D3.20 Overview report of route simulations

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

GRANT AGREEMENT NO.	101096809
DURATION OF THE PROJECT	42 months
DELIVERABLE NUMBER	D3.20
DISSEMINATION LEVEL	PUB - Public
DELIVERABLE LEADER	MARIN
STATUS	FINAL
SUBMISSION DATE	30-07-2025
AUTHOR	P. Garcia Barrena, MARIN p.garcia@marin.nl
CO-AUTHORS	Gianluca Giurco, MARIN g.giurco@marin.nl Friederike Dahlke-Wallat, DST dahlke@dst-org.de Marko Josipović, DST josipovic@dst-org.de

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table of Content

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

List of Figures

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

List of Tables

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Release Approval

Table 1-1: Release Approval

Name	Role	REMARKS
P. Garcia Barrena	WP-Leader	28-06-2025
C. Chirita	Reviewer	30-06-2025
B. Friedhoff	Project Coordinator	29-06-2025

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Abbreviations

BIO	Bunker Independent Operation
CI	Compressed Ignited
CO2eq	Carbon Dioxide equivalent emissions
GHG	Green House Gas
GWP	Global Warming Potential
H2	Hydrogen
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
ITTC	International Towing Tank Conference
MCR	Maximum Continuous Rating
POME	Palm oil mill effluents
PTS	Point Source
SF	Single Fuel
SOG	Speed Over Ground
TTW	Tank to Wake
UCO	Used cooking oil
WTT	Well-To-Tank
WTW	Well to Wake

Executive Summary

This report provides an overview on the route simulations part of Subtask 3.1.2 of SYNERGETICS.

Voyage simulations were carried out using the most representative route and were based on operational and environmental 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.

To compare the emissions level for different energy and power concepts, a baseline architecture running on fossil diesel was developed. 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 3), or by more extensive retrofitting or making a new design to allow the use of alternative fuels (Demo 1 and Demo 6). From the results from the voyage simulations, it can be seen that the target within SYNERGETICS[1] of reducing in 35% in GHG emissions is achieved for most demonstrators.

---

[1] Goals of GHG reduction also defined in the Revised Rhine Navigation Act (Manheim Act) [3].

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

1. Introduction

Subtask 3.1.2 within Innovation Action SYNERGETICS aims to estimate the potential emission savings from implementing retrofit solutions in several demonstrators. SYNERGETICS project has the ambition to demonstrate retrofitting solutions that allow to reduce GHG emissions (by at least 35% compared to the original design), in line with the environmental objectives on the Revised Rhine Navigation Act (Manheim Act) of 2018 [1].

Route simulations provide a method to compare performance and emissions of a ship considering the different working points the power system may be subjected during operation. By doing so, the impact of a specific power and energy concept on emission reduction can be modelled to compare the performance of the vessel.

Due to the significantly variable environment conditions in which the ships will sail, to estimate the required propulsion power voyage simulations were carried out. By doing so, the influence of the environmental conditions (water level, current speed, waves, etc.) on the propulsion power were taken into account.

Voyage simulations of Demo 1 and Demo 6 were performed with MARIN's voyage scenario simulation tool 'Gulliver'. For a specific location and time, Gulliver retrieves sea state, weather data, current speed and direction and water depth from a database of environmental conditions. The algorithm uses a Ship Motion Database with linear and quadratic transfer functions to calculate wave induced forces. For the calculation of wind forces, aerodynamic coefficients and areas of the above-water part of the hull and superstructure are used. For the calculation of the propulsion efficiency, propulsion coefficients of similar vessels were used. The ship resistance in deep calm water, which is used as input in Gulliver, was calculated using MARIN's prediction program DESP, which is based on statistical analysis of ship models tested at MARIN. The additional resistance in shallow water is calculated using Raven's Method [2], recommended by the ITTC.

For the voyage simulations, Gulliver solves the force equilibrium in X-direction. This is done by set-ting the shaft power and solving the resulting sustained speed. After solving the equilibrium, the ship's velocity is determined. Finally, the speed is used to define a new location on the route. In Figure 1-1 a schematic overview of Gulliver is presented.

In the end, the output of the voyage simulations is a table that contains for each time step the propulsion particulars (shaft power, propeller rpm, etc.), environmental conditions (water depth, current speed, significant wave height, etc.) and the ship's speed over ground.

The route and operation (departing time, sailing speed) of the voyages were defined based on the operational analysis developed in deliverable D3.1. The most representative operation (i.e., the operation carried out the most) from the operational analysis was selected for the voyages.

Voyage simulations of Demo 3 were conducted using operational data in combination with a speed power prediction. The voyage simulations for Demo 5 were performed using DST Voyage simulation tool 'Fluvial'.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

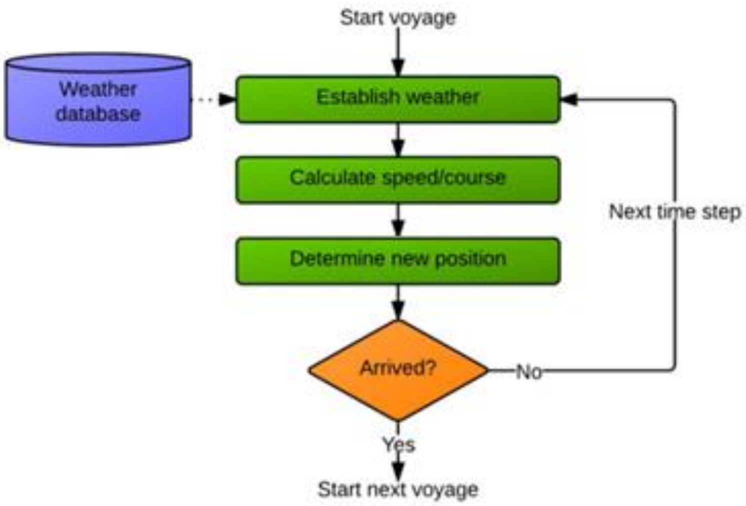

Figure 1-1: Schematic overview of Gulliver.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

2. Voyage simulations for Demo 1

The Hydrocat 48 is a catamaran Crew Transfer Vessel (CTV) owned by Windcat Workboats, which is a subsidiary of CMB.TECH. The vessel operates mainly in the North Sea, transferring crew between shore and offshore wind parks located between Belgium and the East of England. In Table 2-1 the main particulars of the vessel are presented, and a photo of the Hydrocat 48 is shown in Figure 2-1. The vessel is powered by two MAN D2862 LE428 engines which were modified to run either on diesel or on a combination of diesel and hydrogen (dual fuel).

Table 2-1: Main particulars of the Hydrocat 48.

Ship type	**Crew transfer vessel**	
Classification	Lloyd's ✠ 100A1 SSC, HSC, Catamaran, Wind Farm Service Vessel	
Propulsion type	Direct	
Engine type	2 x MAN D2862 Dual-fuel (hydrogen – diesel)	
Length over all	25.00	m
Beam, moulded	7.30	m
Operational draught	1.90	m
Service speed	26	kn
Max. speed	28	kn
Engine power	2 x 749	kW
Propeller type	Controllable Pitch Propeller (CPP)	

Figure 2-1: Photo of the Hydrocat 48 (Demo 1).

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

2.1 Route and operation

The operation of the vessel assumed for the voyage simulations is as follows:

1. Engineers embark at the homeport in the morning
2. Ship departs the homeport towards the offshore wind park at its service speed over ground of 26 kn. The voyage takes approximately 1 h and 10 min.
3. Vessel arrives at the wind park and engineers exit the boat. While engineers are working on the maintenance of the wind turbines, the vessel remains connected to a windmill in order to minimize propulsion and fuel consumption.
4. After approximately 6 h of work, the engineers are embarked again and the ship sails back to its homeport at the service speed
5. After approximately 1 h and 10 min sailing at the service speed, the vessel arrives at Oostende, where engineers disembark. After this the vessel remains at quay until next day.

In Figure 2-2 the route sailed is presented on a map. The same route has been used for both legs, assuming the ship would sail the same (or very similar) route when sailing towards and back from the wind park.

Table 2-2 shows a summary of the operation assumed for the voyage simulations of Demo 1. Each day the ship sails one trip starting at 8:00 in the morning. Each trip consists of two legs: the departure towards the wind park and the return to the homeport. Between the two legs, there is a time difference of 6 hours to account for the time dedicated to the maintenance of the wind turbines. The ship performs this operation all days of the week except in the weekend.

Table 2-2: Overview of a trip assumed for the voyage simulations for Demo 1.

	Distance	Time	SOG		
	km	h	km/h	m/s	kn
Departure Oostende					
Sailing leg 1 (towards wind farm)	57.80	1.20	48.15	13.37	26.00
Wind farm maintenance		6	0	0	0
Sailing leg 2 (return from wind farm)	57.80	1.20	48.15	13.37	26.00
Arrival Oostende					

Figure 2-2: Route sailed during the voyage simulations for Demo 1.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

2.2 Environmental data

To assess the influence of the weather in the power demand and hence on the fuel consumption, time-dependant environmental data was used during the simulations, obtained from the atmospheric reanalysis ERA5.

During the simulations the service speed over ground was kept as target and the engine power is an output. The vessel sails at the target speed, and the corresponding shaft power depends on the environmental conditions (e.g., current, waves, etc.).

2.3 Results

To build sufficient statistical data, voyage simulations were conducted for a period of several years, namely between 2021 and 2023. Every day the ship sailed a trip consisting of the route described in section 2.1.

The results of the voyage simulations provide values of environmental parameters (significant wave height, wave direction, wind speed and direction, current speed and direction, etc.), and propulsion parameters (propeller rpm, shaft power, etc.) as function of time, as presented in Figure 2-3 and Figure 2-4. Time is defined as date and time. For each time step, environmental conditions are defined based on the data from the environmental databases as described in section 2.2. These environmental conditions are used to calculate the added resistance in waves or in shallow water, the windage and the influence of the current on the resistance, among others.

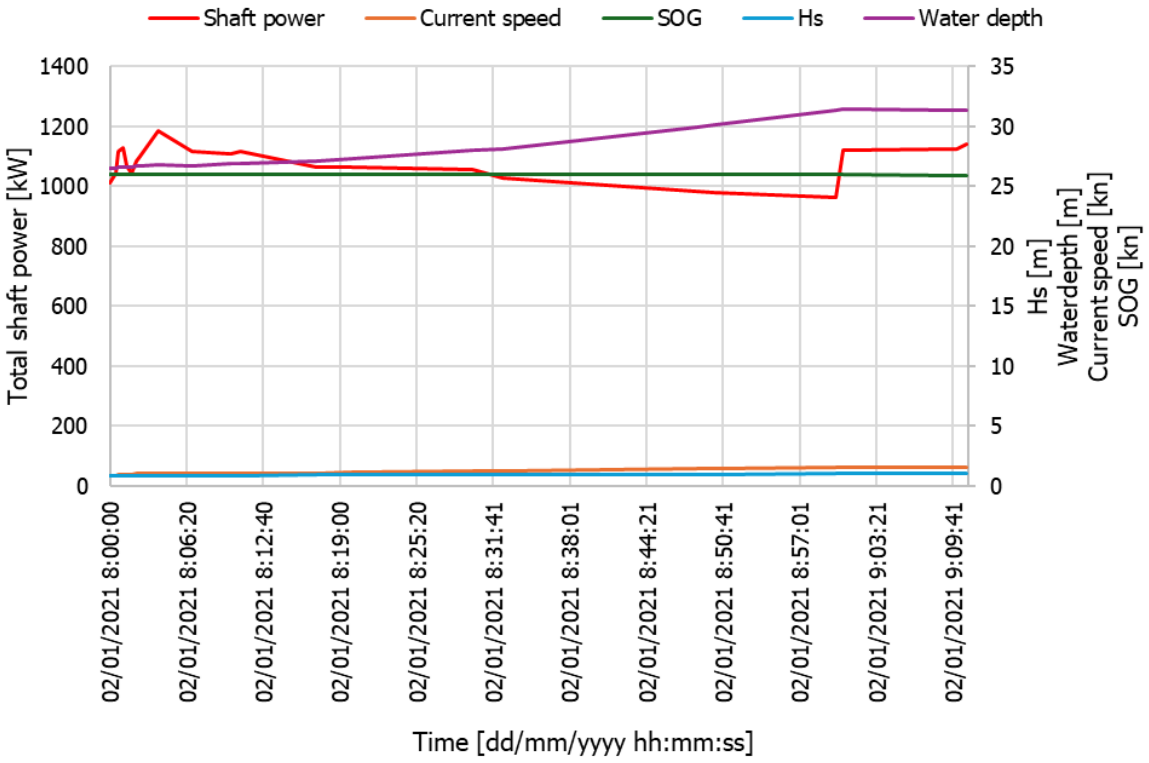

Figure 2-3: Example of output from the voyage simulations of Demo 1 when sailing leg 1.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

