D3.3 Overview performance of the full scale and model scale demonstrators

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

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Release Approval

Table 1: Release Approval

Name	Role	REMARKS
V. Klisarić (CRS)	Reviewer 1	24.06.2026
K. Hoyer (DST)	Reviewer 2	22.06.2026
P. Garcia Barrena (MARIN)	WP-Leader	02.06.2026
B. Friedhoff (DST)	Project Coordinator	27.07.2027

Abbreviations

ARA	Amsterdam, Rotterdam and Antwerp Region
BIO	Bunker Independent Operation
CAPEX	Capital Expenditure
CCNR	Central Commission for the Navigation of the Rhine
CFD	Computational Fluid Dynamics
CI	Compressed Ignited
CO_2, NO_x and PM	Greenhouse Gas Emissions
CTV	Crew Transfer Vessel
GHG	Green House Gas
H2	Hydrogen
HMI	Human Machine Interface
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IWT	Inland Waterway Transport
kW	kiloWatt
OPEX	Operational Expenditure
POME	Palm Oil Mill Effluents
PMS	Power Management System
PPE	Propulsion Power and Energy
PTS	Point Source
PU	Public - dissemination level
SEN	Sensitive - dissemination level
SFC	Specific Fuel Consumption
SPEC	Ship Propulsion, Power and Energy Concepts
UCO	Used Cooking Oil
TTW	Tank to Wake
v-ZEL	virtual - Zero Emission Lab
WTT	Well to Tank
WTW	Well to Wake
ZEL	Zero Emission Lab

Executive Summary

The SYNERGETICS project approaches the decarbonisation of inland and coastal shipping not as a single technological challenge, but as a complex transformation that requires multiple complementary solutions. Instead of pursuing one ideal concept, the project brings together a set of demonstrators, each representing a different pathway toward greener shipping. Together, these demonstrators form a coherent narrative about how existing vessels can be retrofitted and adapted to meet future sustainability requirements.

At the core of this approach lies the idea that ships operating in European waterways differ widely in their routes, power demands, and operational constraints. As a result, the design of each demonstrator reflects a specific context. Some concepts focus on radical transformation, while others prioritise gradual transition and compatibility with existing systems.

This report presents an integrated overview of the performance and emission-reduction results from the various demonstrators, both physical and virtual. Across the project, demonstrators serve as proof-of-concept implementations for different greening pathways, including electrification, alternative fuels (methanol, hydrogen) and energy management optimisation. It reflects the outcomes of SYNERGETICS Subtask 3.1.3, which focuses on harmonizing demonstrator outputs and capturing the key lessons learned.

The SYNERGETICS demonstrators collectively represent a portfolio of complementary design concepts rather than competing solutions. Their comparison highlights a spectrum ranging from fully electric modular systems to transitional dual-fuel retrofits and integrated architectures.

The key contribution of this approach is the recognition that decarbonisation of inland and coastal shipping will rely on a combination of technologies, supported by system-level validation and tailored to specific operational contexts.

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1. Introduction

The Innovation Action SYNERGETICS has the ambition to demonstrate retrofitting solutions that allow to reduce GHG (Green House Gas) emissions (by at least 35% compared to the original design), in line with the environmental objectives of the Revised Rhine Navigation Act (Manheim Declaration) of 2018 [1].

The key objectives of SYNERGETICS may be summarized as follows:

(1) Demonstrate the potentials of retrofit technologies in greening the existing fleets by retrofitting two existing ships in the course of the project duration.
(2) Demonstrate the potentials of hydrodynamic improvements in greening of the existing fleets.
(3) Demonstrate the value of digital assets in greening the existing fleets.
(4) Integrate the knowledge on shipping decarbonisation and air-pollutant emission reduction technologies with experience gained in the pilot projects and in the demonstration performed within SYNERGETICS, and establish a catalogue of greening solutions.
(5) Provide up-to-date Scenarios to policy-makers and a handbook to vessel owners for an accelerated greening of inland and coastal shipping.
(6) Accelerate the uptake of the greening retrofit solutions by streamlining regulatory procedures.
(7) Propagate the use of the catalogue, the scenarios, and the handbook developed within SYNERGETICS beyond Western Europe

Subtask 3.1.3 within SYNERGETICS aims to harmonize the potential emission savings from implementing retrofit solutions in several demonstrators. To demonstrate the feasibility of the shipping decarbonisation by means of retrofit, and to attain the key objectives (1), (2), (3), and (4), several demonstrations are carried out in the course of the project. In some cases, different types of demonstrations are carried out on the same ships with the goal to gain insight in the performance of retrofitted ships in additional complex operational conditions, which may not be frequently encountered in "regular" operations. This will be realized using "real life", full-scale demonstrators, as well model-scale and virtual demonstrators, and system demonstrators. This leads to the following specific objectives for this Subtask 3.1.3:

a. Demonstrate the viability of retrofitting solutions for emission reduction for different vessels in real life operational conditions, either in a physical laboratory environment or via numerical simulations.
b. Compare and verify the performance of the different demonstrators in a harmonized way using the standardised measurements and simulations

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2. The demonstrators

2.1 Selection of fleet families with impact

As discussing the SYNERGETICS project at the project-start, when selecting the ships that served as Demonstrators, one of the factors considered was the possible impact of the retrofit. To estimate the magnitude of the impact, several aspects were taken into account: the absolute and relative[1] CO_2, NO_x and PM emissions of the ships of a certain type and fleet family, the operational area of a ship, etc. The absolute CO_2, NO_x and PM emissions of the European inland fleet families are given in Figure 1, Figure 2 and Figure 3, respectively, based on the data reported for the year 2015 in the CCNR study on energy transition towards a zero-emission inland navigation sector.

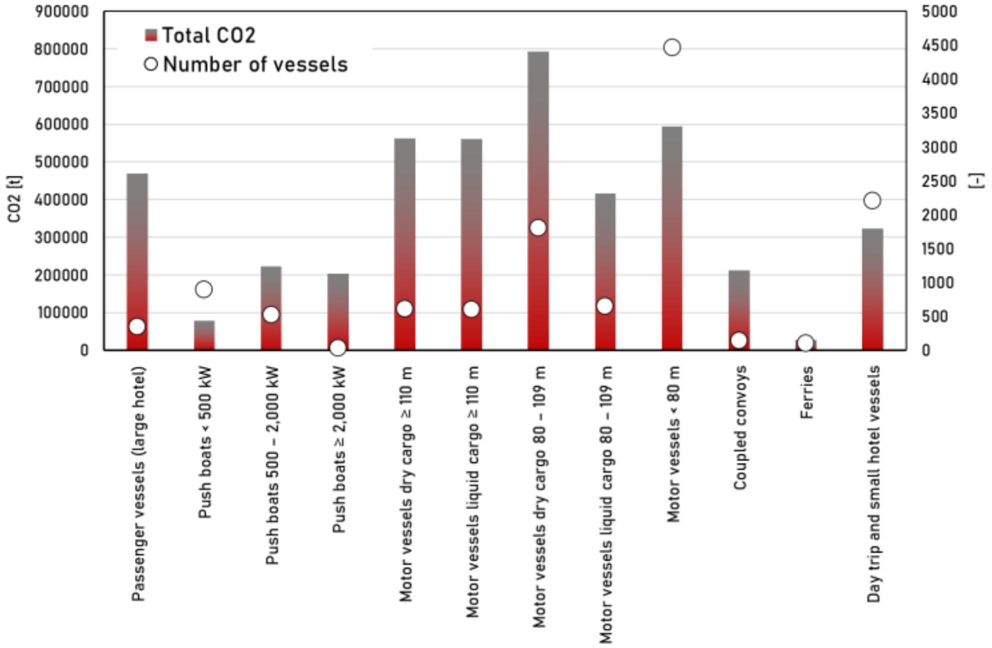

Figure 1 Absolute CO_2 emissions of the fleet families of the European inland fleet and number of vessels within the families in 2015

