozent des weltweiten Warenverkehrs erfolgt per Schiff; January 2023. https://www.industrie-energieforschung.de/interviews/de/act_everlong_ship_based_carbon_capture
- N1. Schiffsbasierte Kohlenstoffabscheidung: Wie der Schiffsverkehr klimaneutral werden kann, 26.01.2023. https://www.industrie-energieforschung.de/news/de/act_everlong_carbon_capture_co2_schifffahrt
- PR2. A press release has been issued to announce the prototype capture unit almost ready to be installed onboard the TotalEnergies vessel. Title "EverLoNG ship-based carbon capture project aims to reduce CO2 emissions by at least 70%", April 2023.
- N2. News item, Dr Erika Palfi, Shipping Interoperability Industry Group gets underway, 23/03/2023. Link: Shipping Interoperability Industry Group gets underway | EverLoNG (everlongccus.eu)
- N3. News item, EverLoNG ship-based carbon capture project aims to reduce CO2 emissions by at least 70%, 14/04/2023. Link: EverLoNG ship-based carbon capture project aims to reduce CO2 emissions by at least 70% | EverLoNG (everlongccus.eu)
- B2. Blog: Some insight into one of the activities of EverLoNG WP3: optimisation of integration of the ship-based carbon capture system, Joan van den Akker, Conoship, 21/04/2023. Link: Some insight into one of the activities of EverLoNG WP3: optimisation of integration of the ship-based carbon capture system with the engine. | EverLoNG (everlongccus.eu)
- Web1. Demonstration of ship-based carbon capture on LNG fuelled ships. Project overview, May 15th 2023. Link: Webinar 1: EverLoNG ship-based carbon capture project updates | EverLoNG (everlongccus.eu)
- O4. Oral Presentation at Business Breakfast Nor-Shipping, Joost Wijdeveld (VDL) & Anette Mathisen (SINTEF), June 7th 2023.
- Oth1. Memo by Juliana Monteiro (TNO) on Feasibility of ship based carbon capture, provided to the Dutch delegation of the marine environment protection committee, 16th June, 2023.
- N4. News item, No regulatory impediments to ship-based carbon capture, 14/06/2023. Link: No regulatory impediments to ship-based carbon capture | EverLoNG (everlongccus.eu)
- V2. Video, Ship-Based Carbon Capture Prototype at Carbotreat, 04/07/2023. Link: https://everlongccus.eu/ships-log#node-content-108
- O5. Oral Presentation at Scotland-Norway Decarbonisation Trade Mission, Romain Viguier (SCCS) and Ragnhild Skagestad (SINTEF), 30-31 August 2023, Oslo, Norway. Link: https://everlongccus.eu/ships-log/everlong-showcased-prestigious-scotland-norway-bilateral-event
- N5. News item, Carbon capture prototype on board, 06/09/2023. Link: Carbon capture prototype on board | EverLoNG (everlongccus.eu)
- WS3. Workshop, 2nd CO2 Shipping Interoperability and Industry Group meeting (CSIIG#2) held, 20 September 2023.

- N6. News item, EverLoNG at IMO CCC 9, 25/09/2023. Link: EverLoNG at IMO CCC 9 | EverLoNG (everlongccus.eu)
- O6. Oral Presentation at IMO CCC 9, Erik Vroegrijk (Lloyd's Register EMEA), 21st September 2023.
- O7. Oral Presentation at Annual Technology Watch Program on CCUS - BT2i, Marco Linders (TNO), September 26th 2023.
- O8. Oral presentation at ACT Knowledge Workshop, Marco Linders (TNO), October 2023, Paris France.
- Po4. Demonstration of ship-based carbon capture on board of two LNG fuelled ships; Marco Linders, Juliana Monteiro, Frank Sanders, Eric Pelard, Leyla Teberikler, Cees Dijkhuizen, René Veldman; ACT Knowledge Workshop, October 2023, Paris France.
- N7. News item, Exploring the future of sustainable shipping: insights from the 2nd CSIIG workshop, 11/10/2023. Link: Exploring the Future of Sustainable Shipping: Insights from the 2nd CSIIG Workshop | EverLoNG (everlongccus.eu)
- O9. Oral presentation at SCOPE project meeting, Ragnhild Skagestad (SINTEF), 19th October 2023 in Porsgrunn, Norway.
- N8. News item, EverLoNG project partners launch Joint Venture, 19/01/2024. Link: EverLoNG project partners launch Joint Venture | EverLoNG (everlongccus.eu)
- PR3. A press release has been issued to announce first successful CO2 capture onboard a ship. Title "Pioneering ship-based carbon capture (SBCC) demonstration initial results very promising", February 2024.
- V3. Video, SBCC demonstration initial results very promising, 19/02/2024. Link: Ship's Log | EverLoNG (everlongccus.eu)
- N9. News item, EverLoNG on the road, 21/03/2024. Link: EverLoNG on the road | EverLoNG (everlongccus.eu)
- N10. News item, 1st capture demonstration campaign results coming soon, 26/03/2024. Link: Ship's Log | EverLoNG (everlongccus.eu)
- O10. Oral presentation at DeCarbScotland 2024, Scotland's Sustainable Tomorrow: A Vision for Industrial Decarbonisation (Edinburgh, UK, 01/02/24); presentation covering project overview with high-level technical detail; R. Stevenson/E. Palfi (SCCS).
- O11. Oral presentation at the University of Strathclyde SNAME (Society of Naval Architecture and Marine Engineering) 7th Annual Glasgow Symposium (February 2024, Glasgow); presentation covering project overview with high-level technical detail; R. Stevenson (SCCS).
- O12. Oral presentation and general discussion at the Port of Aberdeen (Aberdeen, UK, 13/04/24); presentation covering project overview with high-level technical detail; R. Stevenson/E. Palfi (SCCS).
- Po5. EverLoNG: Demonstration of ship-based CO2 capture (SBCC); J. Garcia Moretz-Sohn Monteiro, A. Subramani , J. Ros , R. Zurhorst , F. Sanders , E. Pelard, L. Teberikler, C. Dijkhuizen, R. Veldman, C. Yang, P. Sharan, M.J.G. Linders; 17th International Conference on Greenhouse Gas Control Technologies GHGT-17, October 2024, Calgary Canada.
- O13. Ship-based carbon capture – port infrastructure and implementation roadmap; R. Skagestad, A. Mathisen, K.L. Aas, S. Karunarathne; 17th International Conference on Greenhouse Gas Control Technologies GHGT-17, October 2024, Calgary Canada.

