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HYBRID TANDEM CATALYTIC CONVERSION PROCESS TOWARDS HIGHER OXYGENATE E FUELS

E-TANDEM - Deliverable report

D5.7 Exploitation Roadmap beyond E-TANDEM

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Project summary

E-TANDEM has enabled the efficient and direct production of a new higher-oxygenate, diesel-like e-fuel for the marine and heavy-duty transport sectors. This oxygenated fuel has been produced directly from water and CO_2 as the sole carbon source, with renewable electricity as the sole energy input, through a once-through hybrid catalytic conversion process integrating three key branches of catalysis: (1) high-pressure electrocatalysis for syngas production coupled with tandem catalytic e-syngas conversion, (2) thermocatalysis using solid catalysts, and (3) chemocatalysis employing molecular complexes. The project successfully demonstrated this novel e-fuel production route at bench scale in a continuously operating mini-plant and assessed its capability to operate under fluctuating renewable energy inputs.

Summary

The E-TANDEM project, funded by the European Union's Horizon Europe programme (Grant Agreement No. 101083700), has developed and validated a novel production pathway for Higher Oxygenate E-Fuels (HOEF) aimed at supporting the de-fossilization of maritime transport. The project addresses the urgent need for scalable, low- fossil-carbon marine fuels that can reduce net (life cycle) greenhouse-gas emissions and air-pollutant impacts while remaining compatible with existing ship engines and fuel infrastructure.

At the core of E-TANDEM is a hybrid catalytic process that converts CO_2, water, and renewable electricity into liquid, diesel-like oxygenated fuels. The process integrates high-temperature solid oxide co-electrolysis (co-SOE) for syngas generation with tandem catalytic conversion and advanced separation technologies. This configuration enables the selective production of higher alcohols and ethers with high cetane numbers and low soot-forming tendencies, making HOEF particularly suitable for marine diesel applications.

Within the project, HOEF production and utilization have been validated at laboratory scale (end TRL 4). Fuel characterization and engine-relevant testing demonstrated that HOEF can be blended with marine gas oil (MGO), with blends around 20 % identified as a conservative and technically feasible entry point that does not require engine hardware modifications. Higher blending ratios, up to approximately 50 %, were identified as technically plausible for future demonstrations, subject to further validation in pilot- and demonstration-scale engine tests.

A comprehensive life-cycle assessment (LCA) was performed using a source-to-propeller (well-to-wake) framework covering representative maritime vessel types. The results indicate that HOEF blends can significantly reduce greenhouse-gas emissions and selected local air-pollution impacts compared to conventional marine fuels, with performance influenced by the hydrocarbon chain length distribution (related to flash point) and compositional realization (higher alcohols vs higher ethers) of the final e-fuel mixture of higher oxygenated and non-oxygenated compounds. In parallel, techno-economic analyses show that while production costs remain high at pilot scale, substantial cost reductions are achievable at larger scales, with electricity price emerging as a dominant cost driver.

Building on these results, this deliverable presents an exploitation and development roadmap that defines the key technical, economic, and regulatory steps required to advance HOEF from laboratory validation toward pilot- and demonstration-scale deployment (TRL 6–7). The roadmap focuses on maritime applications and outlines phased actions including pilot-plant implementation, long-duration engine testing, fuel certification activities, and stakeholder engagement. By translating E-TANDEM's validated scientific and technical achievements into a structured development pathway, the roadmap supports future exploitation activities and provides a foundation for follow-up demonstration projects and industrial deployment of higher oxygenate e-fuels in the waterborne transport sector.

Strategic Rationale for the HOEF Exploitation road map.

The exploitation strategy defined in this roadmap is shaped not only by the technical achievements of the E-TANDEM project, but also by extensive stakeholder and round-table discussions addressing market, regulatory, and investment realities. These discussions consistently highlighted that the success of novel e-fuels will depend less on theoretical performance in neat form and more on their ability to integrate pragmatically into existing fuel systems, regulatory frameworks, and industrial decision-making processes.

A central conclusion of these exchanges is that low-percentage blending of Higher Oxygenate E-Fuels (HOEF) into existing fuels represents the most effective near-term deployment pathway. From a system perspective, blending enables immediate emissions reductions across a large fuel volume while avoiding the need for infrastructure modifications, engine redesign, or disruptive changes to fuel logistics. In contrast, the exclusive use of neat fuels or very high blend ratios was widely seen as carrying higher regulatory, technical, and investment risk, particularly in conservative sectors such as maritime transport.

This blending-first strategy aligns with both the technical evidence generated within E-TANDEM and the environmental performance demonstrated by the project's own life cycle assessment. Fuel characterization and engine testing showed that HOEF blends around 20 % can be applied in conventional marine diesel engines without hardware modifications, while higher blends remain technically feasible for future demonstration activities. In parallel, the integrated source-to-propeller LCA performed within the project (refer to D5.6) showed that HOEF blends with MGO can reduce well-to-wake greenhouse-gas emissions by approximately 20-26 % relative to conventional MGO under renewable electricity conditions, while also delivering substantial reductions in acidification, particulate matter formation and eutrophication impacts. Higher-share HOEF blends achieved the strongest local environmental benefits, including reductions of up to ~42% in acidification potential and ~29% in particulate matter formation relative to MGO. The analysis further demonstrated that the magnitude of the climate benefit depends strongly on the electricity mix used for fuel production, highlighting the importance of renewable electricity supply for maximizing lifecycle GHG reductions. Together, these findings support a deployment philosophy focused on incremental substitution and scalable integration within existing marine fuel infrastructures rather than wholesale replacement.

Regulatory and investment considerations further reinforce this approach. Stakeholder discussions emphasized that long-term uncertainty around CO_2 accounting rules, emissions trading coverage, and post-2040 policy frameworks represents a major barrier to capital mobilization for first-of-a-kind fuel pathways. Blending-based deployment mitigates this risk by allowing gradual adoption, learning-by-doing, and policy alignment over time, while preserving flexibility in the face of evolving regulations. This is particularly important in maritime applications, where fuel standards, safety classifications, and liability considerations strongly favor conservative, compatibility-driven innovation.

A round-table discussion held at the E-TANDEM project's Final Event (Mülheim an der Ruhr, DE) also highlighted illustrative use cases outside the maritime sector, such as backup power generators and data centers, to clarify the value proposition of fuel-intrinsic emissions reduction. Backup generators typically lack exhaust gas after-treatment systems to minimize cost and complexity and are often legally restricted to short operating windows. In such contexts, cleaner fuels can be more cost-effective

than retrofitting hardware solutions. While these stationary applications are outside the formal scope of this roadmap, they underscore the broader strategic advantage of HOEF: emissions reduction through fuel properties rather than system modification.

Based on these considerations, the roadmap deliberately prioritizes maritime deployment while embedding a blending-first strategy as its core exploitation principle. This approach maximizes near-term environmental impact, reduces technical and regulatory risk, supports investor confidence, and creates a credible pathway from laboratory validation to pilot- and demonstration-scale deployment (TRL 6–7). By aligning technical readiness with market and policy realities, the HOEF roadmap aims to position higher oxygenate e-fuels as a practical, scalable contributor to maritime decarbonization rather than a niche or high-risk alternative.

Contents

1 Introduction 9
1.1 Strategic objective 9
1.2 Project scope and context 9
1.3 Objectives of the Development Roadmap 10
2 Methods and core part of the report 11
2.1 Background 11
2.2 Procedures 11
2.3 Data Analysis 12
3 Development Road Map & Considerations 14
3.1 The development road map 14
3.2 Fuel Properties and Compatibility Considerations 18
3.3 Application considerations 20
3.4 Market & Deployment Considerations 23
3.5 Key Development Considerations and Mitigation Measures 26
3.6 Contribution to project (linked) Objectives 29
3.7 Contribution to major project exploitable result 29
4 Conclusions and Recommendations 31
4.1 Overall Conclusions 31
4.2 Indicative Funding Mechanisms for Post-Project Demonstration 32
5 Risks and Interconnections 34
5.1 Risks 34
5.2 Interconnections 34
6 Deviations from Annex 1 35
7 References 36
8 Acknowledgement 37

List of Figures

Figure 1: Development Road map proposal..... 17
Figure 2: Organic product fractions of the E-TANDEM process (as estimated from the simulation of a 1 MW demo plant). 21
Figure 3: A small fishing boat, which offers a low-risk, low-volume platform for initial fuel trials in sheltered waters..... 22
Figure 4: A mid-sized passenger ferry, operating on fixed routes with high public visibility and strong decarbonization incentives. 22
Figure 5: A large passenger ferry, which could serve as a high-impact demonstration platform once fuel supply and regulatory approvals are secured. 22
Figure 6: Priority regions for deployment 25

List of Tables

Table 1: HOEF Development Milestones (2026–2032) 16
Table 2: Technical Challenges and Knowledge Gaps..... 18
Table 3: key unknowns (spanning technical, regulatory, and market domains) 27
Table 4: Overview of relevant funding options for a HOEF demonstration (TRL 7–8)..... 33