Figure 1 also gives the number of vessels per fleet family. It may be observed that the largest absolute CO_2-emitter, NO_x-emitter, and PM-emitter is the family of the dry cargo motor vessels with length between 80 m and 109 m. On the other hand, the family consisting of the motor vessels in length below 80 m is the second CO_2-, NO_x- and PM-emitter because this is by far the most numerous fleet family. The dry cargo and the liquid cargo motor vessels with length of 110 m and above share the third spot with respect to the amount of CO_2 emissions in absolute terms and are placed as third and fourth in ranking of absolute NO_x and PM emissions. However, considering that such vessels are not as nearly numerous as smaller ships of the same type, the relative amounts of emissions released (average quantities of CO_2, NO_x and PM per vessel) are up to six times greater. Greening of the self-propelled dry and

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[1] i.e., the absolute CO_2, NO_x and PM emissions of a fleet family normalized by the number of ships within the family.

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liquid cargo vessels with length of 110 m and above is also a way of reducing the emissions of the fleet family of coupled convoys, as this family consist mostly of such vessels and Europe II barges.

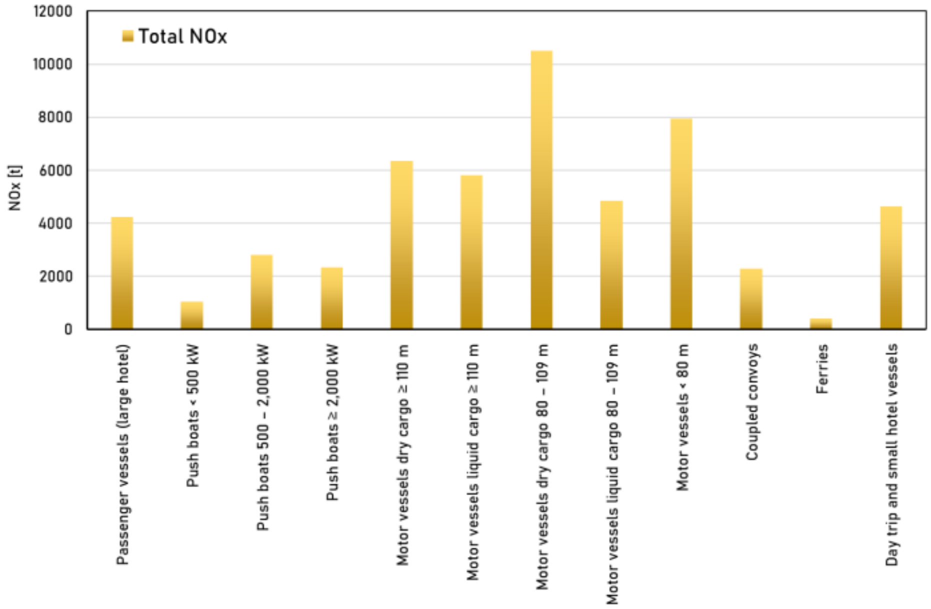

Figure 2 Absolute NO_x emissions of the fleet families of the European inland fleet in 2015

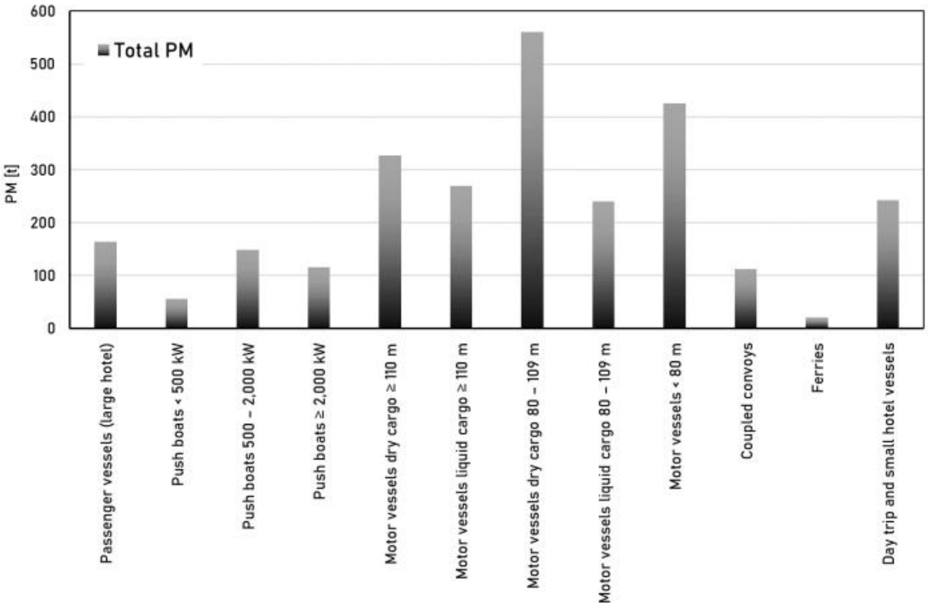

Figure 3 Absolute PM emissions of the fleet families of the European inland fleet in 2015

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During the selection of the high-impact fleet families, the demonstration approach was defined together with the SYNERGETICS consortium partners, resulting in WP3 activities built around three types of demonstrators: full-scale, model-scale, and system demonstrators. Further refinement of what was feasible within the project timeline led to:

- Demonstrations on full-scale ships in operation, performed on a seagoing crew transfer vessel (CTV) and an inland container vessel.
- Demonstrations in DST's towing tank and by means of computational fluid dynamics (CFD) for an inland dry cargo vessel.
- Demonstrations in MARIN's virtual and physical Zero Emission Lab (v-ZEL and ZEL) performed on a push boat.
- Demonstrations by means of voyage simulations performed on a push boat, an inland dry cargo vessel, an inland container vessel, and a seagoing crew transfer vessel.

2.2 Selecting tasks

To demonstrate and harmonise the potential emission savings from implementing retrofit solutions, the work was divided into several specific tasks. The performance of the ship operations was analysed, the needs and requirements were collected, a technology selection (SPEC[2] analysis) was made based on the mission and needs. For some demonstrators a conceptual design of the power system was carried out and for other demonstrators model tests were conducted or a digital twin of the power and propulsion system was developed. In addition, route simulations were performed for several demonstrators.