- O14. Conceptual design of ship-based carbon capture (SBCC) technology on-board of an LNG fuelled large crane vessel and LNG carrier; A. Subramani, J. Ros, J. van der Akker, C. Dijkhuizen, E. Pelard, J. Lauterbach, P. Bagdiya, M.J.G. Linders, J. Monteiro; 17th International Conference on Greenhouse Gas Control Technologies GHGT-17, October 2024, Calgary Canada.
- Po6. Life Cycle Assessment of Ship-based Carbon Capture: An Environmentally Sustainable Measure to Reduce CO2 Emissions in Shipping?; L. Reitz, J. Ros, A. Mathisen, A. Subramani, R. Skagestad, G. Farrell, M. Hellendall, B. Patel, P. Sharan, P. Zapp; 17th International Conference on Greenhouse Gas Control Technologies GHGT-17, October 2024, Calgary Canada.
- N11. News item, April 2-24 Consortium Meeting, 15/04/24. Link: https://everlongccus.eu/ships-log/april-2024-consortium-meeting
- N12. News item, EverLoNG @ the 43rd International Bunker Conference, 02/05/2024. Link: EverLoNG @ the 43rd International Bunker Conference | EverLoNG (everlongccus.eu)
- PR4. A press release has been issued to announce EverLoNG's second demonstration campaign underway as SSCV Sleipnir sets sail, 18/06/2024. Link: EverLoNG's second demonstration campaign underway as SSCV Sleipnir sets sail | EverLoNG (everlongccus.eu)
- V4. Video, Carbon capture demonstration campaign aboard the SSCV Sleipnir, 18/06/24. Link: https://www.youtube.com/watch?v=k7wqXRM9j2w
- Web2. Results from the first EverLoNG capture demonstration campaign on board the SEAPEAK ARWA, 25/06/2024. Link: Webinar 2: Results from the first EverLoNG capture demonstration campaign on board the SEAPEAK ARWA | EverLoNG (everlongccus.eu)
- WS2. Workshop initiated by DNV GL in Stavanger, Norway 11-12 June. The topic for the workshop was onboard CO2 capture, and participants from selected companies/projects like DNC, Stella Maris, Solvang shipping, Bellona, Equnior, Altera, Norwegian Maritime Authority, Total Energies.
- N13. News item, Announcement four conference contributions GHGT-17, 12/07/2024. Link: GHGT-17 | EverLoNG (everlongccus.eu)
- N14. News item, Onboard carbon capture: a feasible pathway to net zero emissions for shipping, 26/09/2024. Link: Onboard carbon capture: a feasible pathway to net zero emissions for shipping | EverLoNG (everlongccus.eu)
- N15. News item, Onboard carbon capture: a feasible pathway to net zero emissions for shipping, Energy institute, 26/09/2024. Link: Onboard carbon capture: a feasible pathway to net zero emissions for shipping | Article Page (energyinst.org)
- I2. Marco Linders and Johannes Lauterbach, 'MAN ES onboard carbon capture continues', Motorship.com, May/June 2024, p.38-39.
- I3. Marco Linders, CO_2-Sauger auf Fracht-schiffen, IT- and Engineering magazine, 12 September 2024, European All-Stars – Connecting Europe (ferchau.com)
- O15. Oral presentation at ACT Knowledge Workshop, Marco Linders (TNO), September 2024, Oslo Norway.
- Po7. Demonstration of ship-based carbon capture on board of two LNG fuelled ships; Marco Linders, Juliana Monteiro, Frank Sanders, Eric Pelard, Leyla Teberikler, Meike Kolthof, René Veldman; ACT Knowledge Workshop, September 2024, Oslo Norway.
- N16. News item, SSCV Sleipnir demonstration campaign successfully completed, 22/10/2024. Link: SSCV Sleipnir demonstration campaign successfully completed | EverLoNG