Abbreviations & Definitions

Abbreviation	Explanation
AiP	Approval in Principle
CAPEX	Capital Expenditure
CCU	Carbon Capture and Utilisation
co-SOE	Solid Oxide co-Electrolysis
DAC	Direct Air Capture
EGR	Exhaust Gas Recirculation
ETS	Emissions Trading System
FT	Fischer–Tropsch
GHG	Greenhouse Gas
HOEF	Higher Oxygenate E-Fuels
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization for Standardization
KER	Key Exploitable Result
LCA	Life-Cycle Assessment
LHV	Lower Heating Value
MGO	Marine Gas Oil
OME	Oxymethylene Ether
OPEX	Operating Expenditure
OSN	Organic Solvent Nanofiltration
PFD	Process Flow Diagram
P&ID	Piping and Instrumentation Diagram
PPA	Power Purchase Agreement
PtX	Power-to-X
RHF	Reductive (olefin) Hydroformylation
RO	Reverse Osmosis
SOE	Solid Oxide Electrolysis
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level
TTW	Tank-to-Wake
WTT	Well-to-Tank

1 Introduction

1.1 Strategic objective

The strategic **objective of this roadmap is to** advance Higher Oxygenate E-Fuels (HOEF) from laboratory validation (TRL 4–5) toward pilot-scale validation (TRL 6) and subsequent demonstration in a relevant maritime environment (TRL 7), subject to the successful completion of defined technical and operational validation steps at each stage. It **outlines the milestones, scale-up needs, and stakeholder actions** for the first full demonstration of HOEF fuels in a marine setting.

This deliverable turns E-TANDEM's technical innovations, i.e. the innovative e-fuel production concept and HOEF e-fuel composition, into a **plan for industrial validation**. It supports the EU's Green Deal, Fit for 55, and the IMO's decarbonization strategy to cut shipping emissions and adopt sustainable fuels. By providing a clear pathway to TRL 7, this roadmap helps **ensure E-TANDEM's technologies can be used beyond the project** and supports Europe's climate-neutral transport goals.

1.2 Project scope and context

The E-TANDEM project addresses the **urgent need for scalable, carbon-neutral fuels in hard-to-abate sectors** such as international shipping. It has developed a novel hybrid process that integrates high-temperature co-electrolysis (co-SOE) with tandem catalytic conversion to produce oxygenated, diesel-like fuels from CO_2 and renewable electricity. These fuels are enriched in mid and long-chain higher alcohols (in a first realization) or aliphatic ether derivatives thereof (in a second realization). They offer high cetane numbers, cleaner combustion and, particularly in the ether-based second realization, high blending capacity with state-of-the-art marine gasoil (MGO) and blend compatibility with existing diesel engines.

The roadmap is focused on maritime deployment, where HOEF's drop-in characteristics and emissions benefits (e.g., near-zero soot, reduced NO_x and SO_x) offer immediate value. While other applications such as heavy-duty road transport or aviation may be technically feasible in the longer term, this deliverable deliberately focuses on maritime applications. The assessment of non-maritime use cases is therefore out of scope for this roadmap and is not considered in the definition of development priorities, milestones, or demonstration activities presented here.

While Higher Oxygenate E-Fuels (HOEF) were discussed during the project as potentially relevant for a broader range of applications—including heavy-duty road transport and stationary power—the consortium concluded that maritime deployment represents the most impactful and realistic initial focus. This conclusion reflects not a limitation of the technology, but the relative maturity of maritime fuel regulation, the high relevance of fuel compatibility, and the opportunity to achieve significant emissions reductions without fundamental changes to existing engines or infrastructure. Insights from stakeholder and round-table discussions highlighted that sectors with conservative safety requirements and long asset lifetimes particularly benefit from drop-in or near-drop-in fuel solutions, reinforcing the strategic choice to prioritize maritime applications within this roadmap.

The roadmap is **informed by technical results from WP3–WP5**, including process simulation, fuel characterization, techno-economic analysis, and life-cycle assessment. It also incorporates **feedback from the project's Stakeholder Board** and external experts to ensure alignment with market needs, regulatory frameworks, and infrastructure realities.

1.3 Objectives of the Development Roadmap

The key objectives of this deliverable are to:

- **Summarize the outcomes and lessons learned** during E-TANDEM, highlighting technical achievements (and any shortfalls) that influence next steps.
- **Define the technical milestones** needed to scale HOEF production and utilization to TRL 6–7, including pilot plant design, fuel testing, and first demonstration in a marine engine or vessel.
- **Provide a strategic blueprint for the exploitation of the project's Key Exploitable Results (KERs)** related to the core e-fuel production technology**,** as identified in Deliverable D5.3, and outline potential pathways for their protection, further development and commercialization through patents, licensing activities, spin-offs and follow-up collaborative projects.
- **Highlight remaining risks, uncertainties, and interdependencies** that need to be managed as the technology scales – covering technical, regulatory, economic, and environmental aspects – and propose mitigation strategies for each.
- **Provide concrete recommendations** for stakeholder engagement (e.g. involving ship owners, fuel suppliers, port authorities) and regional deployment, identifying where and how the first HOEF demonstrations and early market adoption could most effectively occur.

By meeting these objectives, the roadmap will give consortium partners and external stakeholders a **clear guide to move beyond the R&D phase** toward real-world implementation of higher oxygenate e-fuels. Potential applicability of HOEF in non-maritime sectors (e.g., heavy-duty road transport) was identified during the project but is not addressed further in this deliverable, as D5.7 focuses on maritime exploitation pathways.

2 Methods and core part of the report

2.1 Background

The E-TANDEM process is a multi-step hybrid system that combines several innovative elements:

- ***Electrocatalysis:*** **co-SOE** (solid oxide co-electrolysis) converts CO_2 and steam into e-syngas (CO and H_2) at ~700°C, achieving high conversion and electrical efficiency (~80%). Syngas composition is adjustable for downstream needs.
- ***Thermocatalysis:*** Syngas is processed in a **tandem catalytic reactor** with both solid Fischer-Tropsch (FT) and molecular **reductive hydroformylation (RHF)** catalysts. FT converts CO/H_2 into hydrocarbons; RHF converts olefins and CO/H_2 into **oxygenated compounds** (higher alcohols), shifting the product slate toward oxygenates.
- ***Product Upgrading:*** The alcohol mix (mainly C_5-C_{10}) undergoes **catalytic dehydration** to produce aliphatic ether derivatives, which are high-cetane, low-sooting fuel components. Heavier FT hydrocarbons are separated and can be upgraded at a refinery. In the process simulations used in E-TANDEM, alcohols supplied to the dehydration step span a wider chain-length range (approximately C_5-C_{20}).
- ***Separation and Recycle:*** **Organic solvent nanofiltration (OSN)** membranes retain the RHF catalyst while allowing product molecules through, enabling continuous operation. Distillation removes light volatiles so that the final HOEF product is suitable for marine use. In the process simulations used in E-TANDEM, CO_2 is recycled back to the co-SOEC step. Recycling of conditioned water back to co-SOEC is a desirable future improvement to minimize waste, but it was not included in the E-TANDEM simulations

Overall, the E-TANDEM process currently demonstrated at laboratory scale enables the production of diesel-like oxygenated fuels without direct fossil inputs, using CO_2, water and renewable electricity as the sole feedstocks. A key advantage of the process is the formation of higher synthetic ether compounds (ca. 5 wt% oxygen content), which are essentially free of olefinic and aromatic species and therefore offer cleaner combustion properties. Scaling the technology toward industrial implementation will require the validation of each individual unit operation (including co-SOE, e-syngas conditioning, tandem e-syngas conversion, catalyst recycling and product upgrading/work-up) at progressively larger scales, followed by their integration into a fully operational pilot system.

2.2 Procedures

Several methodologies were employed to analyze and plan the scale-up:

- **Techno-Economic Modeling:** A detailed TEA (deliverable report D5.5) assessed the production cost of HOEF fuel at different scales. Using equipment cost scaling factors and quotes, the team built a cost model for a 1 MW pilot vs. a future 50 MW commercial plant. This helped identify cost drivers and break-even prices (e.g., at pilot scale the **production HOEF cost was estimated at €1.5–2.5 per liter**, assuming all co-products are valorized) and how these might improve with scale and learning.

- **Life-Cycle Analysis:** The LCA (Deliverable report D5.6) followed standard procedures to ensure that scaling decisions align with environmental goals. For instance, the LCA was used to compare different CO_2 sourcing options (point-source vs. direct air capture) on overall emissions, which influenced the **roadmap's recommendation to use *unavoidable industrial CO_2* sources initially** (to maximize near-term emission reductions and economics), while planning a transition to DAC as it becomes more viable.
- **Process Simulation and Scale Design:** Using a simulation toolchain (partly based on AVL's in-house process modeling capability), the team designed a notional **pilot plant** that integrates the Co-SOE module with the tandem reactor and separations. This simulation was paramount for energy and mass balance calculations at scale – confirming, for example, that the **pilot can achieve continuous operation** with self-sufficient recycling of solvents and minimal purge streams. It also aided in sizing equipment (e.g., how large a distillation column is needed to ensure HOEF flash point >60°C, or how many SOEC cell stacks to reach the target syngas output). These design calculations underpin the technical milestones laid out in the roadmap.