2.3 Selection of Demonstrators

In 2022, following careful consideration during the preparation of the SYNERGETICS project proposal and signing of the Grant Agreement, the consortium partners decided to demonstrate the following:

Demo 1: Harbour tug, hydrogen combustion gensets

Demo 2: Inland chemical tanker, methanol dual fuel application

Demo 3: Inland container vessel, battery pack application

Demo 4: Inland cement carrier, electrification of main propulsion plant

Demo 5: Inland dry cargo vessel, aft-ship replacement

Demo 6: Via Donau push boat, search for optimal retrofit solution

Demo 7: Methanol conversion

Demo 8: Power management design

The original planned demonstration (Demo1) on the harbour tug "HYDROTUG" by CMB considered the utilization of hydrogen in internal combustion engines. This demonstration and evaluation on board, which was foreseen by CMB at the HYDROTUG, was not possible because the ship was not available due to a delay in commissioning and related downtime of the vessel. Therefore, the CTV of CMB.TECH was selected for onboard demonstration and evaluation of this technology.

As a result, the following vessels and systems were selected as Demonstrators:

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[2] Ship Power and Energy Concepts.

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2.3.1 Demo 1: Hydrogen combustion engines and evaluation onboard a CTV

Within SYNERGETICS, Volvo Penta D8 MG (fixed speed engine) and MH (variable speed engine) were converted and calibrated to dual fuel engines (hydrogen, diesel). The technology of hydrogen dual fuel combustion engines was demonstrated and evaluated on a Crew Transfer Vessel, as Demo 1.

Greening efforts in the maritime transport are mainly directed at the improvement of the environmental performance of large seagoing ships whereas smaller vessels receive less attention. Nevertheless, the ships operating along European coasts and in European ports may have a significant environmental impact with immediate consequences on air quality and health in coastal and port areas. Furthermore, as the number of such vessels is very large, the impact of their retrofit is potentially high.

CTVs, like the Hydrocat (Figure 4), are operated to transport service engineers and material to and from the offshore wind turbines. High speed, reliability and comfort are key requirements for these types of vessels. To meet the power demand and the maximum allowable weight of these high-speed crafts, electric or hybrid propulsion are not suitable due to the weight of the batteries. With future potential offshore hydrogen refuelling in mind, hydrogen has been selected as the most suitable fuel for this application. Knowing the offshore wind production in North-West Europe will grow heavily the next years, also the number of hydrogen-powered CTVs will grow and thus this technology can be implemented on a larger scale. Nevertheless, the impact of the demonstration will go beyond the direct effects of decarbonisation and air-pollutant emissions reduction.

SYNERGETICS deliverable D3.5 - Evaluation report hydrogen-powered CTV, provides an overview of the demonstration actions and lessons learned on Demo 1. (dissemination level: SEN)

Figure 4 Crew Transfer Vessel Hydrocat

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2.3.2 Demo 2: Inland chemical tanker, methanol dual fuel application

Demo 2 involves an analytical and regulatory assessment of the feasibility of converting an inland chemical tanker to a methanol dual-fuel propulsion configuration. This task includes reviewing the technical and regulatory requirements for operating on methanol and conducting an evaluation based on engineering analysis and available data.

The reference vessel is the Stolt IJssel, shown in Figure 5, owned by Mercurius Shipping Group and operated by Stolt-Nielsen Limited. The Stolt IJssel is a type C inland chemical tanker, which transports liquid chemical cargo between Amsterdam, Rotterdam, and Antwerp (ARA), and other smaller ports nearby. Beside sailing in the ARA area, the vessel also operates along the Rhine, sailing up to Ludwigshafen near Mannheim in Germany. The main bunkering location is in Dordrecht.

SYNERGETICS deliverable D3.7 - Evaluation report methanol retrofit inland chemical tanker [2], provides an overview of the demonstration actions and lessons learned on Demo 2. (dissemination level: PU)

Figure 5 Chemical tanker “Stolt IJssel” from the Mercurius Fleet

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2.3.3 Demo 3: Inland container vessel, battery pack application

Demo 3 focuses on a container vessel with a ZES battery pack application (ZESpack). The company Zero Emission Services (ZES) is extending the provision of their ZESpack battery pack services. In this demonstrator the design, preparation, installation on one inland vessel is realized and the operations is monitored and evaluated.

The container vessel Alphenaar (Figure 6) is used for the demonstration of exchangeable battery packs charged with green electricity. This is a vessel of length ≥ 110 m, belonging to the fleet family which ranks third with respect to the absolute amount of CO_2, NO_x and PM emissions. (fleet family: "Motor vessels dry cargo ≥ 110 m").

The vessel was retrofitted in 2021 to allow the use of the ZESpack system. The ZESpacks are connected to the ship's grid by means of an onboard connection located at the forward end of the cargo hold. Two ZESpacks are placed on two 20ft container slots at the forward end of the hold. These two packs are sufficient to provide the energy required for a round trip between Alphen aan de Rijn and Moerdijk.

SYNERGETICS deliverable D3.9 - Evaluation report battery pack application on an inland vessel [3], provides an overview of the demonstration actions and lessons learned on Demo 3. (dissemination level: PU)

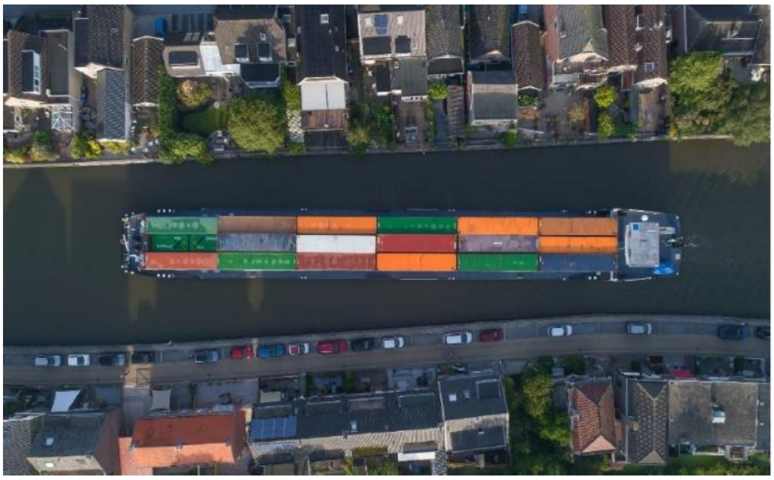

Figure 6 Container vessel "Alphenaar" sailing through a canal near a residential area.

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2.3.4 Demo 4: Cement carrier, electrification of main propulsion plant

Demo 4 is about the analytical assessment of electrification options for an inland cement carrier. This includes determining operational needs and system requirements, developing and evaluating suitable energy and power system configurations.

Le Sandre (Figure 7) is an inland cement carrier vessel dedicated to the transport of cement from Gennevilliers, located at the north of Paris, to Ivry sur Seine, located at the south of Paris. During its route along the Seine River, a densely populated area, the vessel calls at several ports, where cement is discharged. The cement is loaded at the port of Gennevilliers by gravity in combination with a screw conveyor located on deck. Unloading is conducted by liquifying cement using pressurized air and then discharged with flexible hoses. Discharge occurs typically at Issy les Moulineaux or Port-Victor.