- N17. News item, LCA for SBCC: 38-45% CO_2e avoidance possible, 23/10/2024. Link: LCA for SBCC: 38-45% CO_2e avoidance possible | EverLoNG
- O16. Oral presentation (by invitation) of EverLoNG results to date & high-level project overview to the CCSA Non-Pipeline Transport Subgroup, Richard L Stevenson (SCCS), 13 December 2024, online
- O17: Oral presentation (by invitation) of EverLoNG results and focus in the roadmap at DNVs seminar " LNG, Hydrogen and CCUS – maritime sector, Ragnhild Skagestad, 3. December 2024
- O18: Presentation by invitation at Gassco to discuss and the EverLoNG project and roadmap, Ragnhild Skagestad, 10 December 2024
- WS4. Workshop, 3rd CO2 Shipping Interoperability and Industry Group meeting (CSIIG#3) held, 12 February 2025. Link: https://everlongccus.eu/events/3rd-co2-shipping-interoperability-and-industry-group-online-workshop-csiig3
- V5. Vlog from Ragnhild Skagestad, discussing work carried out by WP2, the challenges of integrating OCC into the full CCUS chain, and sharing her thoughts on the future for OCC and CO2 shipping in general; Ragnhild Skagestad (SINTEF), 17 February 2025. Link: https://youtu.be/_yKzx6ceA00
- N18. News item, Charting a course towards CO_2 port readiness: Insights from the 3rd CSIIG workshop, 20 February 2025. Link: https://everlongccus.eu/ships-log/charting-course-towards-co2-port-readiness-insights-3rd-csiig-workshop
- I4. Interview of selected WP leads/contributors covering an overview of the EverLoNG project for Open Access Government – April 2025 edition; Marco Linders, Juliana Monteiro, Jasper Ros (TNO), Ragnhild Skagestad (SINTEF), Richard L Stevenson (SCCS), Petra Zapp (Jülich), 21 March 2025. Link: Onboard Carbon Capture (OCC): The Everlong project
- Oth2. White paper contribution to NECCUS 'CO2 Maritime Opportunity in Scotland', on infrastructure requirements and challenges for CO2 shipping and OCC CO2 handling at port, for release ahead of NECCUS DeCarbScotland 2025 conference, 13 March 2025; Richard L Stevenson & Erika Palfi (SCCS), 28 February 2025.
- O19: Oral presentation by Ragnhild Skagestad of the EverLoNG project at CLIMIT SUMMIT conference 27-28 February 2025 in Larvik, Norway. 350 participants. Link: https://climit.no/en/climit-summit-2025/
- O20: Oral presentation by Guus van der Bles, "EverLoNG-project: advancing LNG as future fuel by Onboard Carbon Capture" at International LNG conference LNGCON, March 2025, Amsterdam, the Netherlands. As part of project deliverable D6.4.3.
- N19. News item, *The good ship EverLoNG returns to 'port'*, 25 March 2025. Link: https://everlongccus.eu/index.php/ships-log/good-ship-everlong-returns-port

9 Acknowledgements

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10 Appendix 1 – ACT Final Financial Report

The table below presents an overview of the financial results per partner, as well as per country and type of funding.

Project name:	Demonstration of ship-based carbon capture on LNG fuelled ships (EverLoNG)								
Project number:	327332								
Actual costs per country / per organisatin									
Country	ACT funding	Other public funds	Private funding, R&D institution	Private funding, industry	In-kind, R&D Institution	In-kind industry	Other funds	Total after 3.5 years per org	Total after 3.5 years per country
Netherlands (k€)									3.638.448
TNO	775.986				346.075			1.122.061	
Conoship International	124.716					43.153		167.869	
Carbotreat	340.527			160.000		1.218.739	78.750	1.798.016	
VDL AEC Maritime	110.925					143.182		254.107	
Heerema Marine Contractors	17.590					200.605		218.195	
Antony Veder	41.020					37.180		78.200	
Germany (k€)									656.670
MAN Energy Solutions	103.783					155.674		259.457	
Forschungszentrum Jülich GmbH	397.213							397.213	
Norway (k€)									1.236.731
TOTAL EP Norge AS	200.000					67.747	132.622	400.369	
SINTEF AS	610.200			67.800				678.000	
Bureau Veritas Norway AS	29.400					30.340		59.740	
ÅKP AS						39.822		39.822	
DNV GL	29.400					29.400		58.800	
United Kingdom (k€)									292.403
University of Edinburgh (SCCS)	195.571				21.730			217.301	
Lloyd's Register	37.551					37.551		75.102	
United States of America (k€)									497.100
Los Alamos National Laboratory	497.100							497.100	
Total per funding	3.510.982			227.800	367.805	2.003.393	211.372	6.321.352	6.321.352