2.3 Data Analysis

The analysis of E-TANDEM data and related studies identified key parameters and open issues:

- **Pilot Plant Throughput:** A pilot-scale reference case of approximately 1 MW electrical input was used within the project analyses and simulations. At this scale, the pilot is expected to produce on the order of 10–15 kg/h of HOEF fuel, together with co-product non-oxygenated (paraffinic) hydrocarbon streams. This scale is considered suitable for technology validation, learning, and fuel supply for engine and vessel trials, rather than for commercial deployment.
- While these co-products have value, they require upgrading for marine use; gaseous alkanes such as methane and ethane can generally only be utilized through incineration, and the side-product CO_2 must either be released or captured for potential future use. Most of the liquid paraffinic fraction can be incinerated, used as conventional fuel, or blended with HOEF (similar to an MGO+HOEF mixture), still offering advantageous fuel properties. A mixed stream of ethers/alcohols and paraffins would also constitute a novel fuel type, characterized by a higher oxygen content than fossil diesel/MGO and the absence of olefins and aromatics. HOEF itself can be used directly as a marine fuel blendstock.
- **Fuel Specifications:** WP3 fuel characterization and ignition studies demonstrated that higher-ether HOEF–MGO blends exhibit highly promising properties for marine fuel applications. In particular, 10% and 20% ether blends complied with most key ISO 8217 DMA requirements, showing acceptable viscosity, density, lubricity, oxidation stability and excellent ignition performance (D3.1). The slightly higher water uptake capacity of HOEF and its blends is accepted under the ISO 8217 DMA as far as the fuel appearance is clear, as it could be confirmed in all cases. While the 20% blend showed a slightly reduced flash point (58 °C), an optimized second-generation ether blend composed predominantly of C_{10}-C_{18} ethers enabled a 50:50 HOEF-MGO blend meeting both ISO 8217 and EN590 flash-point specifications (62 °C) together with excellent cetane performance. In addition, ether-HOEF blends substantially reduced soot formation and ignition delay relative to conventional MGO, supporting their strong potential as cleaner marine fuel components (D3.2).

- **Open Technical Points:** Action items include: validating membrane-based catalyst separation at pilot scale; confirming co-SOE stability over more extended periods of time; and optimizing tandem reactor selectivity for HOEF. These will be addressed in pilot phase testing. In addition, the downstream purification and separation train for higher alcohol and ether products (e.g., fractional distillation, liquid–liquid extraction, and azeotropic distillation) was developed based on process design and available literature and was not experimentally validated within E-TANDEM; validation of this sequence is therefore a key scale-up activity. Furthermore, while the MPG mini-plant represents a simplified continuous process, it omits co-SOE, e-syngas conditioning, product separation steps, and alcohol dehydration; moving to a fully integrated, continuous process (co-SOE + tandem reactor + product work-up + alcohol dehydration) at TRL6-7 remains a central technical milestone for pilot-scale validation.

3 Development Road Map & Considerations

3.1 The development road map

This roadmap outlines the structured development path for Higher Oxygenate E-Fuels (HOEF) from laboratory validation (TRL 4–5) to pilot-scale demonstration and real-world deployment (TRL 6–7), as defined in the official Gantt Figure 1 and milestone plan Table 1. It is organized into five sequential phases, each with defined technical milestones, stakeholder engagement activities, and regulatory steps required to enable the safe, scalable, and economically viable use of HOEF in maritime applications.

The roadmap integrates technical findings from E-TANDEM with market and policy insights to ensure alignment with the European Green Deal, FuelEU Maritime, and IMO decarbonization targets. Each phase concludes with a milestone-based decision gate to ensure technical and economic readiness before progressing to the next stage.

Phase 1: Feasibility & Concept Design (2026–2027)

This phase focuses on de-risking the pilot concept and validating key assumptions. Activities include:

- Completion of the pilot plant concept design and system configuration (Co-SOE + tandem reactor + separations).
- Identification of a suitable pilot site and mapping of potential fuel offtake partners.
- Intermediate-scale testing of critical subsystems (e.g., OSN membrane, CO_2 membrane, continuous FT operation).
- A 500-hour engine test campaign using HOEF20 to validate emissions, durability, and operability.
- Fuel compliance testing against ISO 8217 marine distillate standards.
- A techno-economic checkpoint to validate CAPEX/OPEX assumptions and cost reduction pathways.

This phase concludes with a formal Feasibility Engineering Sign-Off, confirming that the pilot concept is technically and economically viable and ready for detailed engineering.

Phase 2: Engineering, Permitting & Build Readiness (2027–2028)

This phase prepares the project for pilot plant construction:

- Execution of basic and detailed engineering, including PFDs, P&IDs, 3D layout, and safety systems.
- Engagement with permitting authorities and classification societies to secure environmental, ATEX, PED, and marine fuel handling approvals.
- Alignment with ISO 8217 and class society requirements for HOEF/MGO blends.
- Procurement planning and vendor engagement to confirm construction timelines and costs.

The phase concludes with a Build-Readiness Decision milestone, marking the transition to TRL 6 and authorizing pilot plant construction.

Phase 3: Pilot Plant Construction & Commissioning (2029)

Phase 3 represents the first validation of a fully integrated and continuous E-TANDEM process at pilot scale, combining co-SOEC, tandem synthesis, and the downstream separation and upgrading steps.

This phase involves the physical realization of the TRL-6/7 pilot plant:

- Construction and commissioning of a 1 MW-scale integrated pilot plant.
- Achievement of stable operation across all subsystems (Co-SOE, tandem reactor, separations, recycle loops).
- Completion of a 1000-hour continuous operation campaign to validate process stability and catalyst retention.
- Production of several tons of HOEF fuel for downstream testing and demonstration.

Successful commissioning and stable continuous operation of the integrated pilot plant, together with verification of key performance indicators (process stability, product quality, catalyst retention, and energy efficiency), constitute the evidence base for claiming TRL 6.

Phase 4: Engine Testing & On-Board Demonstration (2030)

This phase transitions the technology from pilot validation to operational demonstration:

- Execution of engine trials covering HOEF/MGO blend ratios from approximately 20 % up to higher demonstrator-level blends (potentially approaching 50 %) in a marine auxiliary engine. These tests aim to evaluate emissions behavior, performance, and hardware compatibility under controlled conditions
- Safety validation of HOEF fuel handling, storage, and bunkering under marine conditions.
- Engagement with class societies to obtain Approval in Principle (AiP) for HOEF/MGO blends.

Completion of this phase is intended to generate the technical and operational evidence required to assess readiness for TRL 7, including engine operability, emissions behavior, safety, and fuel-handling performance under representative maritime conditions.

Phase 5: Full-Scale Maritime Demonstration & Pre-Commercial Planning (2031–2032)

The final phase of the roadmap demonstrates HOEF in operational maritime settings:

- A full-scale demonstration aboard a working vessel or across a fleet of pilot vessels.
- Real-world validation of emissions reductions (>80% GHG, >90% PM/SOx) and maintenance neutrality.
- Class society approval for HOEF50 (HOEF:MGO 50:50 blend) use in marine engines and regulatory engagement with IMO and flag states.
- Final techno-economic assessment and business case development for a 50–100 kt/year commercial HOEF facility.

This phase concludes with a demonstration of HOEF/MGO fuel use in a relevant maritime environment, providing the system-level validation required to substantiate a TRL 7 classification.

Development Timeline to TRL 7

The roadmap envisions a staged scale-up and demonstration of HOEF technology over the next 5–7 years. Figure 1 illustrates the timeline and key milestones from the current lab scale to a full-scale demonstration.

Table 1: HOEF Development Milestones (2026–2032)

Milestone ID	Description	Target Date	TRL Level
M1	Completion of E-TANDEM project with TRL 5 lab-scale validation	Q4 2026	TRL 5
M2	Concept design freeze and feasibility sign-off	Q4 2027	TRL 5
M3	Build-readiness decision for TRL 6 pilot plant	Q1 2029	TRL 6
M4	Commissioning of 1 MW pilot plant	Q4 2029	TRL 6-7
M5	Continuous pilot operation (≥1000 hours), fuel output ≥13 kg/h	Q4 2029	TRL 6-7
M6	Engine testing on HOEF/MGO blends (starting at ~20 %, with evaluation of higher demonstrator-level blends)	Q2 2030	TRL 6–7
M7	On-board demonstration of HOEF/MGO blends, with blend ratios selected based on outcomes of prior engine testing and regulatory approval. On-board demonstration of HOEF/MGO fuel use in a working vessel, with blend ratio selected based on prior validation results.	Q4 2031	TRL 7
M8	Class society Approval in Principle (AiP) for HOEF/MGO blends	Q4 2031	TRL 7
M9	TRL 7 demonstration authorization and emissions validation	Q1 2032	TRL 7
M10	Final techno-economic assessment for TRL 8 commercial-scale facility	Q2 2032	TRL 7–8

Progression between TRL levels is not assumed to be automatic; advancement from TRL 5 to TRL 6 and from TRL 6 to TRL 7 is contingent upon meeting predefined technical, operational, and safety validation criteria, as outlined in the corresponding roadmap phase.