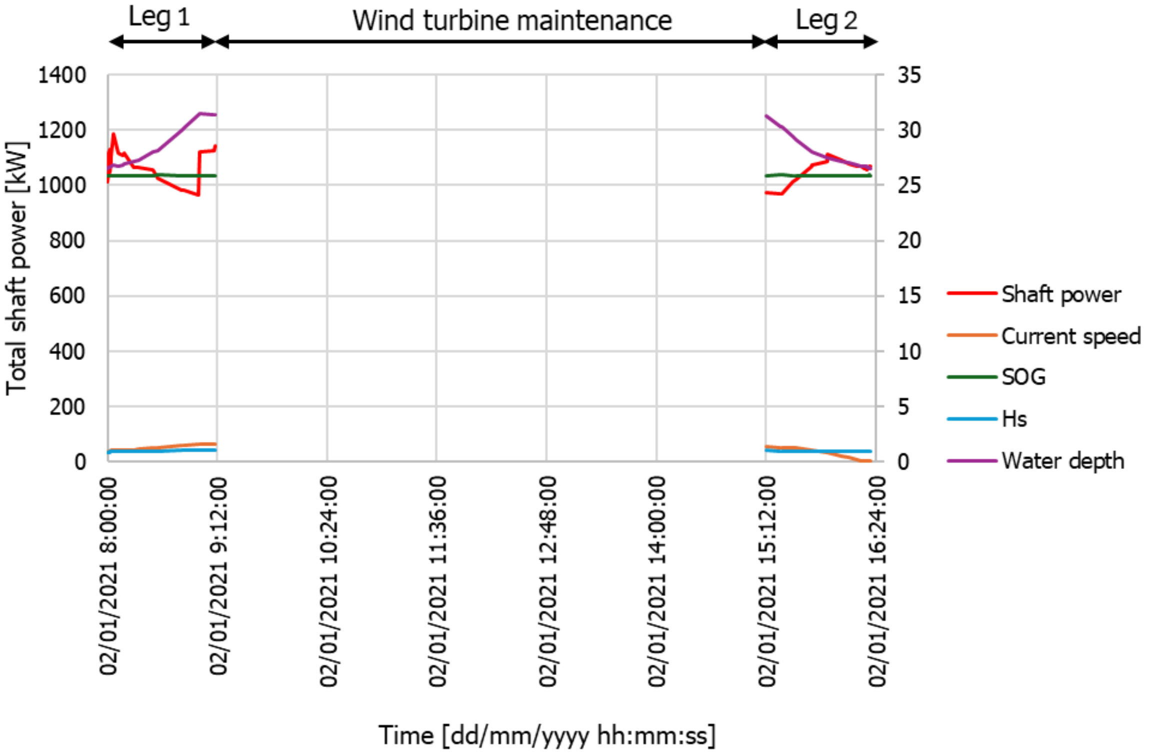

Figure 2-4: Example of output from the voyage simulations of Demo 1 when sailing a whole trip.

In addition, as the required engine brake power is known for each time step, the corresponding fuel consumption is calculated using a mathematical model of the engines. The fuel consumption is converted into energy and then into Tank-To-Wake (TTW) CO2 equivalent emissions using a TTW conversion factor. Similarly, a conversion factor is used to calculate the Well-To-Tank (WTT) CO2eq emissions. In Table 2-3, Table 2-4, Table 2-5 the conversion factors used for this demo are listed, which were taken from deliverable D1.2 [3]. These values correspond to the best guess scenario H1/31.

Table 2-3: Well-To-Tank (WTT) and Tank-To-Wake (TTW) emission factors for the CO2eq emissions used for Demo 1.

	Pathway	WTT		TTW	
		gCO2eq/kWh	gCO2eq/MJ	gCO2eq/kWh	gCO2eq/MJ
Diesel (EN590)		84.00	23.33	266.00	73.89
e-Hydrogen	H1/31	20.00	5.56	0.00	0.00

Table 2-4: Well-To-Tank (WTT) and Tank-To-Wake (TTW) emission factors for the NOx emissions used for Demo 1.

	Pathway	WTT		TTW	
		gNOx/kWh	gNOx/MJ	gNOx/kWh	gNOx/MJ
Diesel (EN590)		0.10	0.03	3.91	1.09
e-Hydrogen	H1/31	0.06	0.02	1.53	0.43

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 2-5: Well-To-Tank (WTT) and Tank-To-Wake (TTW) emission factors for the PM10 emissions used for Demo 1.

	Pathway	WTT		TTW	
		gPM10/kWh	gPM10/MJ	gPM10/kWh	gPM10/MJ
Diesel (EN590)		0.00	0.00	0.08	0.02
e-Hydrogen	H1/31	0.18	0.05	0.04	0.01

For this demo, the following concepts were compared:

1. **Diesel (EN590) CI ICE [Diesel (EN590)]**: Diesel direct propulsion with compression-ignited engines. This concept was selected as reference benchmark as this is currently the most implemented concept on this type of ship.

2. **e-H2 350b/Dsl 78/22%energy CI ICE [Diesel (EN590) + e-Hydrogen (H1/31)]:** Diesel direct propulsion with compression-ignited dual fuel engines using 78/22% energy blend. Compressed hydrogen at 350 bar, generated using electricity from renewable source. This concept represents the retrofitted vessel, which has direct propulsion as well, but with dual fuel (hydrogen-diesel) engines.

The results from the voyage simulations for Demo1 are presented in Table 2-6, and in graphical form in Figure 2-5, Figure 2-6, and Figure 2-7. In addition, in Table 2-7 the average annual emissions are presented. The following section contains the conclusions derived from the results.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 2-6: Results summary of the voyage simulations for Demo 1.

Concept	**Parameter**	**Unit**	**Year**		
			2021	**2022**	**2023**
Diesel (EN590)	Fuel consumed	t	117.93	118.36	117.38
		m3	137.13	137.62	136.49
	CO2 emissions (T2W)	tCO2eq	378.09	379.45	376.33
	CO2 emissions (W2T)	tCO2eq	117.48	117.91	116.94
	Total CO2 emissions (WTW)	**tCO2eq**	**495.57**	**497.35**	**493.27**
	NOx emissions (T2W)	tNOx	5.49	5.51	5.46
	NOx emissions (W2T)	tNOx	0.15	0.15	0.15
	Total NOx emissions (WTW)	**tNOx**	**5.64**	**5.66**	**5.61**
	PM10 emissions (T2W)	kgPM10	110.79	111.18	110.27
	PM10 emissions (W2T)	kgPM10	5.04	5.05	5.01
	Total PM10 emissions (WTW)	**kgPM10**	**115.82**	**116.24**	**115.28**
Diesel (EN590) + e-Hydrogen (H1/31)	Fuel consumed Diesel	t	82.81	83.15	82.44
		m3	0.10	0.10	0.10
	Fuel consumed H2	t	15.37	15.40	15.28
		m3	0.17	0.17	0.17
	CO2eq emissions (TTW) - Diesel	tCO2eq	261.28	262.33	260.09
	CO2eq emissions (TTW) - H2	tCO2eq	0.00	0.00	0.00
	CO2eq emissions (TTW) - Total	tCO2eq	261.28	262.33	260.09
	CO2eq emissions (WTT) - Diesel	tCO2eq	82.50	82.83	82.12
	CO2eq emissions (WTT) - H2	tCO2eq	10.25	10.28	10.19
	CO2eq emissions (WTT) - Total	tCO2eq	92.75	93.11	92.32
	Total CO2eq emissions (WTW)	**tCO2eq**	**354.03**	**355.44**	**352.41**
	NOx emissions (TTW) - Diesel	tNOx	3.85	3.87	3.84
	NOx emissions (TTW) - H2	tNOx	0.79	0.79	0.79
	NOx emissions (TTW) - Total	**tNOx**	**4.65**	**4.66**	**4.63**
	NOx emissions (WTT) - Diesel	tNOx	0.11	0.11	0.11
	NOx emissions (WTT) - H2	tNOx	0.04	0.04	0.04
	NOx emissions (WTT) - Total	tNOx	0.14	0.14	0.14
	Total NOx emissions (WTW)	**tNOx**	**4.79**	**4.81**	**4.77**
	PM10 emissions (TTW) - Diesel	kgPM10	77.79	78.11	77.44
	PM10 emissions (TTW) - H2	kgPM10	20.28	20.33	20.17
	PM10 emissions (TTW) - Total	kgPM10	98.08	98.44	97.61
	PM10 emissions (WTT) - Diesel	kgPM10	3.54	3.55	3.52
	PM10 emissions (WTT) - H2	kgPM10	92.19	92.42	91.67
	PM10 emissions (WTT) - Total	kgPM10	95.73	95.97	95.19
	Total PM10 emissions (WTW)	**kgPM10**	**193.80**	**194.41**	**192.80**

Table 2-7: Comparison of annual emissions between the reference diesel direct concept and the vessel for Demo 1 retrofitted with dual-fuel hydrogen engines. Figures are the average values for the 3 year voyage simulations.

Parameter	**Unit**	**Diesel (EN590)**		**Diesel (EN590) + e-Hydrogen (H1/31)**	
Fuel consumed (diesel)	t	117.89	100%	82.80	70.2%
	m3	137.08	100%	0.10	0.1%
Fuel consumed (hydrogen)	t	n/a	n/a	15.35	n/a
	m3	n/a	n/a	0.17	n/a
CO2eq emissions (T2W)	tCO2eq	377.96	100%	261.23	69.1%
CO2eq emissions (W2T)	tCO2eq	117.44	100%	92.72	79.0%
Total CO2eq emissions (WTW)	**tCO2eq**	**495.40**	**100%**	**353.96**	**71.4%**
NOx emissions (TTW)	tNOx	5.49	100%	4.65	84.7%
NOx emissions (WTT)	tNOx	0.15	100%	0.14	94.6%
Total NOx emissions (WTW)	**tNOx**	**5.64**	**100%**	**4.79**	**84.9%**
PM10 emissions (TTW)	kgPM10	110.75	100%	98.04	88.5%
PM10 emissions (WTT)	kgPM10	5.03	100%	95.63	1899.7%
Total PM10 emissions (WTW)	**kgPM10**	**115.78**	**100%**	**193.67**	**167.3%**

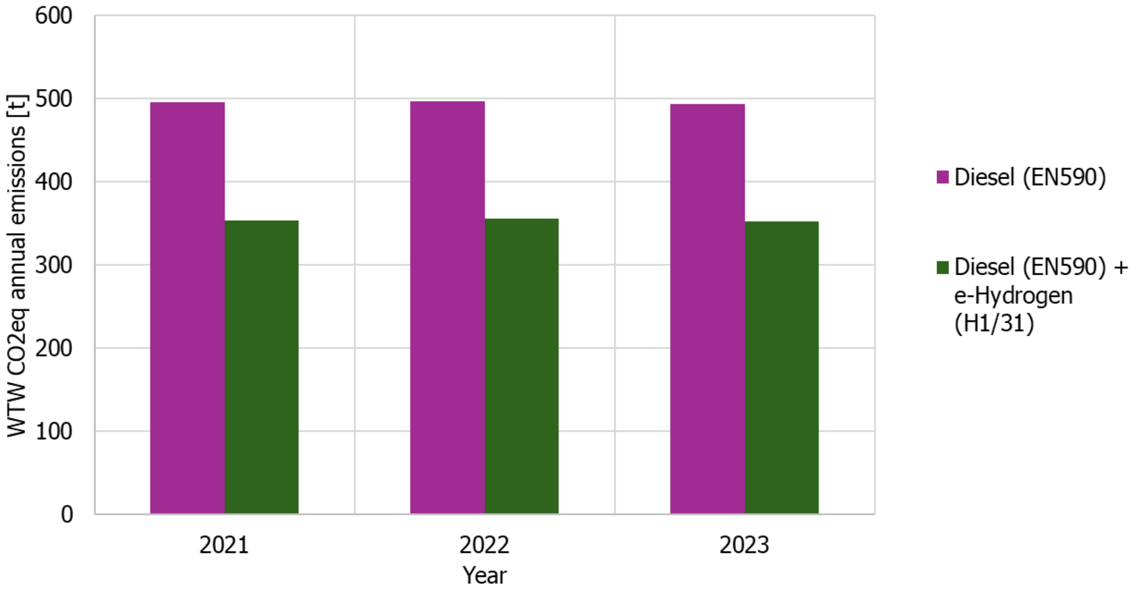

Figure 2-5: Annual Well-To-Wake (WTW) CO2eq emissions for the reference diesel concept and the retrofitted vessel with dual fuel engines (Demo 1).