The Le Sandre (fleet family: "Motor vessels < 80 m") belongs to the fleet family of inland vessels which ranks second with respect to the absolute CO_2, NO_x and PM emissions as shown in Figure 1. Le Sandre has a diesel-electric propulsion system consisting of two main gensets plus one harbour generator.

SYNERGETICS deliverable D3.11 - Evaluation report electrification of inland cement carrier [4], provides an overview of the demonstration actions and lessons learned on Demo 4. (dissemination level: PU)

Figure 7 Vessel "Le Sandre" sailing through the Seine River.

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2.3.5 Demo 5: Inland dry cargo vessel, aft ship replacement

Replacing a complete aft-ship is an extreme retrofit. This enables also a redesign of the aft-ship including the propulsion arrangement with (flex-)tunnel, nozzles and rudders. In Demo 5 hydrodynamic optimizations by CFD, verification by physical model tests and a business analysis were performed. The business analysis was an extremely important aspect given the scope of this retrofit.

The dry cargo motor vessel "Ernst Kramer" (Figure 8) from the fleet of the German shipping company Rhenus, was chosen as reference vessel for the demonstration of the potentials of aft-ship replacement. The "Ernst Kramer" belongs to the fleet family of the most CO_2-, NO_x-, and PM-emitting inland vessels in Europe (fleet family: "Motor vessels dry cargo 80 - 109 m").

SYNERGETICS deliverable D3.15 - Evaluation report aft-ship replacement: "Ernst Kramer" [5], provides an overview of the demonstration actions and lessons learned on Demo 5. (dissemination level: PU)

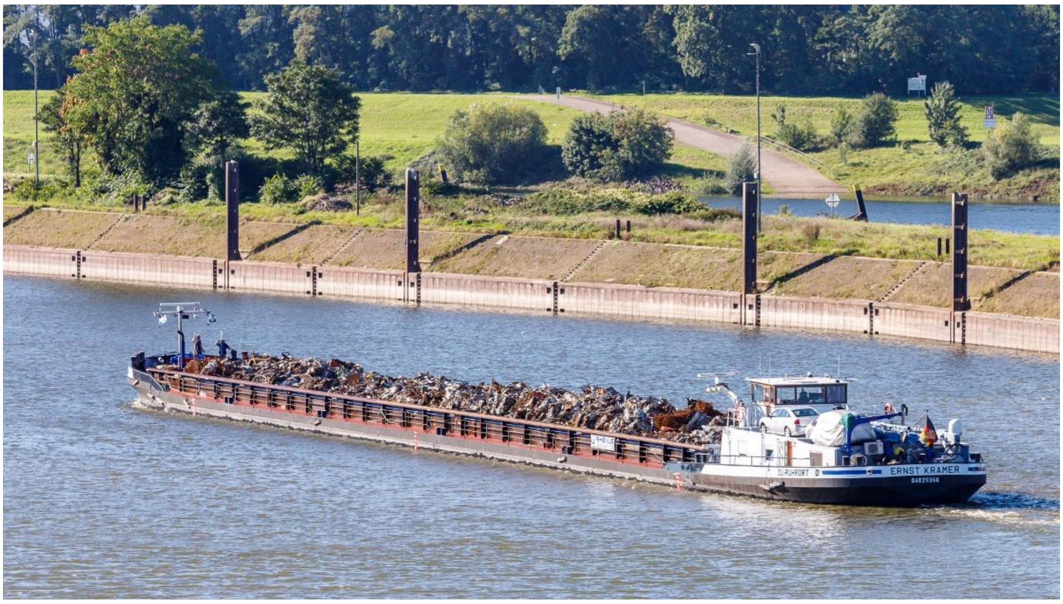

Figure 8 Dry cargo motor vessel "Ernst Kramer"

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2.3.6 Demo 6: Viadonau push boat

Viadonau is preparing the retrofit of a 500 kW pusher. To investigate what retrofit solution will be optimal for the push boat a complete analysis was carried out under Demo 6. The focus of this demonstrator is on determining the needs and requirements, and the design of the energy and power systems, including a model scale test in MARIN's ZEL of the selected energy and power system.

It is also important to demonstrate that the authorities in the waterborne transport sector are active players ready to set an example and lead the way in the greening efforts. This is why SYNERGETICS involves the Austrian Waterway Management Agency Viadonau, which aims to achieve climate and energy neutrality by 2030. Viadonau will explore the options for greening its own fleet, which comprises patrol boats, survey vessels, and push boats. The impact of such greening efforts may not be substantial in terms of absolute amounts of $CO_2/NO_x/PM$ mitigated, but it would send a clear and straightforward message to the shipping industry. Considering the above, their push boat 'Bad Deutsch-Altenburg' was selected as demonstrator.

The 'Bad Deutsch-Altenburg' (Figure 9), as shown in Figure 1, Figure 2 and Figure 3 belongs to the fleet family which is the largest absolute CO2-emitter, NOx-emitter and PM-emitter among the push boat families. Retrofitting a push boat presents specific challenges, considering that a push boat is in fact a "floating engine room" with wheelhouse and accommodation, storage of the energy carrier and other stores. In most cases there is hardly any extra volume and/or possibilities to compensate for the alternative fuels and energy conversion equipment.

SYNERGETICS deliverable D3.13 - Evaluation report Via Donau push boat [6], provides an overview of the demonstration actions and lessons learned on Demo 6. (dissemination level: PU)

Figure 9 Via Donau push boat "The Bad Deutsch-Altenburg"

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2.3.7 Demo 7: Methanol conversion

Consortium member ScandiNAOS (SNAOS) was tasked with demonstrating the performance of marine compression-ignited dual- and single-fuel methanol engines (Figure 10). This system-demonstrator is Demo 7.

Within SYNERGETICS two identical marine high speed diesel engines were converted for methanol combustion: one to a dual fuel engine and the other one to a single-fuel methanol engine. In both cases, engine conversion kits were developed and installed. After installation of the conversion kits, the engines were run in a test setup and compared with respect to a range of performance parameters (cost of engine conversion, fuel efficiency, emissions, etc.) to come up with an optimal solution.

The compression-ignited engine technology, which utilizes an ignition improver, is currently available on the market through Enmar Engines, a sister company of SNAOS. To enable a comprehensive comparison of this technology with dual fuel system, the development of a dual fuel conversion kit for a similar engine is necessary. Dual fuel concept developed for comparison is one utilizing port injection. The dual fuel engine was tested and compared on four characteristics: engine power, engine efficiency, Diesel replacement fraction and emissions.

Testing was conducted in accordance with the ISO 8178 standard, ensuring that the results are reliable and adhere to industry benchmarks. This comparative analysis provided valuable insights into the viability and performance of methanol as a marine fuel, potentially guiding future advancements in sustainable marine propulsion technologies.