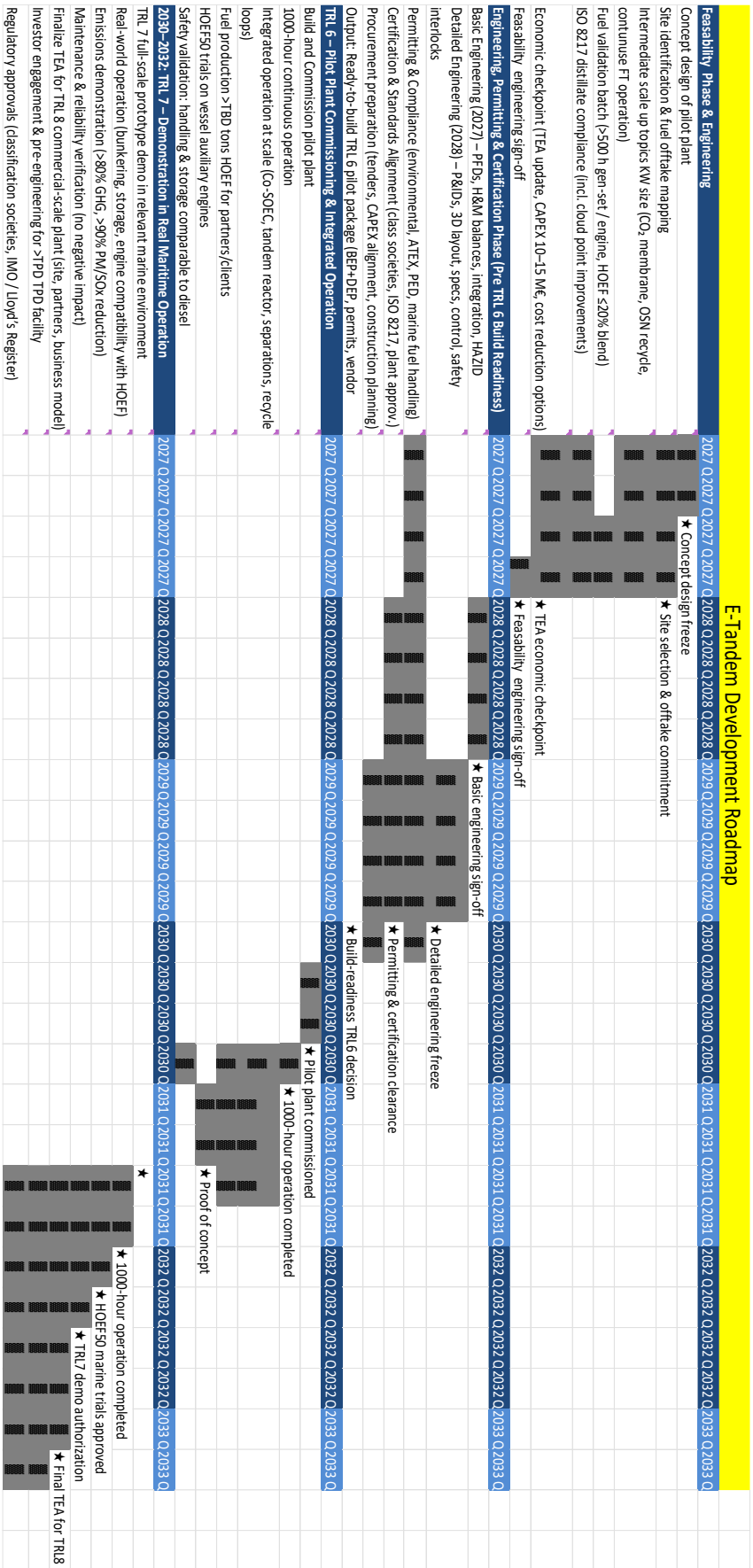


Figure 1: Development Road map proposal

3.2 Fuel Properties and Compatibility Considerations

Despite the positive results so far, several technical challenges must be addressed as we scale to TRL 7. Table 2 summarizes five key challenge areas identified, along with their technical implications and potential mitigation strategies:

Table 2: Technical Challenges and Knowledge Gaps

Challenge Area	Issue	Technical Implications	Mitigation Strategies
Fuel Energy Density	Lower LHV vs diesel	In its preferred realization, HOEF consists predominantly of higher oxygenated ethers. Although oxygenation lowers the lower heating value relative to fossil diesel, the longer-chain ethers targeted in E-TANDEM are expected to provide significantly higher energy density than short-chain OME-type fuels. Nevertheless, the volumetric energy content of neat HOEF remains approximately 15-20% lower than MGO (D3.2), requiring roughly 1.15-1.20 L of HOEF per litre of marine gasoil equivalent.	Ships will need larger fuel tanks or more frequent bunkering if using high HOEF blends. Mitigation: focus initial use on shorter routes and/or install additional tank capacity if feasible. Highlight that this volume penalty is moderate compared to alternatives like LNG or hydrogen, and can be managed in new vessel designs.
Combustion & Engine Tuning	Ignition delay & NO_x control	Very high cetane (80-100) → extremely short ignition delay, advancing combustion timing. Can raise peak pressure and temperatures, potentially increasing NO_x if engine timing and calibration are kept unaltered. Lower LHV means more fuel volume injected for same power → longer injection duration, possibly higher exhaust temperature.	Engine OEMs may need to recalibrate injection timing and duration for HOEF blends. Larger injector orifices or upgraded fuel pumps may be needed for high % HOEF to maintain performance. Use of exhaust gas recirculation (EGR) and/or timing retard can reduce NO_x, leveraging HOEF's negligible soot to avoid the normal soot-NO_x trade-off. Plan dedicated engine tests to optimize these parameters and ensure peak pressures remain within design limits.
Material Compatibility	Elastomers & lubricity	HOEF is oxygenated and polar; it can swell or shrink certain	Perform extended soak tests of fuel system materials (seals, gaskets, pump components) in various HOEF

		elastomers and may have mild corrosivity if formic acid or water impurities are present. Neat HOEF fuels have low viscosity (~0.7 cSt) and almost no sulfur, which can reduce fuel lubricity.	blends. Initial laboratory-scale investigations did not identify severe material-compatibility issues for HOEF blends up to approximately 50 %, although long-duration data are not yet available. Extended endurance testing (≥500 h) is therefore identified as a prerequisite for confirming material compatibility and durability at higher blend levels. Use corrosion inhibitors and ensure fuel purity (remove acids, control water). Add lubricity additives to HOEF or blend with conventional diesel to meet lubricity specs (as is already done for ULSD fuels).
Fuel Stability & Blending	Blending with heavy fuels	The polarity of HOEF may destabilize blends with heavy fuel oil (HFO). In contrast, blends with distillate marine gas oil (MGO) showed no evidence of phase instability in E-TANDEM (D3.1, D3.2), although the HOEF20 blend exhibited a slightly higher cloud point and increased dissolved water content, which is acceptable under ISO 8217.	Focus initial use on MGO or distillate blends (DMA/DMB marine fuels) – avoid HFO blends until stability additives or process tweaks are developed. Introduce HOEF gradually and monitor fuel storage tanks for any sign of stratification or sediments. Implement tighter specs for water content and use standard water separability tests. Also, tailor the HOEF molecular composition (e.g., include some branched species) to improve cold flow performance and compatibility.
Scale-up & Process Integration	Pilot to demo transition	Scaling from a 5 L batch reactor to a continuous pilot and then to a much larger demo introduces challenges: heat removal in larger reactors, maintaining catalyst effectiveness over time, and integrating the novel Co-SOE with chemical synthesis. Catalyst deactivation or loss could reduce yields; heat management issues could affect selectivity.	Mitigate scale-up risk by incrementally increasing scale (e.g., intermediate 10× scale trials before full demo). Use pilot data to refine kinetics and heat transfer models. The OSN membrane developed in E-TANDEM showed excellent performance at small scale,with cobalt retention, for product alcohol separation from the tandem process mixture but not for adjacent etherification; test it under realistic flow rates and pressures in pilot. Design pilots with flexibility (e.g., additional temperature control, ability to swap catalyst quickly) to handle unexpected behavior. Build in redundancy for critical components

			like SOEC stacks to minimize downtime.