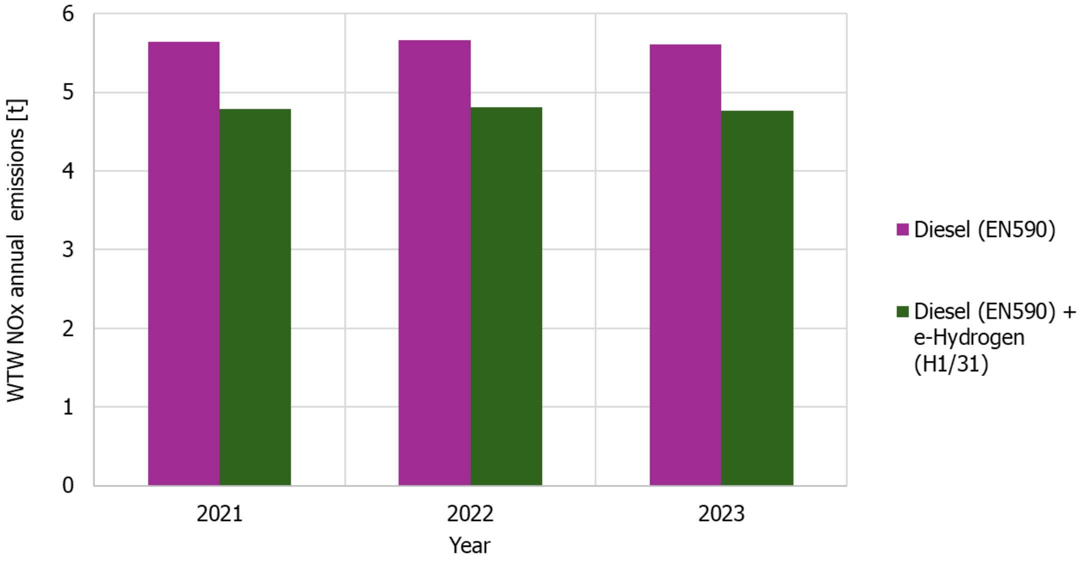

Figure 2-6: Annual Well-To-Wake (WTW) NOx emissions for the reference diesel concept and the retrofitted vessel with dual fuel engines (Demo 1).

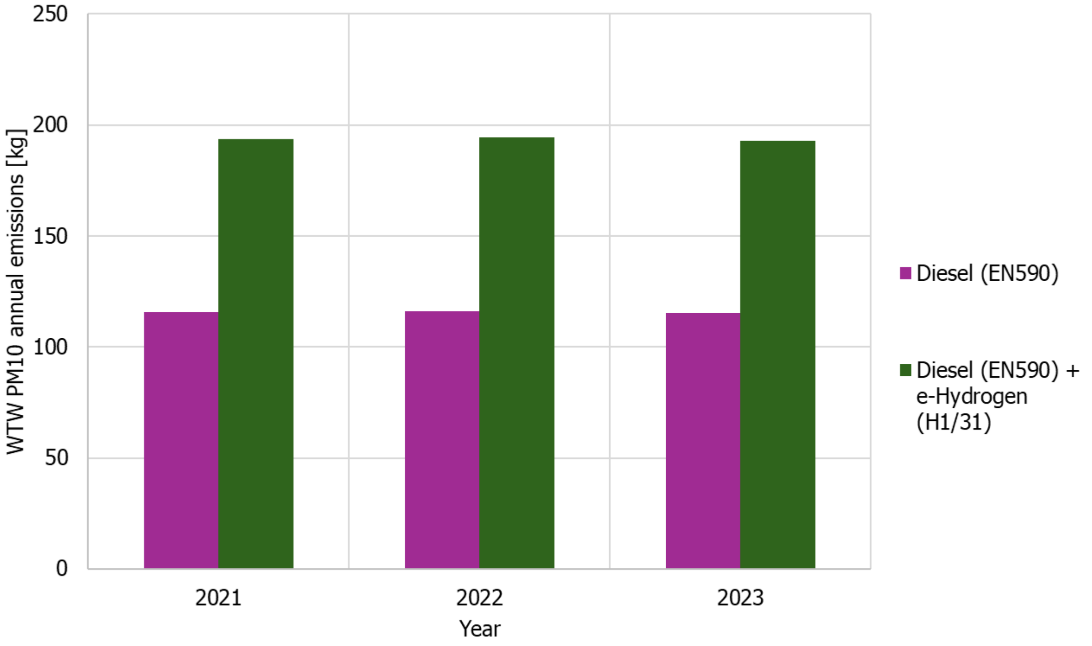

Figure 2-7: Annual Well-To-Wake (WTW) PM10 emissions for the reference diesel concept and the retrofitted vessel with dual fuel engines (Demo 1).

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

2.4 Conclusions from Demo 1

Based on the results of the voyage simulations conducted for Demo 1 summarised in Table 2-7, the following conclusions are derived:

- The retrofitted vessel (Concept e-H2 350b/Dsl 78/22%energy CI ICE), which consists of diesel direct propulsion system using hydrogen as main energy carrier gives a reduction in Well-To-Wake CO2eq emissions of approximately 30% with respect to the reference concept Diesel (EN590) CI ICE. This is a significant reduction in GHG emissions, close to the 35% target for 2035 as defined in CCNR [1].

- The retrofitted vessel (Concept e-H2 350b/Dsl 78/22%energy CI ICE), which consists of diesel direct propulsion system using hydrogen as main energy carrier results in a reduction in Well-To-Wake NOx emissions of approximately 15% with respect to the reference concept Diesel (EN590) CI ICE.

- The retrofitted vessel (Concept e-H2 350b/Dsl 78/22%energy CI ICE), which consists of diesel direct propulsion system using hydrogen as main energy carrier reduces the Tank-To-Wake particulate matter emissions about 12% compared to the reference concept Diesel (EN590) CI ICE. However, due to the high Well-To-Tank emission factor of this fuel pathway, the Well-To-Wake particulate matter emissions increase about 67% compared to the reference concept Diesel (EN590) CI ICE.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

3. Voyage simulations for Demo 3

The Alphenaar is an inland container vessel that transports containerised cargo between the Dutch towns of Alphen aan den Rijn and Moerdijk.

3.1 Route and operation

The Alphenaar sails most of its time a fixed route between Alphen aan den Rijn and Moerdijk, located from each other at a sailing distance of 63 km. Thus, the total distance sailed in a round trip is 126 km. In Figure 3-1 the route of the Alphenaar can be seen on a map. Consequently, only the following route has been used for the operational analysis of this vessel:

Alphen aan de Rijn → Moerdijk (typical route). The ship departs fully loaded at design draft from Alphen aan den Rijn and then discharges the full containers at Moerdijk. Here, the ship is loaded with other containers, and then sails back to Alphen aan de Rijn. Once the ship arrives at Alphen an de Rijn, the containers are unloaded and the ship is loaded again with new containers.

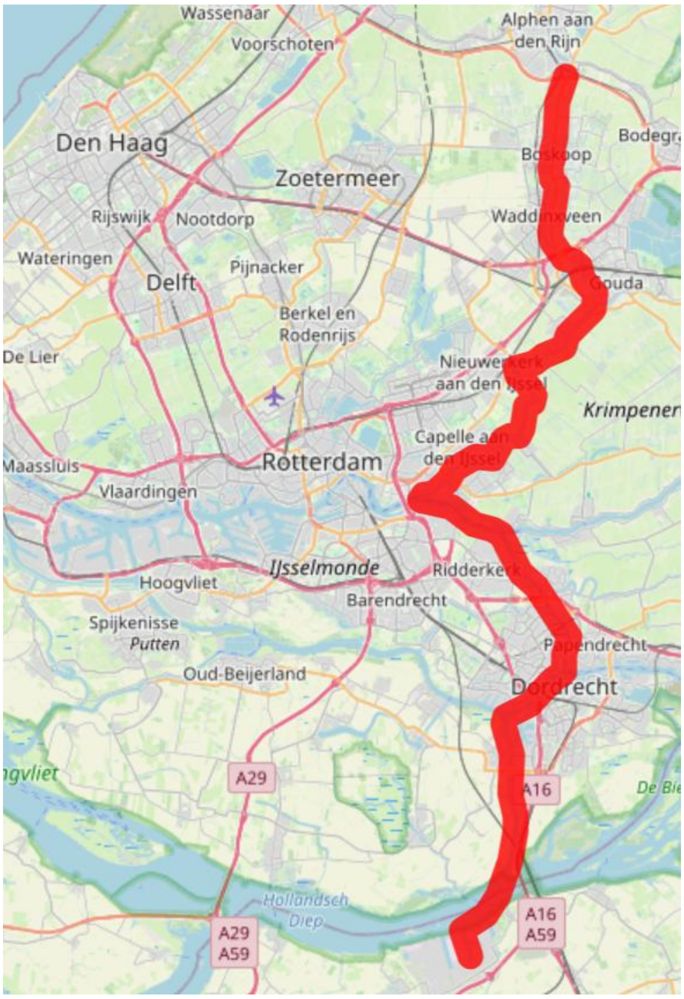

Figure 3-1 Route of the Alphenaar shown on a map.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Zero Emission Shipping (ZES) shared the following speed over ground profiles related to four different days of operations:

- Day 1: 5th of January 2024, profile duration: 13.1 hours (Figure 3-2)
- Day 2: 15th April 2024, profile duration: 11.5 hours (Figure 3-3)
- Day 3: 28th June 2024, profile duration: 12.5 hours (Figure 3-4)
- Day 4: 24th April 2024, profile duration: 12.7 hours (Figure 3-5)