SYNERGETICS deliverable D3.17 - Evaluation report on application of methanol: compression ignited vs dual fuel [7], provides an overview of the demonstration actions and lessons learned on Demo 7. (dissemination level: PU)

Figure 10 Compression ignited methanol (MD97) engine 16LV8 415 kW at 2100 rpm, available from Enmar Engines AB

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2.3.8 Demo 8: Design of power management system

Consortium partner Future Proof Shipping (FPS) owns and operates two inland container barges, H2B1 (former MCS Maas) and H2B2 (former FPS Waal) running exclusively on hydrogen with a fully electrical propulsion system. The vessels were built as traditional inland barges with a diesel engine approximately thirty years ago and were later retrofitted by swapping the combustion engine drivetrain with an electrical propulsion system. All the auxiliary systems that could be adapted to the new propulsion system were kept and are still in operation.

Demo 8 evaluates the Power Management System (PMS) (Figure 11) onboard the two Future Proof Shipping owned inland container vessels. Both vessels are equipped with the same PMS but different versions of it, with the newer version being an improvement over the previous one. This Demo highlights the critical role of adaptive software, iterative system refinement, and operational feedback in pioneering clean propulsion technologies for inland shipping, supporting broader decarbonization goals in the maritime sector.

SYNERGETICS deliverable D3.18 - Evaluation report on Power Management System [8], provides an overview of the demonstration actions and lessons learned on Demo 8. (dissemination level: PU)

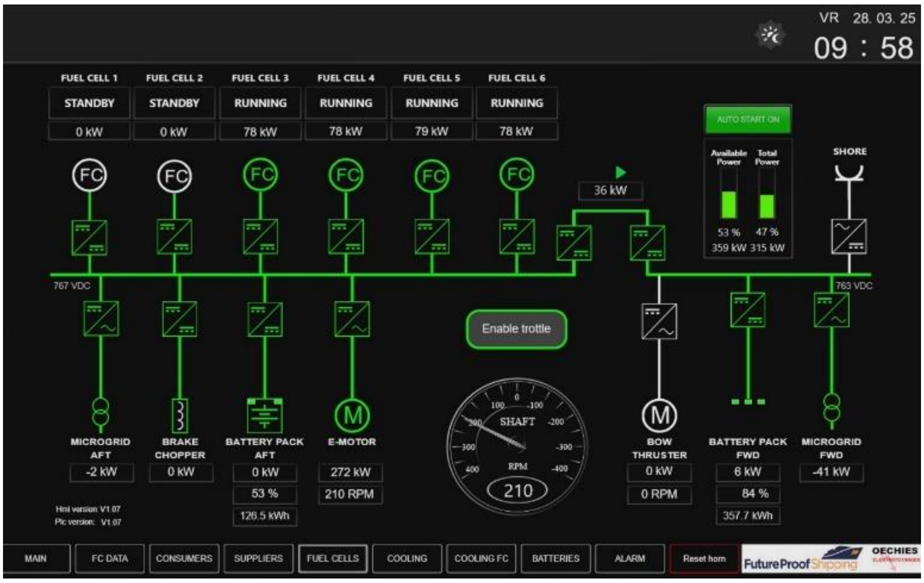

Figure 11 Main page of the PMS human machine interface (HMI) onboard

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3. Analyses

Within the SYNERGETICS project, an operational analysis, technology selection and conceptual design of the power and energy system was conducted to study which power and energy concept was most suitable for each demonstrator, to achieve a lower emission level than current situation. This chapter describes the analysis of each demonstrator, compares and verifies the performance of the different demonstrators in a harmonized way using the standardised measurements and simulations.

SYNERGETICS deliverable D3.1 – SPEC analyses of full scale and model scale demonstrators [9], provides an overview of the different Ship Power and Energy Concept (SPEC) analyses performed including an overview on high level consequences of the new Propulsion Power and Energy (PPE) systems on vessel design and operation. (dissemination level: PU)

3.1 Operational analyses overview

The basic data collected from all demonstrators are summarized in Table 2, allowing for direct comparison. This includes their overall dimensions, operational areas, and longest mission durations, as well as the maximum power required for their specific operations. The operational regions of the demonstrators are also illustrated in this chapter.

Table 2: Overview of demonstrators' operational details

Demonstrators	**Full scale**				**Model scale**		**System**	
Demo nr.	**Demo 1**	**Demo 2**	**Demo 3**	**Demo 4**	**Demo 5**	**Demo 6**	**Demo 7**	**Demo 8**
Consortium partner	CMB	MERC	ZES	CFT	DST	MARIN	SNAOS	FPS
Description	H2 Crew Transfer Vessel	Chemical tanker	Battery pack	Electrific. Cement Carrier	Aft ship replacement	Via Donau push boat	Meth. conversion	Power Management System
Ship	Hydrocat	Stolt IJssel	Alphenaar	Le Sandre	Ernst Kramer	Bad Deutsch-Altenburg	-	-
System							dual fuel (DF) methanol-diesel port injection engine vs Single fuel MD97 methanol compression ignited engine	PMS of H2B1 vs PMS of H2B2
Length over all	25 m	109.9 m	90.0 m	51.2 m	105 m	22.15 m		
Beam	7.3 m	14.0 m	10.5 m	11.4 m	9.5 m	5.6 m		
Draught	1.9 m	4.6 m	3.6 m	3.25 m	3.15 m	1.2 m		
Deadweight	10 t	5000 t	1883 t	980 t	xx	11 t		

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Operational area	BE: North Sea, between shore and offshore wind parks	NL, BE, DE: ARA, Rhine	NL: Alphen - Moerdijk	FR: Gennevilliers - Ivry	DE: Duisburg - Mannheim	AUS: Austrian Danube area		
Longest mission	1 day	1468 km	126 km	40 km	330 km	350 km		
Max total power	1460 kW	1840 kW	715 kW	600 kW	1170 kW	500 kW		

The operational regions of the demonstrators are visualized below in Figures 12 to 18.

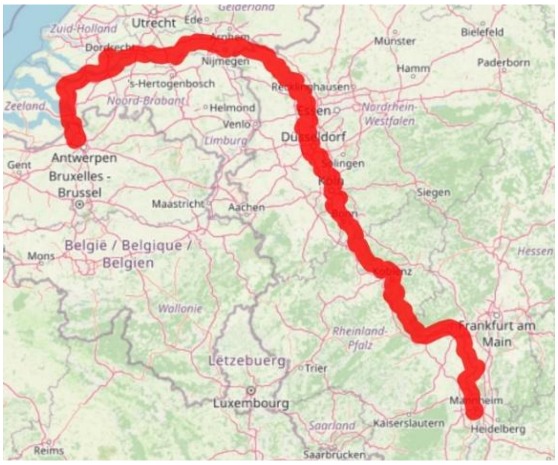

Figure 12 Route of the Stolt IJssel, Demo 2

Figure 13 Route of the Alphenaar, Demo 3

Figure 14 Route of Le Sandre, Demo 4

Figure 15 Canal route of the Ernst Kramer, Demo 5

Figure 16 Rhine route of the Ernst Kramer, Demo 5

Figure 17 Route sailed by the Bad Deutsch-Altenburg, Demo 6

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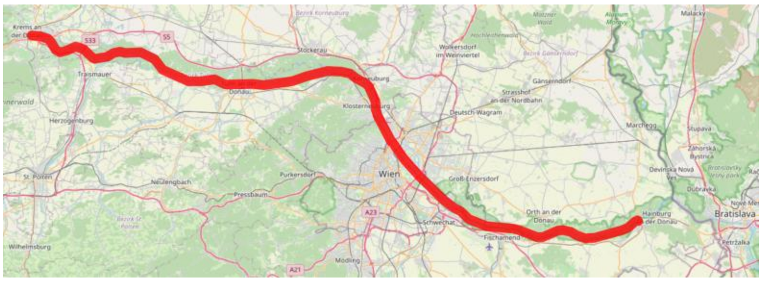