3.3 Application considerations

Based on stakeholder and round-table discussions, **the roadmap deliberately adopts a blending-first deployment strategy for HOEF**. The consortium emphasized that low-percentage blending of novel fuels into existing fuel pools offers a more effective pathway for near-term emissions reduction than the exclusive use of neat fuels or very high blending ratios. This approach reduces regulatory friction, avoids the need for infrastructure or engine hardware changes, mitigates investment risk under evolving policy frameworks, and enables immediate environmental benefits across a larger volume of fuel. From a system and market perspective, incremental blending was therefore identified as the most pragmatic entry point for HOEF deployment.

Given the current status of fuel standardization and engine validation, the **roadmap recommends a conservative, phased approach to introducing Higher Oxygenate E-Fuels (HOEF) into the maritime fuel mix**. The initial deployment strategy focuses on blending HOEF with marine gas oil (MGO) at levels that are technically feasible, operationally safe, and compliant with existing fuel standards.

The proposed **starting point is a 20% HOEF blend with MGO**. This level has been validated through E-TANDEM's laboratory testing and is supported by literature and stakeholder feedback. At this concentration, the oxygen content of the fuel remains around 3–4 wt%, which is comparable to that of B20 biodiesel blends and is generally acceptable under ISO 8217 standards for marine distillate fuels. Importantly, **this blend ratio should not require modifications to existing engine hardware** or fuel handling systems, making it a **low-risk entry point** for real-world trials.

As operational experience and emissions data accumulate, the roadmap allows for the evaluation of **higher HOEF blending ratios, potentially up to approximately 50 %,** as part of controlled pilot- and demonstration-scale activities. Such higher blends are not positioned as an immediate deployment target, but rather as demonstration-level options to be validated through dedicated engine testing, safety assessments, and regulatory engagement before any broader application.

This stepwise approach allows for progressive reductions in greenhouse gas (GHG) and particulate emissions while giving engine manufacturers, ship operators, and classification societies time to adapt and validate performance.

This incremental blending strategy offers several advantages:

- It enables **early emissions reductions** without waiting for full-scale infrastructure or regulatory changes.
- It provides **flexibility**—if unforeseen issues arise at higher blend levels, operators can revert to lower blends without compromising reliability.
- It supports **data collection and learning-by-doing**, which are essential for building confidence among stakeholders and informing future standardization efforts.

The blending based deployment strategy is also supported by published life cycle assessment studies. For example, Walther et al. demonstrate that innovative renewable fuel blends can deliver significant system-level environmental benefits compared to conventional fuels, while offering improved market compatibility relative to neat fuel deployment. In this project, LCA results (D5.6) similarly indicate that the E-TANDEM process can enable GHG emission reductions and bring about other environmental benefits relative to fossil marine fuels like MGO, particularly when operated with renewable electricity and CO_2 as the sole carbon source, while the use of low-to-moderate HOEF blending ratios facilitates compatibility with existing fuel infrastructure and engine platforms (D3.1 & D3.2). These evidences support the roadmap's emphasis on low percentage HOEF blending as a robust pathway for emissions reduction, infrastructure compatibility and accelerated market uptake

To support this strategy, the roadmap also considers the fate of co-products generated during HOEF synthesis, Figure 2. These include hydrocarbon fractions that do not meet marine fuel specifications but retain energy value value as precursors for synthetic aviation or gasoline (naphtha) fuels. The plan assumes that **such co-products, will be sold or delivered to refineries** for upgrading or blending into other fuel streams, thereby **improving the overall economics of the process.**

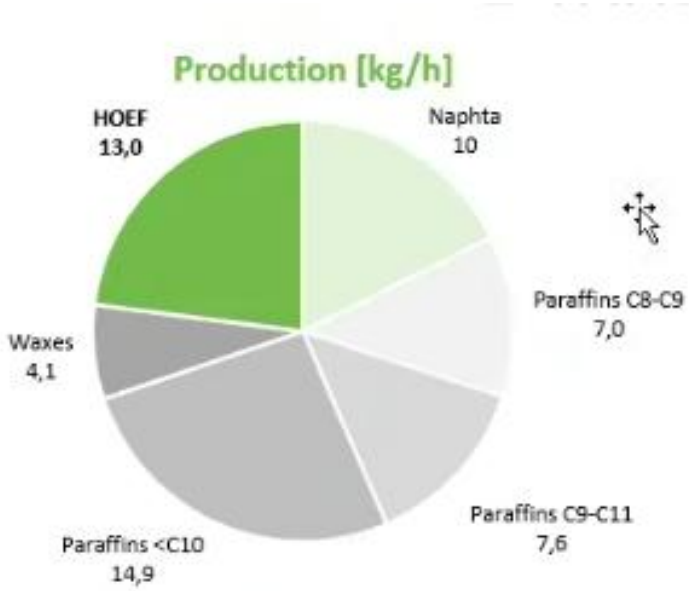


Figure 2: Organic product fractions of the E-TANDEM process (as estimated from the simulation of a 1 MW demo plant).

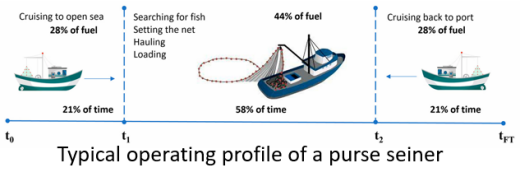
From a deployment perspective, the roadmap emphasizes **the importance of matching pilot plant output to realistic use cases**. In addition to the 1 MW reference case, smaller pilot units may be considered for specific early demonstration scenarios, such as harbor craft or short-route vessels with limited fuel demand. Such reduced-scale units would primarily serve operational learning and risk reduction, rather than representative economics.

While a 1 MW-scale facility is expected to produce approximately 13 kg of HOEF per hour (sufficient to support controlled engine testing campaigns and time-limited vessel trials, where fuel demand, operating conditions, and emissions can be closely monitored) smaller units may be more appropriate for initial applications such as harbor tugs, pilot boats, or short-route . These vessels typically operate

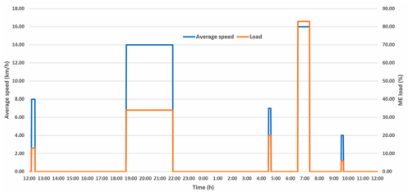
on predictable schedules and within defined geographies, simplifying fuel logistics and enabling close monitoring of performance, emissions, and operational behavior.

To explore this, the roadmap considers **three representative vessel types as potential early adopters** refer to Figure 3, Figure 4 and Figure 5:

✓ **Fishing ship (purse seiner)**



Typical operating profile of a purse seiner



Load profile of a purse seiner on a random fishing trip

Ship type	Purse seiner
Annual operating time of the main engine, $t_{ME,A}$ (h)	800
Annual operating time of auxiliary engine, $t_{AE,A}$ (h)	3000
Annual HOEF20 fuel consumption, *FC* (kg)	**34,302.92**

Figure 3: A small fishing boat, which offers a low-risk, low-volume platform for initial fuel trials in sheltered waters.

✓ **Ro-ro passenger ship (ferry)**
✓ Short-sea shipping

Ship name	Mljet
Passenger capacity	616
Vehicle capacity	145
Trip duration, *t* (min)	50
Route length, *l* (nm)	8.86
Annual number of return trips, N_A	1,095
Annual HOEF20/MGO80 blend fuel consumption, *FC* (kg)	467,008.38
Annual HOEF fuel consumption, *FC* (kg)	**93,401.38**

Figure 4: A mid-sized passenger ferry, operating on fixed routes with high public visibility and strong decarbonization incentives.

✓ **Ro-ro passenger ship (ferry)**
✓ Short-sea shipping

Ship name	Petar Hektorović
Passenger capacity	1,080
Vehicle capacity	120
Trip duration, *t* (min)	140
Route length, *l* (nm)	30.2
Annual number of return trips, N_A	800
Annual HOEF20 fuel consumption, *FC* (kg)	**872,583.88**

Figure 5: A large passenger ferry, which could serve as a high-impact demonstration platform once fuel supply and regulatory approvals are secured.

These **vessel classes represent a scalable progression in fuel demand**, operational complexity, and stakeholder visibility. Starting with smaller vessels allows the project to validate HOEF performance

under real-world conditions while minimizing risk. As confidence grows, the roadmap envisions expanding to larger vessels and higher blend ratios, ultimately enabling full-scale deployment.

During the consortium round-table, stationary applications (particularly **backup power generators and data centers**) were discussed as illustrative cases where fuel-based emissions mitigation is especially relevant. Backup generators are typically designed without exhaust gas after-treatment systems to minimize cost, complexity, and maintenance requirements, and are often legally limited to short operating windows (e.g. approximately 72 hours). In such contexts, **fuels that intrinsically reduce emissions without requiring hardware modifications can offer a compelling alternative to retrofitting exhaust gas treatment systems**. While these stationary applications are outside the scope of the maritime-focused roadmap presented here, they reinforce the strategic emphasis on fuel compatibility and blending-based emissions reduction as key advantages of HOEF.