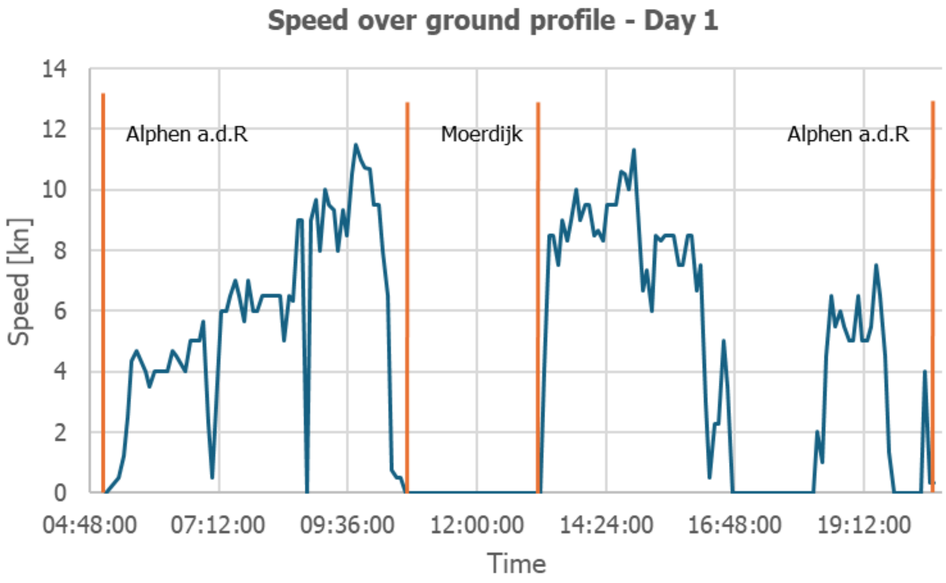

Figure 3-2: Alphenaar speed profile, Day 1

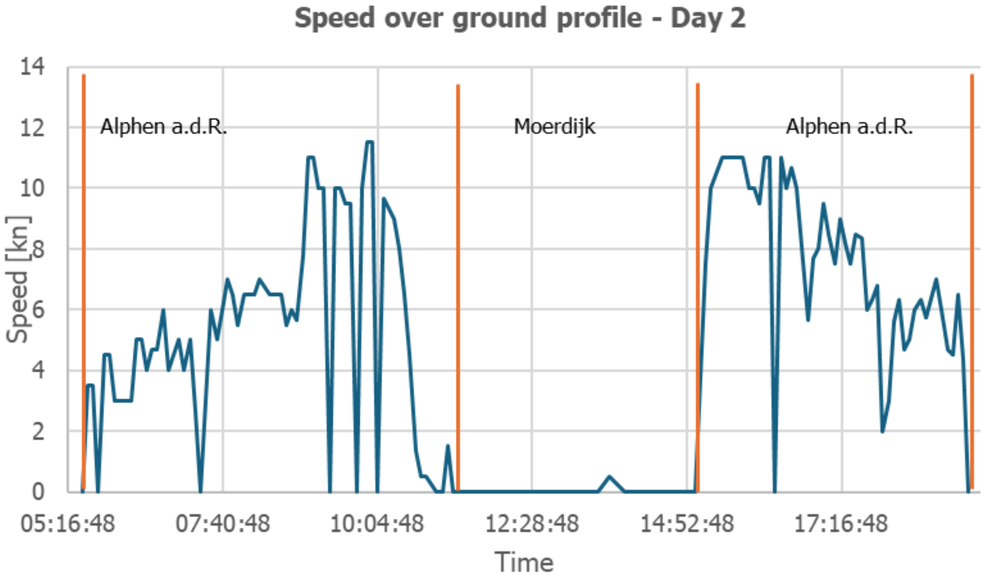

Figure 3-3: Alphenaar speed profile, Day 2

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

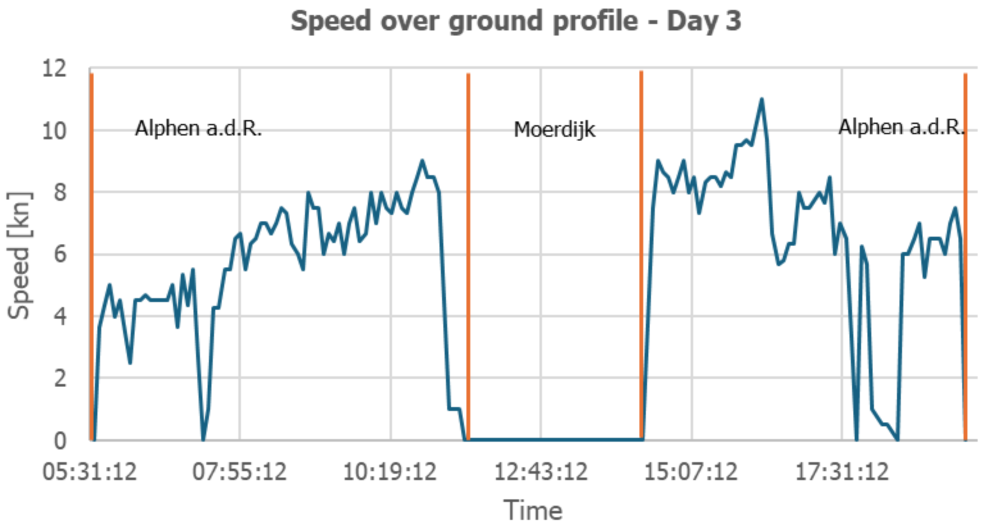

Figure 3-4: Alphenaar speed profile, Day 3

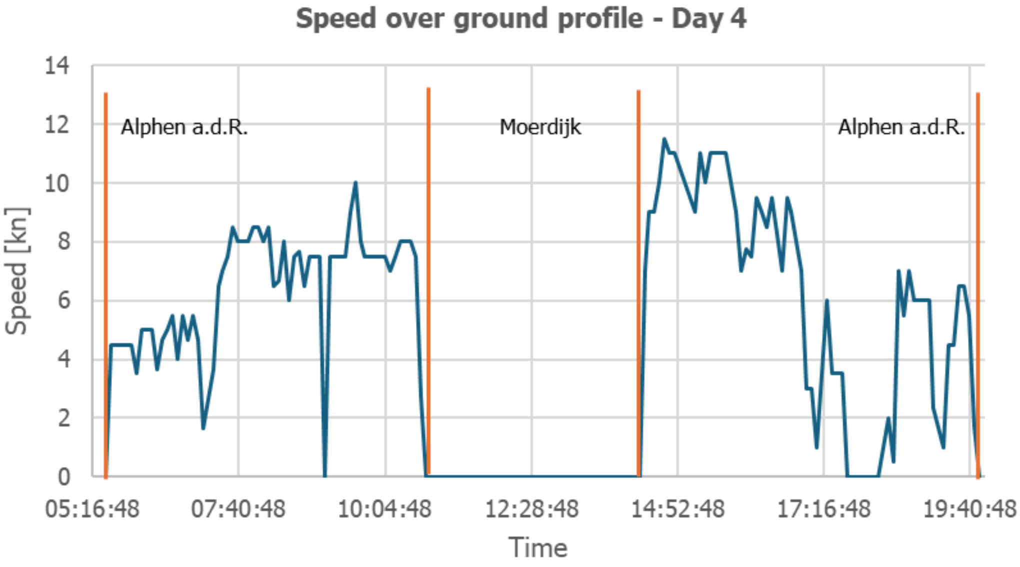

Figure 3-5 Alphenaar speed profile, Day 4

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

3.2 Calculations and architectures set up

No river data was available for this area of operations. An average river depth of 5.5 m was used to calculate the speed power prediction. The speed power prediction was based on an inland vessel with the same characteristics as the reference ship, and was obtained through the combined use of CFD and statistical comparison with similar vessels. Figure 3-6 shows the speed power curve obtained for Demo 3. Despite the typical operation of the Alphenaar does not imply a large change in draught, small variations in power demand due to small change in draught were calculated using the Admiralty coefficient.

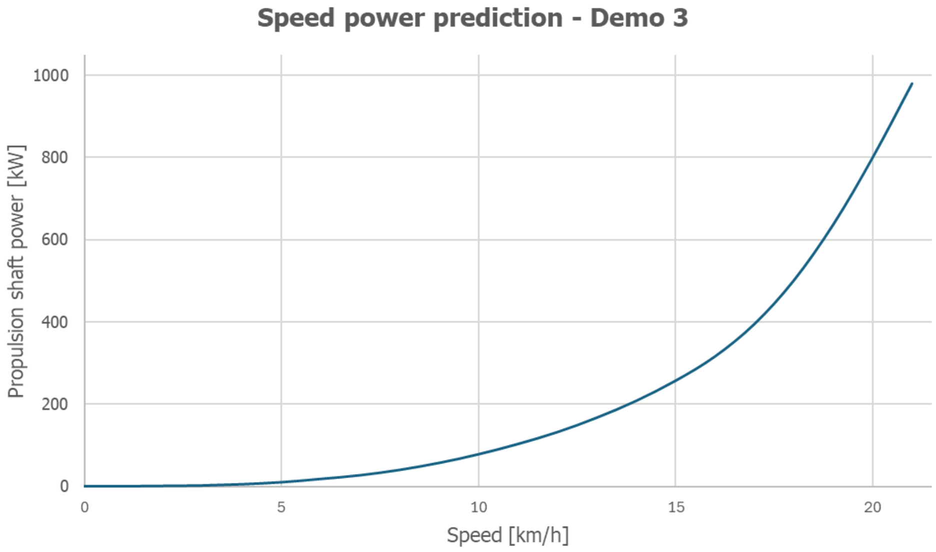

Figure 3-6: Speed power prediction for design draught of Demo 3

The maximum speed over ground reached during the voyages presented in Section 3.1 is equal to 11.5 kn (21.3 km/h), for which total shaft propulsion power of 1040 kW is requested.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

The speed power curve was used to build up the propulsion power profiles starting from the speed profiles showed in Section 3.1. The propulsion power profiles are presented in Figure 3-7, Figure 3-8, Figure 3-9 and Figure 3-10.