Figure 18 Route between Bad Deutsch-Altenburg to Krems an der Donau, Demo 6

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3.1.1 Needs and requirements:

To build the operational profile, the operations of the vessel were analysed to understand how the new design will be operated, and what the requirements in terms of power and energy are. Generally, the operations of a vessel can be broken down into tasks. A task is defined as the combination of a reference vessel in its state (e.g. draught), environmental condition (e.g. sea state, shallow water) and a certain operation (in Dynamic Positioning (DP), anchorage, economic cruising, harbour). For each task the power is divided into propulsion power, auxiliary power and payload power. Propulsion power is the power consumed by the propulsion system. Auxiliary power is the part of the total power that does not belong to the propulsion power. Payload power is the part of the auxiliary power used for the cargo-related (payload-related) operations e.g., deep-well pumps on a tanker, deck cranes on a multipurpose coaster, etc.

3.1.2 Options & Ship Power and Energy Concept analyses overview

The goal of the Ship Power and Energy Concept analysis was to evaluate what solutions (energy carrier + energy converter) are feasible within a reference vessel based on a set of operational requirements. The Ship Power and Energy Concepts analysis is carried out using a MARIN in-house tool. This tool, called SPEC, allows, through a weighted multi criteria analysis, to compare together different solutions and to assess what their impacts are on the design, in terms of weight, volume, efficiency and costs. The SPEC analysis uses as inputs the outputs of the operational analysis, and it is divided in three parts: Preselection, Ranking and Design Cases.

The Preselection phase uses requirements on a macro level to filter out solutions that are completely unfeasible. The output of this step results in a large list of energy and power solutions.

In the Ranking phase, stakeholders and users can influence the results of the analysis by weighing the different criteria based on what is more relevant for them. If no input has been given for the criteria, they are equally weighted so that all parameters are equally relevant for the solution. Based on the weights given to the technology, investment and operational parameters, SPEC ranks the concepts from 1 to 9, being these the lowest and highest score, respectively. These rankings provide an overview of what is the least and the most suitable PPE concept with regards to the foreseen operations of the vessel or to the type of technology and required investment to implement a solution.

Last, both the operational as well as the technology and investment rankings are weight-averaged depending on how important they are for the client.

3.2 Route simulations overview

Voyage simulations were carried out using the most representative route and were based on operational data of the vessels. Simulations were conducted over multiple days to gain a clearer understanding of the vessel's performance and to obtain a statistical overview. The results showed that a significant reduction in emissions can be achieved either through conventional retrofitting measures (Demo 5), by a small retrofit with limited impact on the design of the vessel (Demo 1), or by more extensive retrofitting or making a new design to allow the use of alternative fuels (Demo 3 and Demo 6). The results of the voyage simulations showed that the target within SYNERGETICS of reducing 35 % of GHG emissions can be achieved for many demonstrators.

SYNERGETICS deliverable D3.20 – Overview report of route simulations [10], provides an overview of the simulations part of Subtask 3.1.2 of SYNERGETICS. (dissemination level: PU)

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4. Design concepts

During the development of the Concept Designs, requirement analyses were conducted to determine the performance targets of the new designs and to validate pre-selected measures. These analyses considered user and owner needs, as well as safety requirements in accordance with ES-TRIN regulations. This section lists out the most suitable retrofit technology Design Concepts after analyses for the different demonstrators as described in SYNERGETICS reports D3.1 to D3.20. All Demos have the Diesel technology benchmark #16 and #52. Nearly all of the demonstrators are successfully implemented. There are two Demo's with hurdles, Demo 2 and Demo 4. Out of the hurdles we can derive lessons learned.

Table 3 provides an overview of the eight demonstrators, four full-scale, two model-scale and two system-focused, covering the range of vessel types and technologies. Key findings show that most demonstrations were technically successful, though challenges remain. The greenhouse gas (GHG) reduction potential varies significantly depending on the technology applied. Battery-electric solutions offer up to 100% GHG savings, while hydrogen, methanol, and improved conventional systems typically achieve reductions in the range of 30% to 40%.

Table 3: Design concepts overview and key takeaways

Demonstrators	**Full scale**				**Model scale**		**System**	
Demo nr.	**Demo 1**	**Demo 2**	**Demo 3**	**Demo 4**	**Demo 5**	**Demo 6**	**Demo 7**	**Demo 8**
Consortium partner	CMB	MERC	ZES	CFT	DST	MARIN	SNAOS	FPS
Description	H2 Crew Transfer Vessel	Chemical tanker	Battery pack	Electrific. Cement Carrier	Aft ship replacement	Via Donau push boat	Meth. conversion	Power Management System
Ship	Hydrocat	Stolt IJssel	Alphenaar	Le Sandre	Ernst Kramer	Bad Deutsch-Altenburg	-	-
System							dual fuel (DF) methanol-diesel port injection engine vs Single fuel MD97 methanol compression ignited engine	PMS of H2B1 vs PMS of H2B2
Max total power	1460 kW	1840 kW	715 kW	600 kW	1170 kW	500 kW		
Technology benchmark	#16 = Diesel (EN590) CI ICE (hi-speed)	#16 = Diesel (EN590) CI ICE (hi-speed)	#16 = Diesel (EN590) CI ICE (hi-speed)	#16 = Diesel (EN590) CI ICE (hi-speed)	#52 = Diesel (EN590) CI ICE (hi-speed) Direct	#52 = Diesel (EN590) CI ICE (hi-speed) Direct HVO100		PMS of H2B1

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Winning Retrofit Technology after analysis	#47 = H_2 300b/Dsl 96/4%vol CI ICE	#9 = e-CH_3OH (CO_2 PTS)/Dsl 95/5%vol CI ICE	#21 = Battery-electric (renewable) or #48 = Battery-electric (fossil)	#21 = Battery-electric (renewable)	Aft ship replacement + #4 = Diesel (POME, UCO) CI ICE	#9 methanol-electric using methanol compression-ignited single-fuel gensets		PMS of H2B2
GHG savings potential after retrofit (WTW)	30%	n.a.	100%	100%	35%	35- 40%	-	-
Key takeaway	Successful demo. Hydrogen refueling infrastructure and upscaling production is key.	Demo with hurdles: Methanol is not listed as a reference fuel under Regulation (EU) 2016/1628 (NRMM Stage V) for application in inland waterway transport	Successful demo. Can be implemented relatively easy on existing vessels, especially with already Diesel-electric propulsion	Demo with hurdles: Required investment into the power supply is not supported by customers, port operator and local authorities	Successful demo. Updated conventional drive system and the optimisation of the hydrodynamics of the aft ship leads to GHG emission goals with moderate effort	Successful demo. Methanol can be used when regulations are tackled (see Demo 2)	Successful demo. Methanol can be used when regulations are tackled (see Demo 2)	Successful demo. Improved PMS extend component life.