In summary, the blending strategy **and pilot deployment plan are designed to balance technical feasibility, regulatory compliance, and market readiness**. By starting small and scaling responsibly, the next phase of the project can de-risk HOEF adoption and lay the groundwork for broader commercialization in the maritime sector.

3.4 Market & Deployment Considerations

Given the early stage and current cost of HOEF, market adoption will require supportive conditions. In the near term, **policy incentives are crucial** – for instance, revenues from the EU Emissions Trading System (which will soon cover maritime emissions) could be recycled to offset the cost gap for e-fuels, or mandates like FuelEU Maritime could create guaranteed demand for such fuels. The roadmap anticipates that HOEF fuel will initially come at a premium, so securing **subsidies or green fuel premiums** is vital for pilot deployments. Accordingly, market, policy, and stakeholder considerations discussed in this section are limited to the maritime sector and do not imply parallel deployment strategies in other transport modes.
Recent analyses of the global maritime decarbonization landscape show a rapidly growing number of pilot and demonstration projects, highlighting strong industry engagement and a highly collaborative approach to alternative fuel deployment (Bureau Veritas, 2024).

Round-table discussions highlighted that **regulatory uncertainty—particularly with respect to long-term CO_2 accounting rules, emissions trading coverage, and post-2040 policy frameworks—represents a major barrier to investment in novel fuel pathways**. In this context, blending-based deployment was identified as a risk-mitigation strategy, allowing incremental adoption and learning while preserving flexibility under evolving regulatory conditions. By enabling partial substitution rather than full fuel replacement, blending reduces exposure to future policy shifts and supports earlier capital mobilization for pilot and demonstration activities.

We have identified initial markets that offer favorable conditions for HOEF introduction:

- **Geographic "Green Corridors":** Regions like Northern Europe lead thanks to decarbonization policies, renewable energy, and early adopters. Scandinavian ferries on fixed routes make fuel logistics easy and operate in emission-controlled areas. A Baltic ferry using HOEF20 would nearly eliminate particulate and SO_x emissions. Ports and harbor craft in "green port" initiatives also present opportunities. East Asia (Japan, Singapore, South Korea) is promising with government support and major engine manufacturers for demonstrations. The **roadmap targets early adopters prioritizing sustainability**; as with biofuel blends, there will be customers for carbon-neutral shipping HOEF can supply.
- **Stakeholder Engagement:** Engine OEMs and fuel suppliers are critical. Continued collaboration ensures engines are HOEF-ready, exemplified by AVL and WinGDs involvement in engine testing. Formal agreements (e.g**., OEMs providing test engines for early access**) will be pursued. Marine fuel suppliers may help with logistics and blending, using existing biofuel networks. Major shipping companies' interest during E-TANDEM signals commercial uptake if fuel is available. Ongoing dialogue and early-offtake agreements help secure demand and de-risk investment in pilot production.
- **Regulatory Pathways:** Deployment means engaging with regulations. Since HOEF lacks a marine fuel standard, moderate blends can fit under current diesel specs as oxygenated blend components. The plan is to **work with standards bodies** to add higher oxygenate limits. Classification societies will be involved for Approval in Principle before ship trials. HOEF blends with flash point ≥60°C should be handled like conventional fuels; a hazard identification study will check for risks. Early engagement with flag states and IMO will aid regulatory acceptance. The ultimate aim is to have all required standards and guidelines ready as HOEF becomes widely available.

Based on techno-economic analysis, life-cycle considerations, and stakeholder input, the roadmap identifies illustrative priority regions that offer favorable conditions for early HOEF pilot and demonstration activities: **North Sea, East Asia, US Gulf Coast** (high CO_2 source density, renewable potential), refer Figure 6. Open Points: Align on stakeholder feedback regarding location strategies; secure feedstock supply chains and renewable electricity sourcing; develop regulatory compliance roadmap for HOEF blends. These regions were selected based on a combination of factors, including:

- Availability of renewable electricity at competitive prices
- Access to CO_2 feedstock (industrial clusters, biogenic sources, or DAC potential)
- Existing or planned infrastructure for alternative fuels
- Engagement of local stakeholders (ports, shipowners, fuel suppliers)
- Supportive regulatory and policy frameworks

Feedstock availability (locations)

Region	CO_2 Source Density	Renewable Energy Potential	Proximity to Ports
North Sea (Europe)	High (industrial clusters)	Very High (offshore wind)	Excellent
US Gulf Coast	High (refineries, petrochemicals)	High (solar, wind)	Excellent
East Asia (China/Korea)	High (steel, cement)	High (solar, wind)	Excellent
Middle East	Medium (oil & gas)	Very High (solar)	Good
Brazil	Excellent	High (hydro, solar)	Good
Mediterranean		High (solar, wind)	Excellent
Australia	Medium (mining, LNG)	Very High (solar, wind)	Excellent
South Africa	High (coal-based industry)	High (solar)	Good
India	Very High (cement, steel)	High (solar, wind)	Excellent

Figure 6: Priority regions for deployment

These regions are presented as representative examples, rather than fixed deployment commitments, and final site selection will depend on stakeholder interest, regulatory readiness, and access to renewable electricity and CO_2 at the time of implementation.

The successful **deployment** of Higher Oxygenate E-Fuels (HOEF) will depend not only on technical readiness but also on regional alignment with infrastructure, policy, and market conditions. Based on techno-economic and environmental analyses, as well as stakeholder input, the roadmap identifies three priority regions for early HOEF deployment:

- **North Sea Region (e.g., Netherlands, Denmark, Germany):**
  This region offers a strong combination of renewable electricity availability (notably offshore wind), established CO_2 capture infrastructure, and progressive maritime decarbonization policies. Ports such as Rotterdam and Hamburg are already engaged in green shipping initiatives and have experience with alternative fuels like LNG and biofuels. The presence of industrial clusters provides opportunities for sourcing CO_2 from point sources in the short term, with potential for integration of Direct Air Capture (DAC) in the longer term.
- **East Asia (e.g., Japan, South Korea, Singapore):**
  East Asia is actively positioning itself in clean maritime technologies, with strong engagement from major shipbuilders and engine OEMs developing dual-fuel and alternative-fuel engines. Singapore, in particular, is emerging as a hub for maritime decarbonization initiatives and could serve as an entry point for HOEF demonstration activities in Asia. At the same time, the current electricity mixes in several East Asian countries remain dominated by coal and natural gas, which would limit the lifecycle greenhouse-gas benefits of electricity-intensive e-fuel production in the near term. As a result, any HOEF deployment in this region would need to

be carefully linked to low-carbon electricity sourcing or targeted demonstration use cases rather than continuous large-scale fuel production.

- **US Gulf Coast (e.g., Texas, Louisiana):**
  The Gulf Coast region combines extensive petrochemical infrastructure, a high density of CO_2 point sources, and proximity to major domestic and international shipping routes. While the region offers significant industrial integration potential for e-fuel concepts, the availability of consistently low-carbon electricity and long-term policy support for deep decarbonization remain more uncertain than in some European regions. Consequently, HOEF deployment in the US Gulf Coast would depend strongly on access to dedicated renewable electricity supply and a stable regulatory framework to ensure both environmental performance and investment viability.

However, several open points remain and must be addressed to enable successful regional deployment:

- **Stakeholder Alignment:** Further engagement is needed with local shipowners, port authorities, and fuel suppliers to validate assumptions about fuel demand, infrastructure readiness, and willingness to participate in pilot demonstrations.
- **Feedstock and Energy Supply Chains:** Securing reliable and sustainable sources of CO_2 and renewable electricity is critical. Regional supply chain mapping and long-term sourcing agreements will be necessary to ensure economic and environmental viability.
- **Regulatory Compliance Roadmap:** Each region has its own fuel standards, safety regulations, and certification pathways. A tailored regulatory engagement strategy is required to ensure that HOEF blends can be approved for use under local and international maritime rules (e.g., ISO 8217, IMO IGF Code, FuelEU Maritime).

In conclusion, regional deployment of HOEF should follow a targeted approach, focusing on areas with the highest potential for early success. By aligning technical readiness with regional strengths and stakeholder priorities, the E-TANDEM roadmap can accelerate the transition from pilot-scale production to real-world maritime applications.
The suitability of pilot and demonstration plant size, cost, and location has been addressed within this roadmap through reference-case analysis (1 MW scale) and illustrative regional assessment. Final decisions are deferred to follow-up projects and investment-specific studies.