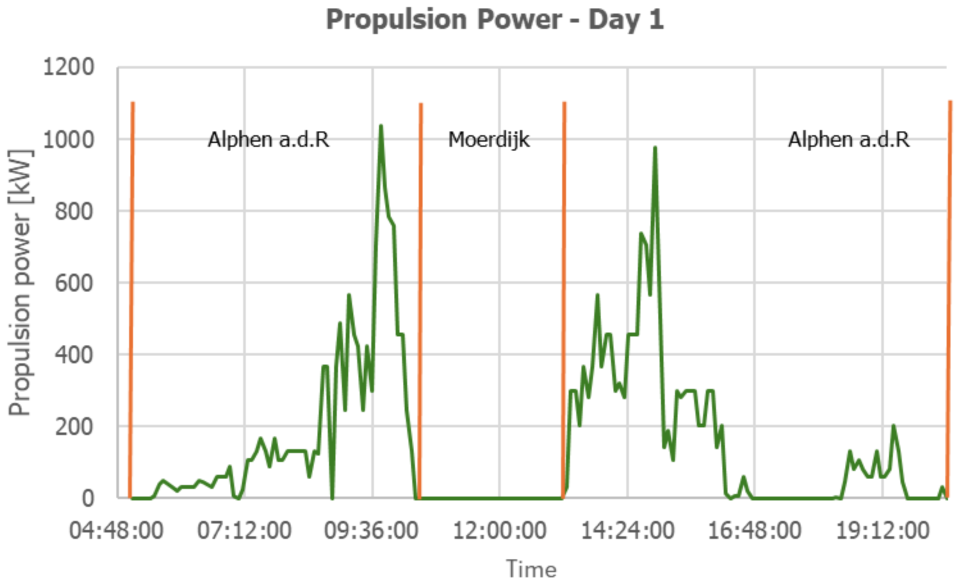

Figure 3-7: Alphenaar propulsion power profile, Day 1

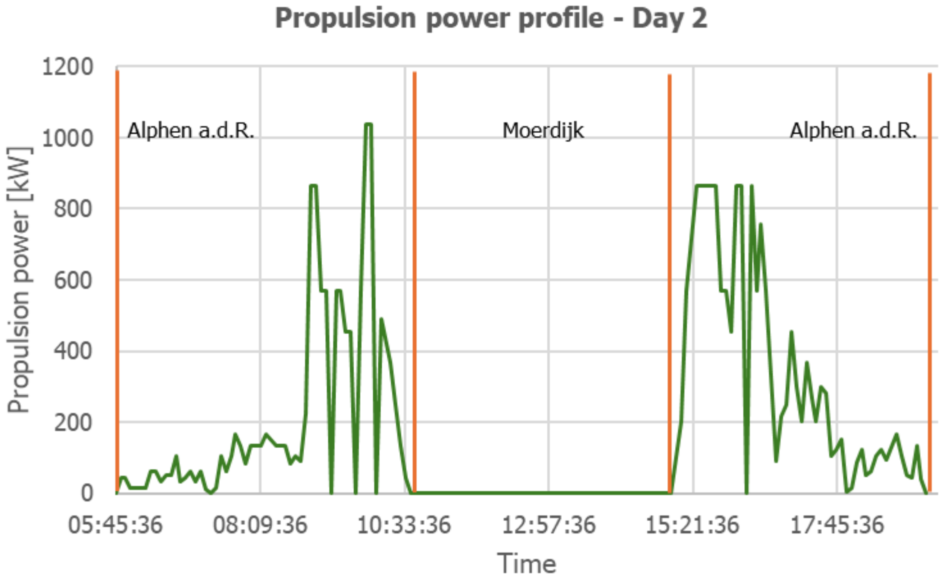

Figure 3-8: Alphenaar propulsion power profile, Day 2

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

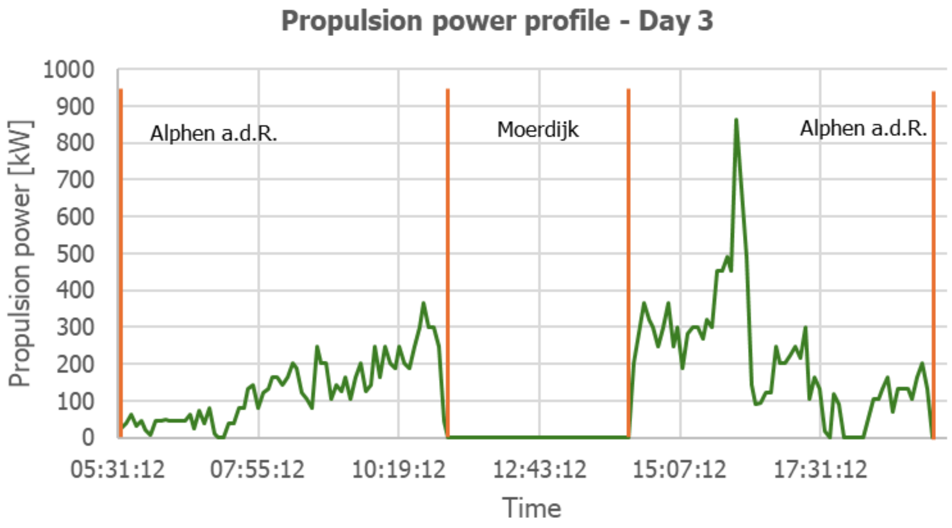

Figure 3-9: Alphenaar propulsion power profile, Day 3

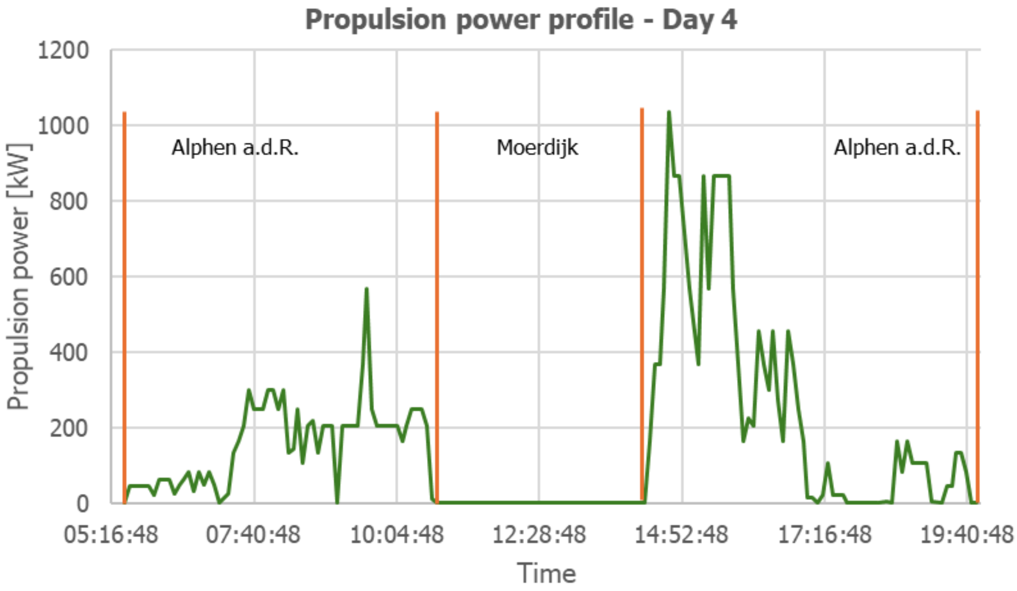

Figure 3-10: Alphenaar propulsion power profile, Day 4

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

To evaluate the emission performance of the ZES solution, a comparison was made with a diesel electric architecture. Figure 3-11 and Figure 3-12 show the two architectures evaluated along the speed profiles presented in Section 3.1.

Battery electric architecture

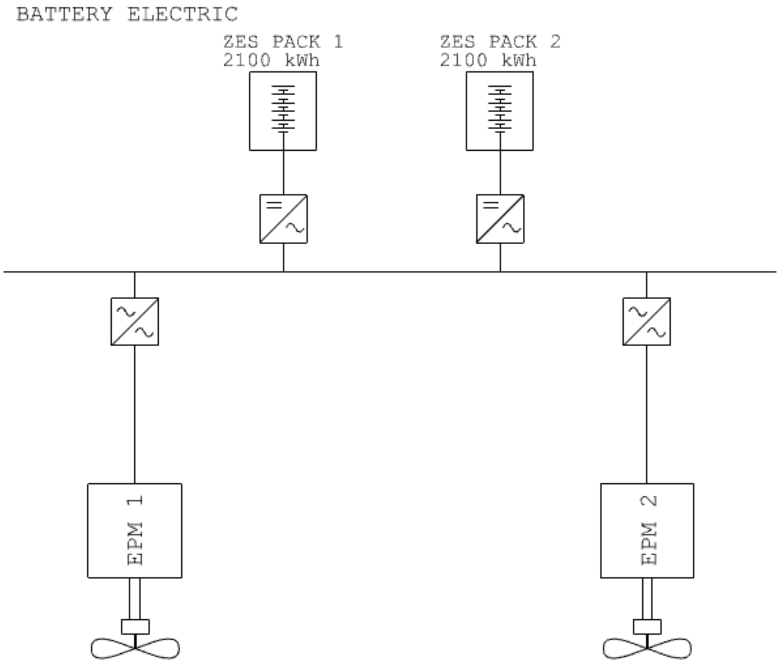

Figure 3-11: Battery electric architecture

The battery electric architecture consists of two electric motors powered by the ZES battery packs.

The following efficiencies were used to calculate the energy requested to the battery system:

- From shaft power to (and including) electrical distribution: 0.91
- Battery internal efficiency plus battery converter efficiency: 0.92

In addition to the propulsion power, an auxiliary load of 22.2 kW was added, which was obtained from the operational data shared by ZES.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Diesel electric architecture

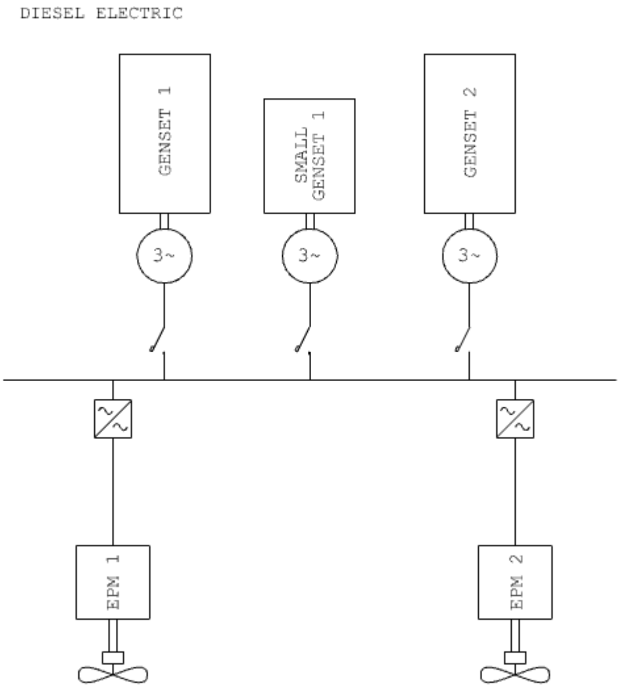

Figure 3-12: Diesel electric architecture

The diesel-electric architecture was used as a reference to compare the emission savings achievable with the battery-electric architecture and it is made by two electric propulsion motors powered by a set of generators.

The number of gensets and their nominal power were determined based on the power profiles, as defined above (Figure 3-7, Figure 3-8, Figure 3-9 and Figure 3-10), and the maximum requested brake power (1200 kW). This led to two gensets of equal power (600 kW) and a small genset (50 kW) for lower loads.

The following efficiencies were used to calculate the power requested from the gensets:

- From shaft power to (and including) electrical distribution: 0.91
- Generator efficiency: 0.95

On top of the propulsion power an auxiliary load of 22.2 kW was added, which was obtained from the data shared by ZES.

Different power sources were allocated depending on the requested power load, specifically:

- Small genset on only (for power loads lower or equal to 50 kW);
- One main genset on only (for power loads between 50 kW and 600 kW);
- Both main gensets on (for power loads above 600 kW).

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 3-1, Table 3-2 and Table 3-3 show the emissions and pollutants factors that were used in the analysis. These factors were taken from deliverable D1.2 of this project.

Table 3-1: CO2 equivalent emissions factors used in the analysis of Demo 3.

	Pathway	WTT		TTW	
		gCO2eq/kWh	gCO2eq/MJ	gCO2eq/kWh	gCO2eq/MJ
Diesel (EN590)		84.00	23.33	266.00	73.89
electricity	E1/21	25.00	6.94	0.00	0.00

Table 3-2: NOx emissions factors used in the analysis of Demo 3.

	Pathway	WTT		TTW	
		gNOx/kWh	gNOx/MJ	gNOx/kWh	gNOx/MJ
Diesel (EN590)		0.10	0.03	3.91	1.09
electricity	E1/21	0.05	0.01	0.00	0.00

Table 3-3: PM10 emissions factors used in the analysis of Demo 3.

	Pathway	WTT		TTW	
		gPM10/kWh	gPM10/MJ	gPM10/kWh	gPM10/MJ
Diesel (EN590)		0.00	0.00	0.08	0.02
electricity	E1/21	0.02	0.01	0.00	0.00

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

3.3 Results

The results from the voyage simulations are presented in Table 3-4 and graphically in Figure 3-13, Figure 3-14 and Figure 3-15. The fuel consumption of the generator was calculated using an efficiency map of an engine running at 1500 rpm (50 Hz electrical distribution).

Table 3-4: Results of the voyage simulations of Demo 3.

	Unit	**Trip 1**	**Trip 2**	**Trip 3**	**Trip 4**	**Average**
Voyage duration	h	13.1	11.5	12.5	12.7	12.4
Tot. fuel cons.	kg	605	617	521	590	583
Tot. energy in	MJ	25835	26366	22258	25197	24914
EN590 TTW CO2$_{eq}$ emissions	kgCO2$_{eq}$	1909	1948	1645	1862	1841
EN590 WTT CO2$_{eq}$ emissions	kgCO2$_{eq}$	602	614	519	587	581
EN590 WTW CO2$_{eq}$ emissions	**kgCO2$_{eq}$**	**2511**	**2563**	**2163**	**2449**	**2422**
	tCO2$_{eq}$	2.5	2.6	2.2	2.4	2.4
EN590 WTT NO$_x$ emissions	kgNO$_x$	0.7	0.7	0.6	0.7	0.7
EN590 TTW No$_x$ emissions	kgNO$_x$	28.1	28.6	24.2	27.4	27.1
EN590 WTW NO$_x$ emissions	**kgNO$_x$**	**28.8**	**29.4**	**24.8**	**28.1**	**27.8**
EN590 WTT PM10 emissions	kgPM10	0.02	0.02	0.02	0.02	0.02
EN590 TTW PM10 emissions	kgPM10	0.57	0.59	0.49	0.56	0.55
EN590 WTW PM10 emissions	**kgPM10**	**0.60**	**0.61**	**0.51**	**0.58**	**0.57**
Energy from the battery (voyage simulation)	**kWh**	**2809**	**2896**	**2337**	**2767**	**2702**
Electricity WTW CO2$_{eq}$ emissions	**kgCO2$_{eq}$**	**70.2**	**72.4**	**58.4**	**69.2**	**67.6**
Electricity WTW NO$_x$ emissions	**kgNO$_x$**	**0.14**	**0.14**	**0.12**	**0.14**	**0.14**
Electricity WTW PM10 emissions	**kgPM10**	**0.06**	**0.06**	**0.05**	**0.06**	**0.05**

In Table 3-5 a summary of the average values is presented, as well as relative comparison in emissions in form of percentage with respect to the reference diesel-electric architecture.

Table 3-5: Comparison of average emissions per round trip between the reference diesel electric concept Diesel (EN590) and the vessel for Demo 3 retrofitted with the battery electric (Electricity) concept.