4.1 Comparison of design concepts of the different Demonstrators

This section compares the design philosophies, system architectures, and innovation focus of these demonstrators. The SYNERGETICS project adopts a demonstrator-based approach to validate retrofit solutions for decarbonising inland and coastal shipping. Rather than proposing a single universal solution, it tests multiple design concepts on real vessels and systems, each tailored to distinct operational profiles, energy carriers, and technological maturity.

One of the approaches within the project is the move toward full electrification. In this concept, represented by Demo 3, conventional fuel-based propulsion is supported by a battery system. The design is built around modular battery containers that can be installed on vessels with relatively limited structural modifications. These batteries are not simply onboard storage units; they are part of a broader operational model in which energy can be supplied as a service. This allows vessels to exchange battery units in a way that resembles container logistics, reducing upfront investment and increasing operational flexibility. The concept emphasises standardisation, scalability, and integration into emerging charging infrastructures. At the same time, it reveals inherent limitations, such as restricted range and dependence on the availability of charging or swapping facilities.

In contrast to this fully electric vision, another group of demonstrators (Demo 1, 2 and 6) explores the use of alternative fuels, particularly methanol and hydrogen. These concepts build on the existing propulsion paradigm rather than replacing it entirely. Methanol, for example, is introduced as a substitute fuel in adapted engines, allowing vessels to retain much of their original architecture while significantly reducing emissions. The design process focuses on integrating new fuel storage systems and ensuring safe and efficient combustion. Hydrogen on the other hand, is applied in a dual-fuel configuration, where it is combined with diesel in modified engines. This approach represents a transitional solution: it reduces emissions while maintaining compatibility with current infrastructure and operational practices. Both concepts illustrate a design philosophy that values continuity and practicality, enabling operators to move toward sustainability without undergoing a complete technological overhaul.

Additionally, in the case of Demo 6 the vessel design is not tested in practice but analysed through detailed modelling of operational profiles, energy consumption, and system behaviour. This approach allows researchers and operators to explore different configurations before committing to costly retrofits. Importantly, it also incorporates human expertise, such as feedback from captains, ensuring that technical solutions align with real-world operational needs. In this sense, the design concept extends beyond the vessel itself to include the decision-making processes that shape its development.

Complementing these physical demonstrators is demonstrated in the concept Demos 7 and 8, that operates at the system level: the use of advanced simulation and validation environments.

Case study Demo 5 showed that with an updated conventional drive system and the optimisation of the hydrodynamics of the aft ship, at the CCNR's targets for 2035 climate-impacting emissions can be achieved with moderate effort. The hydrodynamic redesign of the aft ship incorporates the propulsion configuration, including (flexible) tunnels, nozzles, and rudders, to maximize flexibility and efficiency, thereby reducing overall power demand.

When these different concepts are compared, a clear pattern emerges. Electrification stands out as a radical but infrastructure-dependent solution, offering very high emission reduction potential at the cost of operational constraints. Meanwhile, the simulation-based demonstrators play a crucial supporting role, enabling informed choices and reducing uncertainty.

Ultimately, the comparison of the demonstrators reveals that the transition to sustainable shipping will not be achieved through a single breakthrough technology. Instead, it will depend on a portfolio of solutions, each suited to a particular context and stage of the transition. The strength of the SYNERGETICS approach lies in demonstrating how these solutions can coexist and complement each other. By exploring different design concepts in parallel and grounding them in real-world applications, the project provides a nuanced and realistic vision of how inland and coastal shipping can evolve toward a low-emission future.

5. Performance comparison of the different demonstrators

A quantitative comparison of the SYNERGETICS demonstrators is difficult because of the multitude of dependencies. At the core of the performance comparison lies the use of operational profiles and power demand modelling (SYNERGETICS deliverable D3.1 – SPEC analyses [9]). For each vessel, the mission profile is decomposed into representative tasks, such as cruising, manoeuvring, etc., over a defined period of time between bunkering or charging events.

Using these standardised mission profiles, simulation tools such as those implemented in the Zero Emission Lab, allow for a direct comparison between baseline (diesel) configurations and retrofit solutions. These simulations evaluate key performance indicators including fuel or energy consumption, emissions, and system responsiveness. Importantly, they also account for hydrodynamic behaviour and vessel-specific constraints, ensuring that the results are not purely theoretical but grounded in realistic operating conditions.

For the electrification demonstrator (Demo 3), performance is primarily evaluated in terms of energy efficiency and zero-emission operation. Simulation results typically show a substantial reduction in total energy consumption compared to diesel systems, due to the high efficiency of electric propulsion. However, the performance is strongly dependent on battery capacity and discharge cycles, which are assessed using standardised route simulations. The concept of containerised battery packs introduces an additional parameter: energy amount per swap cycle, which becomes a key indicator of operational feasibility. Measured performance during real deployments has highlighted practical aspects such as optimised battery placement and handling efficiency, which influence turnaround times and therefore system productivity.

In contrast, the methanol-based demonstrator (Demo 7) is evaluated through a combination of simulation and engine testing, focusing on specific fuel consumption (SFC), emission factors, and system efficiency under varying loads. By comparing compression ignition and dual-fuel modes, the project assesses how combustion strategies influence performance. Standardised measurements allow for direct comparison with diesel benchmarks, showing reductions in greenhouse gas emissions while maintaining comparable operational ranges. However, simulations also reveal the impact of methanol's lower energy density, which requires larger storage volumes and influences the vessel's endurance and payload capacity. The hydrogen dual-fuel demonstrator (Demo 1) introduces another layer of complexity in performance evaluation. Here, standardised testing focuses on fuel substitution ratios, indicating the proportion of hydrogen used relative to diesel, as well as resulting emission reductions. Engine dynamometer tests were used to calibrate performance and ensure compliance with emission standards. The results demonstrate a measurable decrease in CO_2 and particulate emissions, but also highlight efficiency trade-offs depending on engine load and hydrogen integration levels. Simulation tools further assess how hydrogen availability and storage constraints affect operational performance across different routes.

In addition to individual propulsion concepts, the SYNERGETICS approach compares the different concepts. For all demonstrators, performance is assessed in terms of greenhouse gas emissions and cost-effectiveness. The use of simulation environments allows for comparison, evaluating each technology. This is essential to determine not only absolute performance, but also contextual suitability, such as which solution performs best for short inland routes versus longer coastal operations.

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An important insight emerging from this comparative analysis is that performance is not a static property of a technology, but a function of its interaction with operational conditions. For example, battery-electric systems perform well in short, predictable routes with access to charging infrastructure, whereas alternative fuels demonstrate stronger performance in longer or more variable missions. The simulation framework thus reveals trade-offs that would not be apparent from isolated testing.