3.5 Key Development Considerations and Mitigation Measures

As the technology progresses from laboratory validation toward pilot and demonstration scale, several development considerations and remaining uncertainties must be addressed. These are typical for technologies transitioning from TRL 5 to TRL 7 and do not represent fundamental barriers, but rather focused areas for further validation and optimization within follow-up activities. Table 3 lists some of the key unknowns (spanning technical, regulatory, and market domains) and how the follow-up activities should target them:

Table 3: key unknowns (spanning technical, regulatory, and market domains)

Area	Open Issue	Relevance for Scale-Up	Mitigation / Validation Approac
Engine Durability	Long-term wear & deposits	Even though hardware-in-the-loop (HiL) experimentation in E-TANDEM (D3.3) has conclusive shown HOEF blend stability under relevant application conditions (excluding combustion) for 200 h, longer-term storage behavior and performance under extreme temperature conditions have not yet been systematically evaluated at scale.	Run extended engine endurance tests on HOEF blends (e.g., 500+ hours on a test engine) to monitor component wear, lubrication, and deposit formation. Analyze engine oil samples for fuel contamination. Use results to inform additive packages or material upgrades if necessary.
Fuel Handling & Stability	Storage and cold climates	Formal recognition of higher-oxygenate fuel blends in existing marine fuel standards is still evolving and requires structured engagement with standardization bodies	Conduct storage stability tests for HOEF and HOEF/diesel blends over several months in varying conditions (ambient, heated tanks, etc.). Implement standard fuel management practices (more frequent drain-off of water from storage tanks, biocide additives if needed). Test cold flow performance and use cold-flow improvers; if necessary, establish a winter-grade specification for HOEF blends with lower OME content or with cold flow additives.
Emissions Profile	Unregulated emissions	No data yet on certain emissions like formaldehyde, or particle number (PN) from HOEF combustion in full-scale engines. These could be relevant for environmental compliance (e.g., N_2O is a potent GHG, and aldehydes are air toxics). Need to verify that new issues don't arise even as traditional pollutants (PM, SO_x) drop.	Include comprehensive emissions measurements in engine and vessel trials. Measure aldehydes, ketones, NOx, and particle number/size distribution when running on HOEF blends, under various loads. If any pollutant is significant, evaluate aftertreatment solutions (e.g., oxidation catalysts for aldehydes). Engage with regulatory bodies to ensure these factors are addressed in future emission standards or guidelines for e-fuels.
Regulatory & Standards	Lack of formal specs	Uncertainty about how and when HOEF will be recognized in fuel standards (ISO 8217 for marine fuels currently does not account for high oxygenate content). Also, the IMO's IGF Code might apply if any neat HOEF has flash point <60°C. In addition, frameworks like FuelEU Maritime or CII need	Work with standards organizations (ISO, CIMAC) starting early to introduce HOEF's properties and gain acceptance of oxygenated fuel blends. Ensure pilot-produced HOEF meets a proposed specification (possibly requiring a new standard or an amendment to existing ones). For

		clear LCA values for HOEF to award credits for its use.	safety, commit to producing only high-flashpoint formulations (e.g., OME_3 and above) to remain outside the IGF Code's strict requirements – this will be a design criterion for fuel synthesis and blending. Develop documentation and share data with flag states and class societies, aiming for interim "alternative fuel" approvals for trial purposes by 2028–2030.
Economic Viability	Cost & scale uncertainty	The real production cost of HOEF at scale is still uncertain. The pilot will provide data, but many assumptions (future renewable electricity prices, electrolyzer costs, etc.) have inherent uncertainty. The market's willingness to pay a premium for HOEF over conventional fuel is also not well known, especially as competing options (e.g. green methanol or ammonia) become available. Market demand and willingness-to-pay will need to be refined through pilot operation, stakeholder engagement, and policy evolution.	Use pilot operation to refine cost models: gather actual performance and efficiency data to update the TEA. Conduct market analysis and engage with ship operators to gauge willingness-to-pay for emissions reductions (possibly through surveys or by leveraging the existing customer relationships of project partners in the fuel supply business). Continue to monitor competing fuel developments – ensure flexibility by designing the HOEF process to co-produce other fuels if needed (for example, the tandem reactor could potentially be adjusted to produce more FT hydrocarbons if market conditions favor that). Diversify end-use markets where possible (e.g., HOEF for heavy-duty trucks or as stationary applications as in data centers.) to broaden demand. Finally, advocate for strong policy measures (carbon pricing, e-fuel mandates) that will improve the cost-competitiveness of HOEF relative to fossil fuels.
Sustainability	CO_2 sourcing & perception	Scaling HOEF requires a large, sustainable source of CO_2. Relying on fossil-derived CO_2 (e.g. from flue gas) could be criticized as prolonging fossil operations or might become unavailable as industries decarbonize. Water and land/energy use for HOEF production also need consideration. Clear communication of life-cycle performance and sustainability	Prioritize emissions as feedstock (e.g., CO_2 from biogenic sources or hard-to-abate industrial processes) in the near term. Simultaneously, support development of **Direct Air Capture (DAC)** technologies to enable a shift to atmospheric CO_2 in the longer term. Emphasize the closed-carbon-cycle aspect in communications. Implement efficient water use practices

		credentials will be important to ensure broad stakeholder acceptance of HOEF as a climate-relevant fuel option.	(water recycling, use of non-potable water sources if possible) and power the process with certified renewable energy (through PPAs or on-site generation) to ensure genuine GHG benefits. Be transparent by publishing LCA results and engaging with environmental stakeholders to build trust in HOEF as a truly sustainable fuel, not a "delay tactic."

Addressing these challenges and gaps forms a core part of the roadmap action plan. Many of the items above are translated into **specific tasks for the next phase** (e.g., designing long-duration engine tests, initiating standardization efforts, securing CO_2 sources for pilots). In the remainder of this document, we outline the recommended actions, risk mitigation approaches, and stakeholder engagement required to reach TRL 7 and position HOEF for commercialization.

3.6 Contribution to project (linked) Objectives

This roadmap contributes to the following objectives as set in the Description of Action of the Grant Agreement for the E-TANDEM project:

To assess the technical, economic and sustainability aspects of the new e-fuel production concept and set the basis for further upscaling developments beyond the current E-TANDEM project.

By consolidating and translating key technical achievements into forward-looking development actions required for the transition from **TRL 4 to TRL 6-7**, this roadmap document integrates results from WP3, WP4 and WP5 as defined in the DoA and sets the foundation for scale-up by identifying the conditions and performance levels that the technology must satisfy to meet project objectives. Specifically, it reflects on the translation **of validated performance indicators into TRL-advancing actions**. In this way, the roadmap **does not re-validate past objectives**, but ensures that the *path forward* continues to support, operationalize, and extend the project's original targets by linking today's validated performance to tomorrow's scale-up requirements.

3.7 Contribution to major project exploitable result

This roadmap contributes to the project's **major key exploitable results (KERs)** by defining how each validated scientific and technical outcome will be leveraged, extended, or industrialized in the transition toward pilot- and demo-scale implementation. In particular:

- It draws directly on the LCA results demonstrating that **HOEF blends reduce GHG emissions compared to MGO and LNG**, and that the **WTT phase may become negative with renewable electricity**, positioning HOEF as an environmentally competitive marine fuel and supporting exploitation pathways associated with KERs tied to environmental performance and market uptake.

- It incorporates ongoing open points (such as the need to validate higher blend ratios, confirm TTW emissions through real-world engine tests, and estimate fuel quantities for demonstration) which are explicitly required to mature the underlying KERs and ensure their readiness for scale-up and future commercialization.
- It aligns roadmap actions with TEA (D5.5) and LCA (D5.6) inputs to define **cost and sustainability KPIs** for TRL 6-7, as recommended in this D5.7, ensuring KERs transition from component-level insights to full system-level exploitation strategies.

By embedding these results and requirements into the forward development plan, the roadmap **acts as the bridge between validated project outputs and their conversion into industrially deployable, exploitable outcomes**, thus supporting the maturation and future adoption of the project's key technologies and assessments.

4 Conclusions and Recommendations

4.1 Overall Conclusions

In conclusion, the E-TANDEM project has demonstrated the technical **feasibility of producing and utilizing HOEF fuels**, confirming their potential as a promising, drop-in blending component for maritime decarbonization, subject to further validation at pilot and demonstration scale. By integrating innovative technologies (co-electrolysis, tandem catalysis, membrane separation), E**-TANDEM succeeded in making a synthetic oxygenated fuel that can blend with marine diesel** and drastically cut emissions. If developed further, HOEF fuels could play a pivotal role in the maritime fuel transition, enabling existing ships to achieve significant greenhouse-gas reductions and near-zero pollutant emissions with minimal modifications, while complementing other maritime decarbonization pathways

At the same time, bringing HOEF to market will require **continued pioneering efforts**. The project's findings point to several critical next steps. The roadmap beyond E-TANDEM is designed to tackle these, focusing on scaling up production, validating fuel performance in real engines, driving down costs, and ensuring all safety and regulatory bases are covered. A **strong collaboration between technology developers, industry partners, and regulators** will be needed to realize the first HOEF-powered ship in the coming years. Fortunately, interest from stakeholders is evident – engine manufacturers, fuel suppliers, and progressive ship operators are already engaged through the project, and they are poised to support the transition from lab to market.