Parameter	**Unit**	**Diesel (EN590)**		**Electricity**	
Fuel consumed	kg	583	100%	n/a	n/a
	m3	137.08	100%	n/a	n/a
CO2eq emissions (T2W)	kgCO2eq	1841	100%	0.0	0.0%
CO2eq emissions (W2T)	kgCO2eq	581	100%	67.6	11.6%
Total CO2eq emissions (WTW)	**kgCO2eq**	**2422**	**100%**	**67.6**	**2.8%**
NOx emissions (TTW)	kgNOx	0.7	100%	0.00	0.0%
NOx emissions (WTT)	kgNOx	27.1	100%	0.14	0.5%
Total NOx emissions (WTW)	**kgNOx**	**27.8**	**100%**	**0.14**	**0.5%**
PM10 emissions (TTW)	kgPM10	0.02	100%	0.00	0.0%
PM10 emissions (WTT)	kgPM10	0.55	100%	0.05	9.1%
Total PM10 emissions (WTW)	**kgPM10**	**0.57**	**100%**	**0.05**	**8.8%**

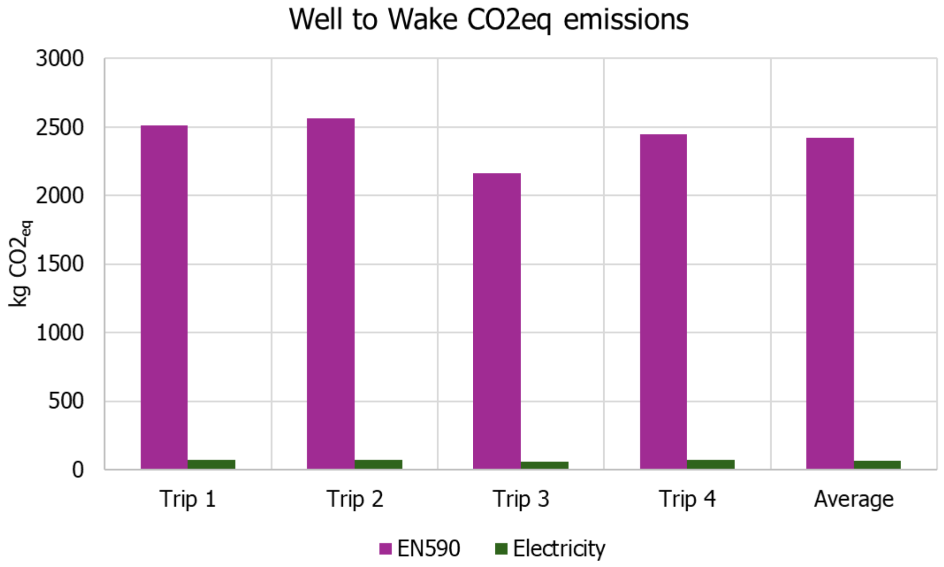

Figure 3-13: Well-To-Wake CO2eq emissions comparison between the reference diesel electric architecture (EN590) and the new battery electric one (electricity).

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

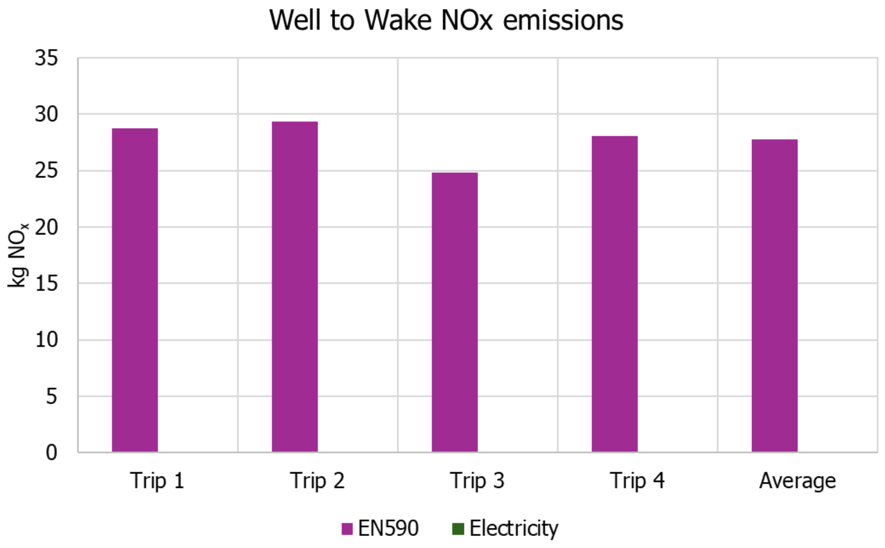

Figure 3-14: Well-To-Wake NOx emissions comparison between the reference diesel electric architecture (EN590) and the new battery electric one (electricity).

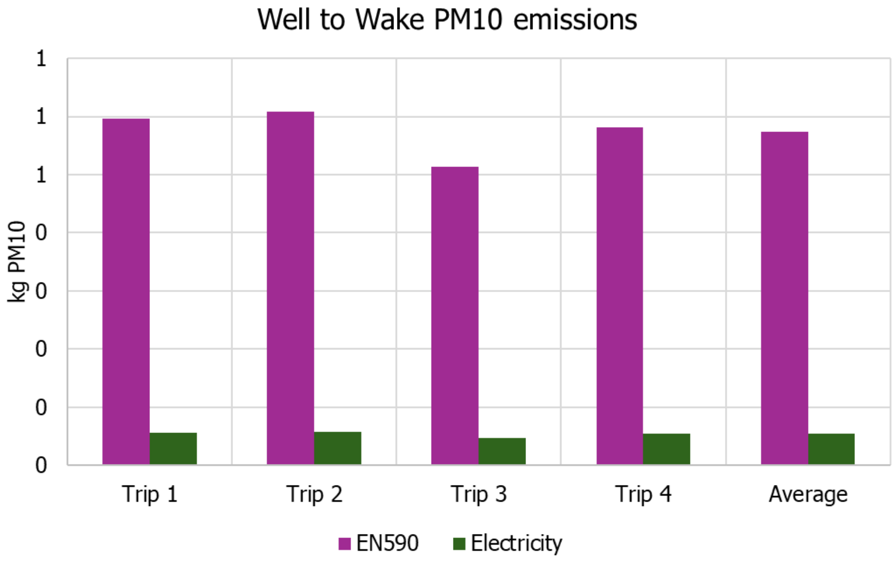

Figure 3-15 Well-To-Wake PM10 emissions comparison between the reference diesel electric architecture (EN590) and the new battery electric one (electricity).

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

3.4 Conclusions for Demo 3

Based on the results of the voyage simulations conducted for Demo 3, the following conclusions summarise the findings of this work:

- The installed battery capacity is sufficient to fulfil the operations identified by the speed profiles shared by ZES;
- The higher efficiency of the battery electric architecture implies a lower energy demand to fulfil the operational profile;
- The battery-electric architecture using electricity from the pathway E1/21 achieves a 97%, 99.5% and 91% reduction in of CO2eq, NOx and PM10 emissions, respectively. This makes this solution a nearly zero Well-To-Wake emission solution, and achieves amply the emission reduction targets for 2035 with 35% less GHG emissions, as defined in CCNR [1].

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

4. Voyage simulations for Demo 5

SYNERGETICS Demo 5 covers a case study on the potential of modernising inland waterway vessels by replacing the entire aft section. This measure can be used to optimise the hydrodynamic interaction of the hull, ducted propeller(s) and manoeuvring devices as well as the propulsion concept in the engine room. At the same time accommodation and wheelhouse are renewed while the cargo section remains the same. Two representative voyages, Figure 4-1, of the Ernst Kramer (dry cargo motor vessel - CEMT Class Va) demonstrator are selected for a detailed performance evaluation: the Rhine corridor between Mannheim and Amsterdam (572 km), and the canal route between Duisburg and Wolfsburg (367.5 km).

As outlined in Deliverable 3.15, Evaluation report aft-ship replacement: "Ernst Kramer", the new aft-ship geometry was developed by means of a parametric CFD optimization and validated in scale model tests. In addition, the analysis of engine load distributions (onboard measurements) revealed significant inefficiencies during low-power operation, particularly in canal navigation. This insight led to the layout of a "Father&Son" dual-engine configuration, in which a smaller auxiliary engine is employed for low-demand segments (e.g. canals), while the larger engine or both in parallel serve during high-load conditions such as upstream Rhine voyages. While Deliverable D3.15 provides an estimation of efficiency improvements based on real onboard measurements for individual journeys, the following analysis builds upon these results using the DST voyage simulation tool taking into account the variability of environmental boundary conditions.

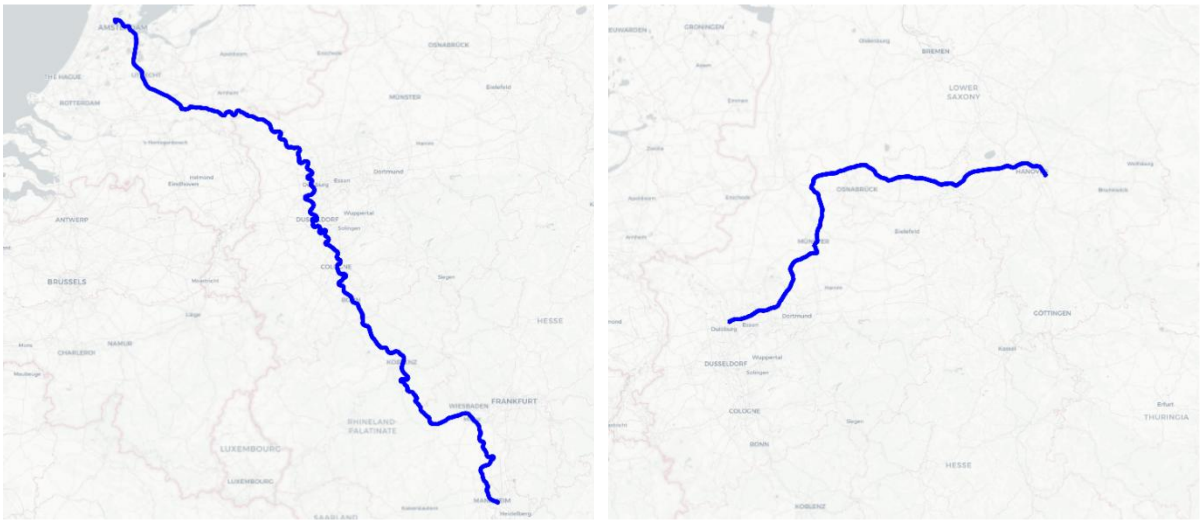

Figure 4-1: Routes on the Rhine (left) and the canals (right) of the Ernst Kramer.

Overall, the case study demonstrated that emission reduction targets for 2035 with 35% less GHG emissions, as defined in CCNR [1], can be achieved through conventional retrofitting measures, i.e. hydrodynamic optimization and new engine layout, while maintaining the proven concept of diesel combustion engines. This pathway offers a technically and economically viable means to green existing inland waterway vessels without requiring a transition to alternative fuels. The following sections present the simulation validation of these findings along the selected voyages.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

4.1 DST Voyage simulation tool Fluvial

Within the DST tool Fluvial, the characteristics of the ship and the behaviour of the boatmaster are modelled for daily upstream and downstream journeys. Temporally and spatially resolved hydrological data is available for the German Rhine. Simplified assumptions or averaged data is used for the Dutch waters. For the Ernst Kramer the results of the scale model tests were used to model the power demand of the original and the optimized hull in a range of water depths and loading conditions. Figure 4-2 shows the functional diagram of the simulation.

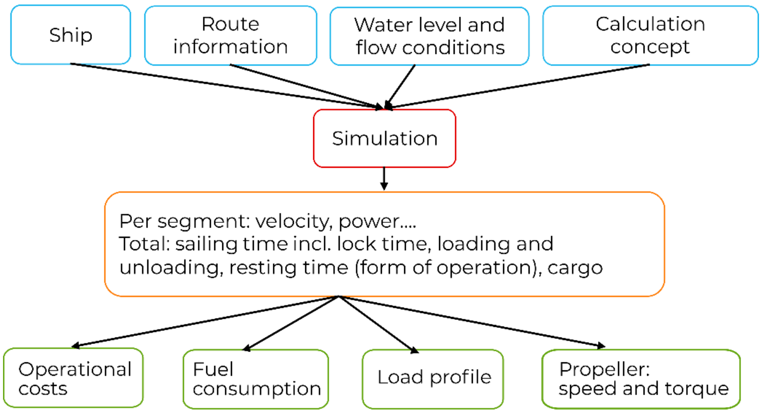

Figure 4-2: Schematic illustration of the software for determining load profiles. The input is in blue, the results in orange and the values for analysis in green.

Fluctuations in water levels over time not only have a significant impact on transport performance (maximum draught), but also on fuel consumption. Shallow water and strong currents lead to increased consumption. To capture realistic long-term effects, the simulation incorporates flow conditions spanning 27 years, enabling a representative average of varying hydrological scenarios. On the canal, the water levels are always the same due to the damming, and there is no current. However, the restricted waterway has a significant impact on the power demand. In the following Figure 4-3 the fluctuating water levels are shown with time series of the level gauge in Duisburg Ruhrort for a selection of four years. The water levels within a single year differ by as much as about 8 metres.