Finally, the integration of real-world measurements and simulation results strengthens the robustness of the comparison. Field data from demonstrators, such as energy use, handling times, and engine performance, are used to validate and refine simulation models. This iterative process ensures that performance assessments are both accurate and transferable to other vessels and operational contexts.

In conclusion, the comparison of the SYNERGETICS demonstrators using standardised measurements and simulations provides a rigorous basis for evaluating retrofit solutions. By combining detailed technical modelling with real-world validation, the project moves beyond isolated case studies and establishes a systematic framework for performance benchmarking. This approach makes it possible to identify the strengths and limitations of each concept, not in abstract terms, but in relation to the specific operational environments in which they are expected to perform.

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6. Lessons learned and Conclusion

The Innovation Action SYNERGETICS adopts a demonstrator-based approach to validate retrofit solutions for decarbonising inland and coastal shipping. Rather than promoting a single universal solution, it evaluates multiple design concepts on real vessels and systems, each tailored to specific operational profiles, energy carriers, and levels of technological maturity.

Eight demonstrators were selected at the start of the project, based on their potential impact, with the magnitude of this impact assessed against several criteria. These include the absolute and relative CO_2, NO_x and particulate matter emissions of different vessel types, the operational areas in which they are deployed, and the extent to which the insights gained can be applied across the broader European inland shipping fleet.

To demonstrate and harmonize the potential emission savings from implementing retrofit solutions, the work was divided into several specific tasks. The performances of the ship operations were analysed, the needs and requirements where collected, and then a technology selection was carried based on the mission and needs. For some demonstrators a conceptual design of the power system was carried out and for other demonstrators model tests were conducted or a digital twin of the power and propulsion system was developed. In addition, route simulations were performed for several demonstrators. To compare the emissions level for different energy and power concepts, an architecture running on fossil diesel was used as baseline. The results showed that a significant reduction in emissions can be achieved either through conventional retrofitting measures (Demo 5), by a small retrofit with limited impact on the design of the vessel (Demo 1 and Demo 3), or by more extensive retrofitting or making a new design to allow the use of alternative fuels (Demo 6).

Nearly all of the demonstrators were successfully implemented. There are two Demos that had some obstacles: Demo 2 and Demo 4. Out of these obstacles we can derive lessons learned.

Demo 2 involves an analytical and regulatory assessment of the feasibility of converting an inland chemical tanker to a methanol dual-fuel configuration. The Ship Power and Energy Concept (SPEC) analysis was based on the mission and needs. The difficulty with this Demo was that methanol is not listed as a reference fuel under Regulation (EU) 2016/1628 (NRMM Stage V) for application in inland waterway transport (IWT). The certified engine for IWT, a smaller engine that is used by seagoing vessels, is not (yet) available. Demo 6 and 7 are also based on methanol as an alternative fuel. Here too, the regulatory boundaries are a point of attention.

Demo 4 looked into the analytical assessment of electrification options of an inland cement carrier. The Ship Power and Energy Concept analysis was based on the mission and needs. Also, the Concept design was started. In this Demo, the main obstacle was the investment required for shore power facilities. Shore power is essential for electrification, but it was not supported by customers, the port operator, or local authorities. A key lesson learned is that earlier involvement in the project might have helped to prevent this hurdle.

The following points summarise the lessons learned from all the Demo's;

1. **Provide clarity of regulatory procedures:** Clarity and streamlining of the regulatory procedures for greening retrofit solutions on board helps to define major bottlenecks that hinder the accelerated adoption of greening retrofit solutions. During the SYNERGETICS project this is addressed in Task 4.5; Outlines the overview of the existing and near future legal framework. It also addresses the regulatory bottlenecks that hinder the accelerated adoption of greening retrofit solutions and provides suggestions for streamlining approval procedures, identifies gaps in existing regulations.

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2. **Inform and convince key stakeholders to cooperate and invest:** A lesson learned is to inform stakeholders adequately at an early stage to enable effective collaboration to eliminate hurdles. This aligns with the objectives of SYNERGETICS, which aim to engage policy makers and other stakeholders by providing insights into updated Transition Pathways Task 5.2 and scenarios for policy makers Task 5.3.
3. **Entrepreneurial willingness is not the limiting factor for decarbonisation in inland shipping:** Instead, uncertainty in regulations and the lack of commercially available engine solutions create a bottleneck that discourages first movers. Future innovation programmes should explicitly recognise this risk and create frameworks in which pioneering vessel owners are enabled rather than exposed.
4. **Provide insights in total business case:** SYNERGETICS is providing a Decision Support Tool for Vessel Owners (Task 5.1) to provide clear insights in the whole picture of the type of vessel and the sailing profile in order to make an informed decision. This includes impact on operational profiles, energy and emission savings and changes to business cases (CAPEX, OPEX, financing options). The final assessment of the business cases showed that the price difference between fossil and renewable fuels is the decisive factor for refinancing the investment. It would therefore be important to not only introduce subsidy programmes to reduce the investment, but also to align fuel prices, either by imposing sanctions on fossil fuels or by promoting renewable alternatives.
5. **Availability of alternative fuels or hardware:** The availability of alternative fuels and associated components is progressing, but remains uneven across technologies and applications. A wide range of options is already technically accessible, including hydrogen, methanol, biofuels, and battery-electric systems, alongside enabling hardware such as fuel cells, dual-fuel engines, and advanced battery packs. Several of these solutions have reached a level of maturity suitable for demonstration and early deployment, as reflected in Demo's focusing on hydrogen dual-fuel engines, methanol applications, and onboard battery installations. However, their large-scale uptake is still constrained by limited fuel infrastructure, varying TRL's, and integration challenges within existing vessels. As such, while both fuels and components are increasingly available, their practical adoption depends on local supply chains, regulatory frameworks, and the specific retrofit context, reinforcing the need for a flexible, multi-technology approach to the energy transition in inland and coastal shipping. This aligns with the objectives of SYNERGETICS, which aim to engage policy makers and other stakeholders by providing insights into updated Transition Pathways (Task 5.2) and scenarios for policy makers (Task 5.3).
6. **There is no one "Golden Egg" solution:** The comparison of the demonstrators shows that the transition to sustainable shipping will not be driven by a single breakthrough technology. Rather, it will rely on a diverse portfolio of solutions, each tailored to specific contexts, operational profiles and phases of the transition. The strength of the SYNERGETICS approach lies in illustrating how these solutions can coexist and reinforce one another. By exploring multiple design concepts in parallel and anchoring them in real-world applications, the project offers a nuanced and practical perspective on how inland and coastal shipping can progress toward a low-emission future.

The results show that significant emission reductions can be achieved through a range of approaches, from conventional retrofitting, to limited-impact modifications, to more extensive redesigns enabling alternative fuels. Voyage simulations indicate that the SYNERGETICS target of a 35% reduction in greenhouse gas emissions is achievable for many cases.

Overall, the project confirms that decarbonisation through retrofitting of inland and coastal shipping will depend on a combination of technologies, validated at system level and tailored to specific operational contexts, rather than a single universal solution.

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SYNERGETICS deliverables are available via: https://www.synergetics-project.eu/downloads