Recommendations: Based on our analysis, we propose the following key actions to achieve TRL 7 and prepare for commercialization:

- **Build and operate an integrated pilot plant** (~1 MW scale) by 2028 to produce HOEF fuel in sufficient quantity for engine and vessel trials. This facility will provide crucial data on process performance, catalyst longevity, and product quality at scale. It should be designed with flexibility to incorporate any improvements (e.g., upgraded catalysts or additional distillation) as needed.
- **Optimize catalyst retention and separation systems** to minimize operating costs and ensure long run times. In particular, implement the OSN membrane separation at pilot scale and refine it if necessary (e.g., multiple membrane stages) to keep catalyst losses and deactivation rates low. This will protect against one of the biggest cost risks (catalyst replacement) and improve process reliability.
- **Secure sustainable CO_2 and renewable power supplies** for scale-up. Begin establishing agreements for CO_2 feedstock from industrial sources or pilot-scale DAC, and for green electricity (e.g., a long-term PPA for wind/solar power). This will ensure that pilot and demo operations meet the intended carbon-neutral targets and build public credibility.
- **Engage early with regulators and classification societies**. Initiate the process of getting a "New Fuel" approval or interim guidelines for HOEF use. Work with an organization like DNV or Lloyd's Register to conduct a risk assessment and issue an Approval in Principle for HOEF/MGO fuel in marine engines, facilitating the planned vessel trial. Simultaneously, contribute project

data to the development of fuel standards (ISO 8217 revision or a new standard) to formally define allowable properties for oxygenated diesel fuels.

- **Coordinate stakeholder partnerships for demonstrations.** Select the first demonstration vessel and location in consultation with industry partners. Ideal candidates are likely a coastal vessel or ferry in a region with policy support (e.g., a Scandinavian ferry operator). Ensure the involvement of the engine OEM for that vessel to assist with any needed engine recalibrations and to monitor performance. Collaborate with a fuel supplier for blending and logistics. Establishing a clear responsibility matrix and communication plan among these stakeholders is crucial for a smooth demonstration.
- **Conduct further engine and fuel system testing at increasing HOEF blend ratios.** Leverage the fuel produced from the pilot plant to systematically test blends of 20%, 50%, and eventually up to 100% HOEF in controlled engine environments. These tests should include not only performance and efficiency mapping, but also durability testing (as noted, e.g., 500+ hour continuous operation) and full emissions characterization (including NO_x, PM, UHC, aldehydes, etc.). The findings will inform the maximum safe blend for early real-world use and any design tweaks needed for fuel systems (such as material changes or additive requirements).
- **Plan for a larger demonstration and subsequent scale-up.** Assuming pilot and initial vessel tests are successful, begin front-end engineering design (FEED) for a **first commercial-scale plant** in the early 2030s. Use the data from the pilot to refine this design. Identify potential sites (for instance, locations like the North Sea region or the U.S. Gulf Coast, which combine abundant renewables and available CO_2, have been highlighted for their strategic fit). Explore public funding or private investment opportunities for this scale-up, making the case with the proven data on HOEF's performance and environmental benefits.
- **Prioritize compatibility-driven deployment pathways.** Emphasize blending-based introduction of HOEF as a pragmatic route to achieve early emissions reductions, de-risk investment, and accelerate market acceptance, while allowing regulators, engine manufacturers, and operators to validate performance under real-world conditions before considering higher blend ratios or neat fuel use.

By following these recommendations, the consortium and its partners can maintain the momentum generated by E-TANDEM and address the remaining challenges methodically. HOEF has the potential to be a **pioneering clean fuel** for shipping, but time is of the essence: other solutions are moving forward, and delays in development could narrow the window for impact. Therefore, a concerted effort, guided by this roadmap, is required to bring HOEF fuels to TRL 7 and ultimately to market in time to contribute to 2030 and 2040 emission targets.

4.2 Indicative Funding Mechanisms for Post-Project Demonstration

The transition of Higher Oxygenate E-Fuels (HOEF) from the laboratory and pilot scale achieved within E-TANDEM toward a TRL 8 demonstration plant will require a blended financing approach, refer Table 4. Experience from comparable Power-to-X, e-fuel, and hydrogen demonstration projects in Europe shows that no single funding instrument is sufficient at this scale (≈€20 million CAPEX). Instead, successful projects typically combine EU-level grant funding, national co-financing, and public or private investment instruments to de-risk first-of-a-kind installations.

At EU level, non-dilutive grants from programmes such as Horizon Europe (Innovation Actions) and, in particular, the EU Innovation Fund represent the most relevant anchors for a HOEF demonstration. These instruments are explicitly designed to support technologies progressing from advanced pilot scale toward industrial demonstration, including synthetic fuels, CCU, hydrogen and Power-to-X pathways.

In parallel, national funding schemes in several EU Member States provide complementary support for industrial decarbonisation and renewable fuel demonstrations. Selecting a host country where HOEF deployment aligns with national hydrogen, e-fuel, or maritime decarbonisation priorities can significantly enhance funding prospects.

Finally, public finance institutions and private investors play a critical role in closing the remaining financing gap. Instruments such as EIB or InvestEU-backed loans, blended finance facilities, and public–private partnerships can provide long-tenor debt or co-investment once grant support is secured.

Table 4: Overview of relevant funding options for a HOEF demonstration (TRL 7–8)

Funding Instrument	Level	Typical Form of Support	Relevance for HOEF Demo	More Information
EU Innovation Fund	EU	Non-repayable grant (up to ~60% of eligible costs)	Highly relevant for first-of-a-kind e-fuel demonstrations	https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/innovation-fund_en
Horizon Europe – Innovation Actions	EU	Grant funding for large pilot and demo projects	Relevant for late-stage development and integration	https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/horizon-europe_en
National Hydrogen / E-Fuel Programs	Member State	Capital grants, operating support, CfD-type instruments	Strong co-funding potential if aligned with national priorities	https://hydrogeneurope.eu/
IPCEI (Hydrogen / PtX)	EU / Member States	State-aid-based grants for strategic projects	Potential option within a wider European value chain	https://competition-policy.ec.europa.eu/state-aid/ipcei/approved-ipceis/hydrogen-value-chain_en
EIB / InvestEU Financing	EU	Loans, guarantees, blended finance	Supports remaining CAPEX after grants	https://www.eib.org/en/products/mandates-partnerships/investeu/index
Public–Private Partnerships (e.g. Catalyst)	EU + Private	Matched public and private capital	Can reduce effective demo cost and accelerate scale-up	https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_5647

5 Risks and Interconnections

5.1 Risks

The development and deployment of Higher Oxygenate E-Fuels (HOEF) beyond the E-TANDEM project involve a number of technical, regulatory, and economic risks that are typical for technologies transitioning from laboratory validation toward pilot and demonstration scale (TRL 6–7). Key risks include long-term engine durability and material compatibility at higher HOEF blend ratios, scale-up and integration challenges associated with continuous operation of the co-SOEC and tandem catalytic process, regulatory and standardisation uncertainty for oxygenated marine fuel blends, and economic risks related to electricity prices and overall production costs.

These risks are **not treated in isolation**, but are discussed in detail throughout this deliverable, in particular in **Section 3.1.5 (Key Development Considerations and Mitigation Measures)** and **Table 3**, where their implications for scale-up are assessed and corresponding mitigation strategies are outlined. No critical show-stoppers have been identified at this stage; rather, the identified risks define clear validation and demonstration activities to be addressed in follow-up pilot and demonstration projects.

5.2 Interconnections

This roadmap draws upon and integrates results from several other E-TANDEM deliverables: notably, **WP2** outputs on catalyst development and Co-SOE performance (which inform scale-up technical design), **WP3** results on fuel properties and engine tests (providing data on blend limitations and material compatibility), **WP4** process simulation studies (to design the pilot and demo system), and **WP5** analyses (the TEA and LCA that underpin economic and environmental aspects of the roadmap). As such, the successful execution of this roadmap is inherently linked with those prior results – for example, the need for an efficient catalyst recycling method (a major project result) is carried forward as a prerequisite for pilot scale. Conversely, this deliverable will feed into the project's **overall exploitation and dissemination activities**. It provides a framework that consortium partners will use when seeking additional funding (e.g., for a follow-up Horizon Europe demonstration project or private investment) and when engaging with industry groups about the future of HOEF fuels. In summary, D5.7 serves as a bridge between the foundational research done in earlier WPs and the future efforts required to commercialize that research, ensuring continuity and coherence in the project's innovation pipeline.

6 Deviations from Annex 1

No deviations from Annex 1 are reported for this deliverable

7 References

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Project partners:

#	Partner short name	Partner Full Name
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2	MPG	MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTEN EV
3	DTU	DANMARKS TEKNISKE UNIVERSITET
4	OWI	OWI SCIENCE FOR FUELS GMBH
5	UNR	UNIRESEARCH BV
6	T4F	TEC4FUELS GmbH
7	AVL	AVL LIST GMBH
9	UZ	SVEUCILISTE U ZAGREBU, FAKULTET STROJARSTVA I BRODOGRADNJE
10	UCT	UNIVERSITY OF CAPE TOWN
11	KAUST	KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

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