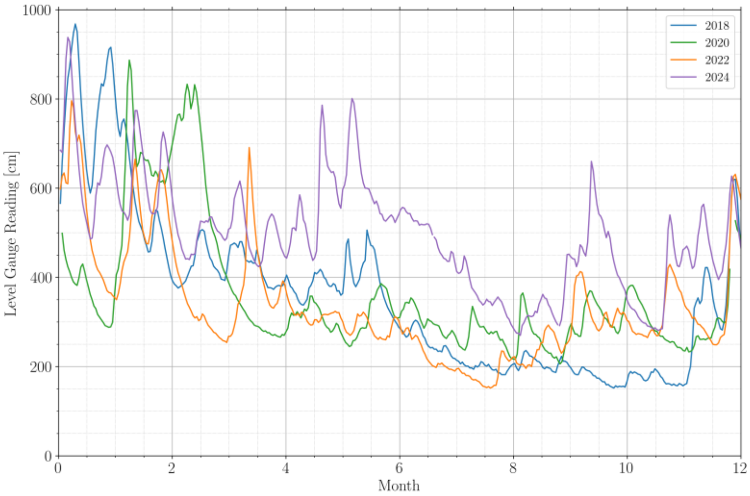

Figure 4-3: Example for fluctuating water levels on the Rhine at the level gauge Ruhrort. The year 2018 had exceptional low water levels.

4.2 Results of voyage simulation

The following Figure 4-4 and Figure 4-5 present a direct comparison of the main engine power demand for the original and optimized hull configurations during upstream and downstream voyages on the Rhine, as well as during a representative canal voyage. The impact of hull optimization on propulsion performance is clearly discernible across all scenarios, with consistently reduced power requirements observed for the optimized design.

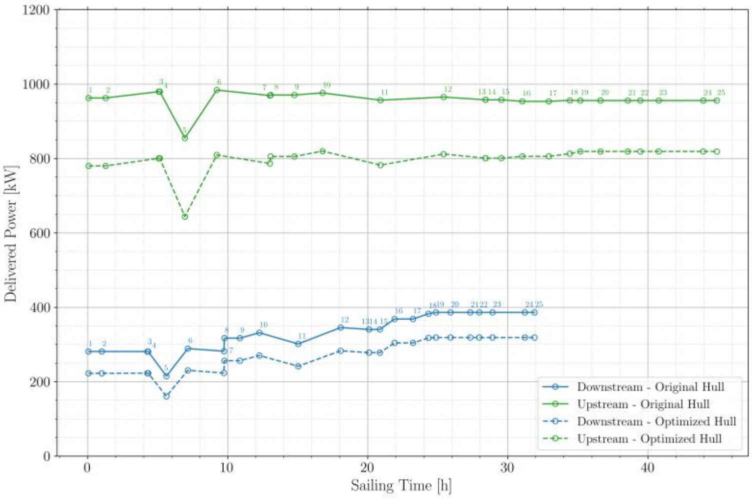

Figure 4-4: Comparison of power demand for the original and the optimized hull on the Rhine. The numbers on the curves correspond to individual river segments of the simulated voyage, as follows: (1) Mannheim - Mouth of the Neckar, (2) Mouth of the Neckar - Worms, (3) Worms - Mouth of the Main, (4) Mouth of the Main - Mainz, (5) Mainz - Bingen-Oestrich, (6) Bingen-Oestrich - Kaub, (7) Kaub - Koblenz, (8) Koblenz - Deutsches Eck, (9) Deutsches Eck - Andernach, (10) Andernach - Oberwinter, (11) Oberwinter - Cologne, (12) Cologne - Düsseldorf, (13) Düsseldorf - Ruhrort, (14) Ruhrort - Mouth of the RHK (Rhein-Herne Canal), (15) Mouth of the RHK - Rhine km Orsoy, (16) Rhine km Orsoy - Mouth of the WDK (Wesel-Datteln Canal), (17) Mouth of the WDK - Rees Gauge, (18) Rees Gauge -Border Gauge Strommitte, (19) Border Gauge Strommitte - Junction Neder Rijn, (20) Junction Neder Rijn - Merwede Canal, (21) Merwede Canal - Amsterdam-Rhine Canal, (22) Tiel - Wijk bij Duurstede, (23) Wijk bij Duurstede - Heemstede, (24) Heemstede - Zeeburg, and (25) Zeeburg - Western Port of Amsterdam.

For downstream navigation between Mannheim and Amsterdam, the average propulsion power of the original hull was calculated at 334.7 kW, whereas the optimized hull required only 272.2 kW, corresponding to an average reduction of 18.7%. The relative improvement varied across the 25 representative points, with reductions ranging between 17.0% and 25.2%.

In upstream conditions, the same retrofitting measures resulted in an average reduction of 16.6%, decreasing the required power from 958.3 kW (original) to 799.3 kW (optimized). The observed savings ranged from 14.3% to 24.7%, highlighting the effectiveness of the optimized aft-ship even under high-power-demand scenarios.

In contrast to river operations, canal navigation takes place under constant water levels and without current. The average propulsion power required by the original hull across all segments was 252.88 kW, while the optimized configuration required only 182.72 kW. This corresponds to an average power reduction of 27.5%, with recorded segmental savings ranging between 25.5% and 28.0%. These values represent the highest relative gains achieved across the evaluated scenarios.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

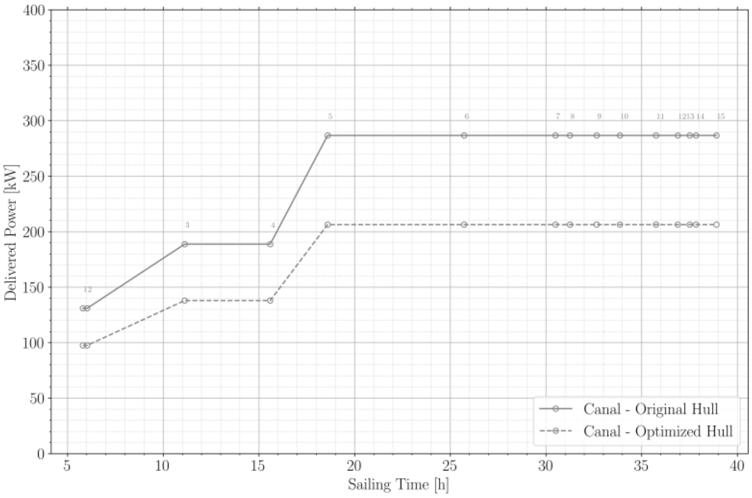

Figure 4-5: Comparison of power demand for the original and the optimized hull on the canal. The numbers on the curves correspond to individual canal segments of the simulated voyage, as follows: (1) Duisburg Ports - Datteln-Horneburg, (2) Datteln-Horneburg - Datteln, (3) Datteln - Münster, (4) Münster - Bevergern, (5) Bevergern - Achmer, (6) Achmer - Minden, (7) Minden - Lohnde, (8) Lohnde - Stöcken-North Port, (9) Stöcken-North Port - Misburg, (10) Misburg - Sehnde, (11) Sehnde - Peine, (12) Peine - Wendeburg-Botfeld, (13) Wendeburg-Botfeld - Veltenhof, (14) Veltenhof - Thune, and (15) Thune - Edelsbüttel.

4.3 New Father&Son engine concept

The second measure for the Ernst Kramer was the update of the main engine to a Father&Son layout with a smaller engine for the canal and a larger one or both in parallel for the Rhine. It is described in more detail in D3.15.

The existing engine of the test case vessel complies with the CCNR1 emissions standard. If the engine were to be replaced, engines complying with the Stage V emissions standard would be used, which would lead to a reduction of 97 % PM and 80 % NO_X.

Here, the following reductions of fuel consumption were calculated, resulting from more favourable engine load profiles:

Table 4-1: Saving potential of the Father&Son engine layout, derived from D3.15.

Journey type	Saving potential fuel consumption
Downstream	5%
Upstream	4%
Canal	15%

Those numbers can be added to the savings from the hydrodynamic optimisation. Since the reduction is not always sufficient to reach the target of 35% less CO_{2eq} emissions, theoretical blend of HVO to the Diesel is used in in the following. What this means in absolute numbers can be seen in Table 4-2.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 4-2: Voyage simulation, Demo 5 results.

	Average fuel consumption [l]		**Savings potential [%]**		**HVO blend**	
	Original hull	**Optimized hull**	**Hull**	**Father&Son**	**[%]**	**[l]**
Rhine River Mannheim - Amsterdam						
Downstream	2790	2295	18%	5%	17.9	288
Upstream	11155	9339	16%	4%	20.1	1383
Canal Duisburg-Wolfsburg						
Per trip	2592	1942	25%	15%	-	

4.4 Results of emissions calculations

The emissions were calculated based on the pathways and emission factors derived in SYNERGETICS WP1. For the HVO upstream chain the values from the best guess scenarios *61* in D1.2 [3] were used. The upstream chain for Diesel is calculated with 180.7 g_{CO2e}/kWh, 10.86 g_{NOx}/kWh and 1.91 g_{PM10}/kWh according to [4].

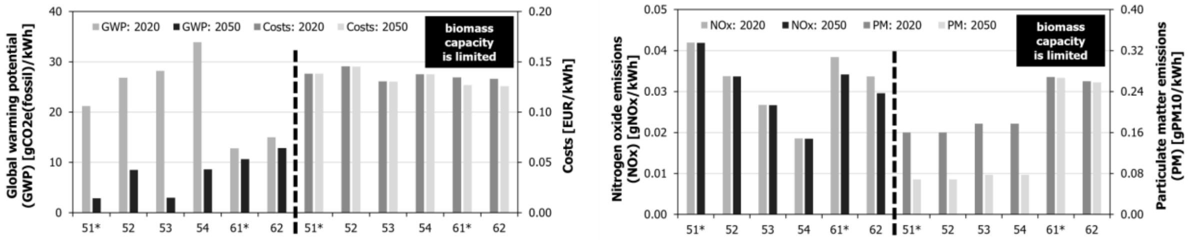

Figure 4-6: Global warming potential [g_{COe}/kWh], nitrogen oxide emissions in [g_{NOx}/kWh] and particulate matter emissions in [g_{PM10}/kWh] for the years 2020 and 2050 in the best guess scenario for the Well-to-Tank part. Best guess paths are marked with an asterisk. [3]

The following Table 4-3 and Table 4-4 show the emission savings potential. According to the calculations, as shown above, HVO would not be necessary for canal navigation; instead, the ship would run on pure diesel. Therefore, no savings from the upstream chain are included here, as is the case for HVO. In real operation, the Ernst Kramer would of course always run on an HVO blend.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 4-3: WTW and TTW emissions for different HVO pathways for the upstream and downstream journey. In the HVO-scenarios the hull optimisation is included.

	Upstream		**Downstream**	
	Diesel	**HVO61 + Diesel**	**Diesel**	**HVO61 + Diesel**
Emission Standard	CCNR 1	Stage V	CCNR 1	Stage V
WTT CO_{2e} [t]	7.60	5.05	1.90	1.25
TTW CO_{2e} [t]	29.25	18.88	7.31	4.73
WTW CO_{2e} [t]	36.85	23.93	9.22	5.97
WTW CO_{2e} Savings compared to Diesel CCNR 1 [%]		35.07%		35.19%
WTW CO_{2e} Savings compared to Diesel CCNR 1 [t]		12.93		3.24
WTT NOx [t]	0.457	0.2952	0.114	0.07
TTW NOx [t]	0.372	0.0612	0.093	0.01491
WTW NOx [t]	0.830	0.3564	0.207	0.08880
WTW NOx Savings compared to Diesel CCNR 1 [%]		57.03%		57.19%
WTW NOx Savings compared to Diesel CCNR 1 [t]		0.4731		0.12
WTT PM [t]	0.080	0.0537	0.020	0.013
TTW PM [t]	0.023	0.0005	0.006	0.00012
WTW PM [t]	0.103	0.0542	0.026	0.01350
WTW PM Savings compared to Diesel CCNR 1 [%]		47.47%		47.66%
WTW PM Savings compared to Diesel CCNR 1 [t]		0.03		0.012

When considering the CO_{2eq} savings of the fuel blend, the influence of the improved upstream chain of HVO is also evident in that the emissions of the total WTW chain are even lower.

Table 4-4: WTW and TTW emissions in the Canal.

	Canal	
	Diesel Original Hull	**Diesel Optimised Hull**
Emission Standard	CCNR 1	Stage V
WTT GWP [t]	1.77	1.06
TTW GWP [t]	6.80	4.07
WTW GWP [t]	8.56	5.13
WTW GWP Savings [%]		40.05%
WTW GWP Savings [t]		3.429
WTT NOx [t]	0.106	0.064
TTW NOx [t]	0.087	0.011
WTW NOx [t]	0.193	0.074
WTW NOx Savings[%]		61.49%
WTW NOx Savings [t]		0.119
WTT PM [t]	0.019	0.011
TTW PM [t]	0.005	0.0001
WTW PM [t]	0.024	0.0111
WTW PM Savings [%]		52.90%
WTW PM Savings [t]		0.013

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

4.5 Conclusions for Demo 5

Based on the results of the voyage simulations conducted for Demo 5, the following conclusions summarise the findings of this work:

- Greening with the "conventional" measures aft-ship replacement and new engine layout for older vessels can have a significant potential
- This example shows the potential that exists in large parts of the fleet.

It is important to take into account the upstream chain of a fuel, not only for different renewable fuels but also when comparing to fossil fuels.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

5. Voyage simulations for Demo 6

The Bad Deutsch-Altenburg is a push boat dedicated to the maintenance of the Danube River, owned by the Austrian waterway operator viadonau. Its capabilities include marking of waterways and maintenance of buoys and other aids to navigation to ensure the safe passage of vessel traffic through the Danube. The main particulars of the vessel are presented in Table 5-1, and a photo of the boat is displayed in Figure 5-1.

From the concept design carried out in deliverable D3.13 [5], a methanol electric architecture was developed, which will be used as starting point for a new design in the future. The voyage simulations performed in this task aim to calculate the reduction in emissions to be expected between the reference vessel Bad Deutsch Altenburg and the new design with methanol-electric propulsion system.

Table 5-1: Main particulars of the Bad Deutsch Altenburg, Demo 6.

Ship type	**Push boat**	
Propulsion type	Direct	
Length over all	22.15	m
Beam, moulded	5.40	m
Draught, design	1.10	m
Max. speed	19.9	km/h
Engine power	2 x 257	kW
Propeller type	Fix Pitch Propeller (FPP)	

Figure 5-1: Photo of vessel Bad Deutsch-Altenburg sailing on the Danube River.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

5.1 Route and operation

To evaluate the power demand and CO2 emissions, the operation waterway maintenance was selected as this is the operation the vessel will carry out most of the time. This operation was described during the operational analysis by the Bunker Independent Operation BIO II, defined in deliverable D3.1 [6], and is conducted by the push boat with lighter. In Figure 5-2 the route used for the voyage simulations is shown. Depending on the conditions of the waterway, the push boat is in operation one or a few days a week. To represent this, the simulations have been conducted for the ship operating every other day, resulting in an average of 3 to 4 days per week.

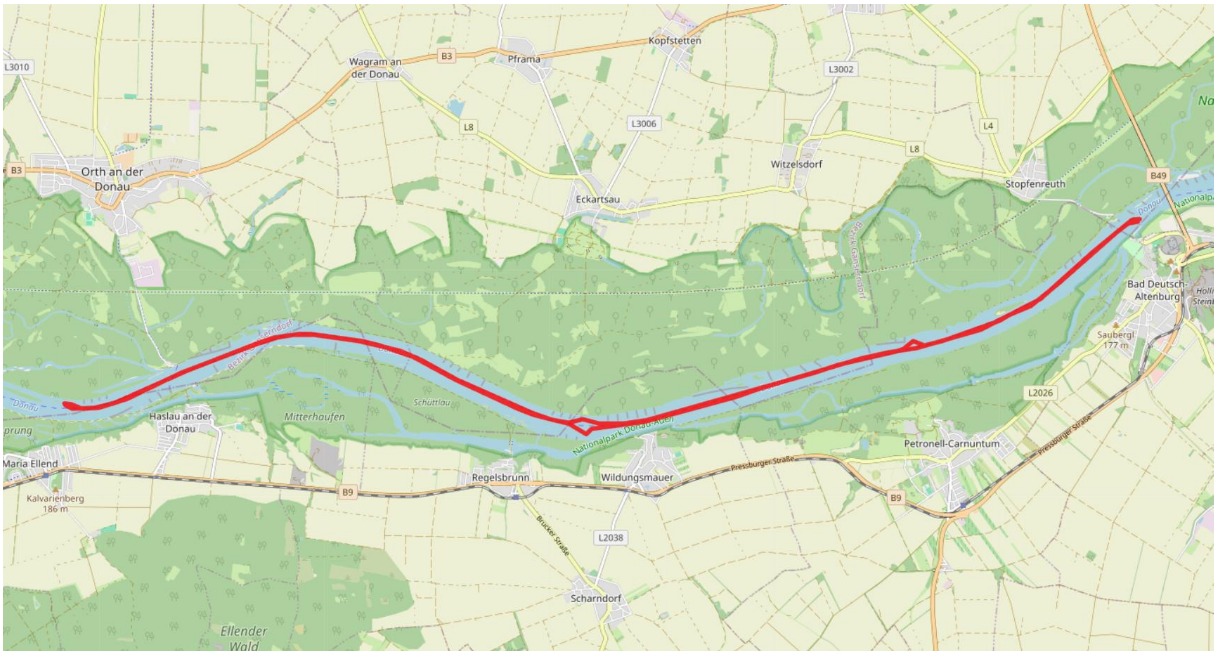

Figure 5-2: Route sailed during the voyage simulations for Demo 6.

Each day one trip is sailed, consisting of the five legs presented in Table 5-2, following BIO II. The whole trip consists of a total of seven and a half hours which, assuming a half an hour break for lunch, result in a total of eight hours per day. For each leg the ship sails for one hour, and between legs buoy manipulation is carried out. Once the ship arrives back to port, it remains there the next day, and departs again the day after at 8:00. This operation is repeated throughout the year.

Before a trip starts, the water level at the nearest gauge station is read. If the water level exceeds the highest navigable water level, navigation is not allowed and the ship remains therefore in port. The water level at the Wildungsmauer gauge was used as reference, due to its proximity to Bad Deutsch Altenburg.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 5-2: Overview of a trip assumed for the voyage simulations for Demo 6.

	Distance	Time	SOG	
	km	h	km/h	m/s
Departure Bad Deutsch Altenburg				
Sailing leg 1 (upstream)	4.12	0.52	8	2.22
Bouy manipulation		0.5	0	0
Sailing leg 2 (upstream)	4.989	0.62	8	2.22
Bouy manipulation		0.5	0	0
Sailingl leg 3 (upstream)	7.98	1.00	8	2.22
Bouy manipulation		0.5	0	0
Sailing leg 4 (downstream)	8.06	0.67	12	3.33
Bouy manipulation		0.5	0	0
Sailing leg 5 (downstream)	9.098	0.76	12	3.33
Arrival Bad Deutsch Altenburg				

5.2 Environmental data

To define the environmental conditions for the voyage simulations, a database of the Austrian Danube was built. This database contains the water depth, water level, current speed, current direction, etc. for a given time and location, the latter given as a pair of latitude and longitude coordinates.

The water level and discharge at the gauge stations was obtained from the Austrian Ministry of Agriculture and Forestry, Climate and Environmental protection, Regions and Water Management. In the online tool eHyd (https://ehyd.gv.at/) of this Ministry, historical data can be downloaded for a total of 625 gauge stations, identified by their HZB number. Out of these gauge stations, the stations of the Austrian Danube, presented in Table 5-3, were selected.

Combining the water depth values at RNW and MW of the hydrological model with the gauge water levels at RNW and MW, the values of water depth, current speed, current direction, etc. were obtained as function of time and location.

The available data depends on the purpose of the gauge, as some gauges measure only water level, others only water temperature or discharge. Some measure both water level and discharge, and other gauges measure discharge water level and water temperature. Regarding the water level and discharge, the values for daily average, monthly maximum and monthly minimum are included in the dataset. To build the database for the environmental conditions, the daily average values of water level and discharge was used.

The water level measured at the gauges is not the water depth of the river. To calculate the water depth and current speed, the data provided by Via Donau was used. Using a hydrological model, Via Donau provided the water depth and current speed for all the Austrian Danube as a function of the river km. The water depth and current speed was provided for the mean (MW) and low (RNW) navigable water level.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Using the information available from the website of Lower Austria[2], Upper Austria [3] and Via Donau[4], the following values were retrieved for each gauge:

- **PNP (Pegelnullpunkt):** Height of the zero-water level value of the gauge with respect to the Adriatic Sea level.
- **RNW2020 (Regulierungsniederwasser):** Regulatory low water level, which is the water level that is reached or exceeded at a Danube gauge on an average of 94% of the days in a year (i.e. on 343 days) over the long-term comparison period.
- **MW2020 (Mittelwasser):** Water level that corresponds to the calculated mean of the annual discharge for a long-term observation period (e.g. 30 years).
- **HSW2020 (Höchster Schifffahrtswasserstand):** Highest navigable water level, which is the water level that was reached or exceeded at a Danube gauge on an average of 1% of the days of a year (i.e. on 365 days) over the long-term comparison period.

Combining the water depth values at RNW and MW of the hydrological model with the gauge water levels at RNW and MW, the values of water depth, current speed, current direction, etc. were obtained as function of time and location.

Table 5-3: Properties of the main gauge stations of the Austrian Danube.

HZBNR	Gauge station	River km	Lat [deg]	Long [deg]	PNP [m]	RNW2020 [cm]	MW2020 [cm]	HSW2020 [cm]
207019	Achleiten	2223.05	48.582	13.503	288.04	258	310	485
207340	Wilhering	2144.05	48.330	14.181	249.12	214	322	584
207084	Mauthausen	2111	48.239	14.533	235.98	379	425	499
207100	Grein	2079.1	48.227	14.857	219.43	668	714	860
207134	Melk	2035.98	48.234	15.329	199.97	237	390	733
207357	Kienstock	2015.2	48.382	15.463	194.00	161	300	601
207241	Korneuburg	1941.46	48.327	16.334	159.87	196	290	545
207373	Wildungsmauer	1894.72	48.116	16.804	139.48	155	281	605
207407	Thebnerstraßl	1879.25	48.166	16.984	133.26	141	274	633

---

[2] https://www.noe.gv.at/wasserstand/#/de/Messstellen

[3] https://hydro.ooe.gv.at/#/overview/Wasserstand?filter=%7B%7D

[4] https://www.doris.bmimi.gv.at/en/fairway-information/water-levels

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

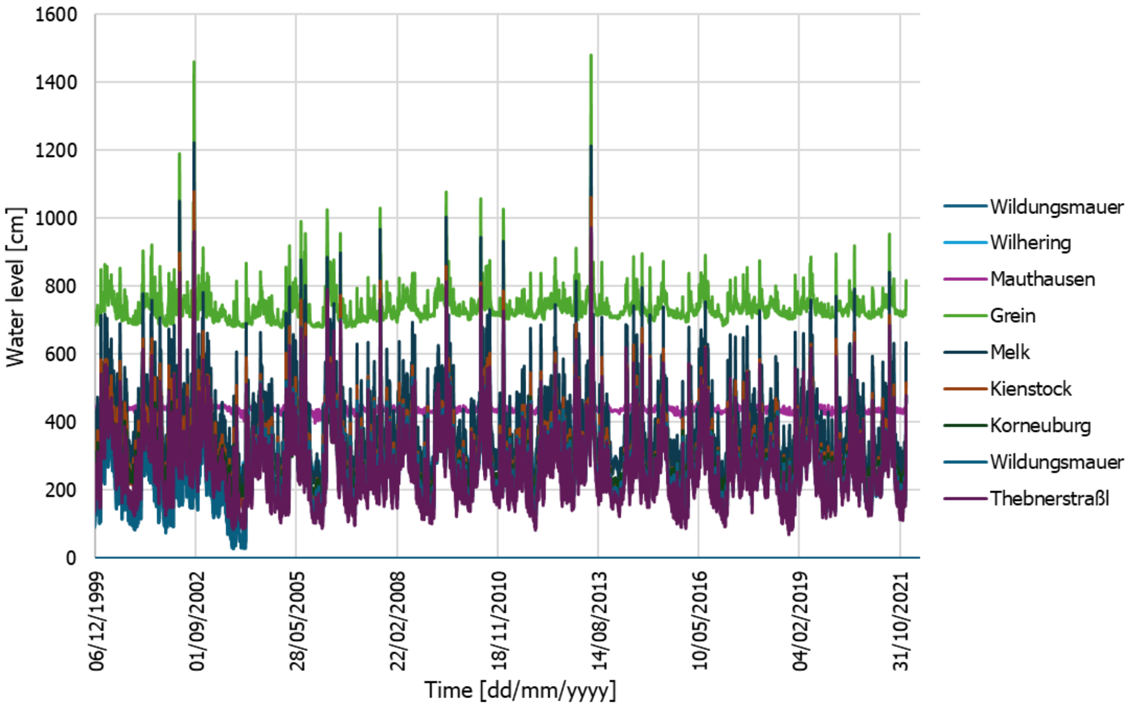

Figure 5-3: Time series of the average daily water level at the gauge stations of the Austrian Danube.

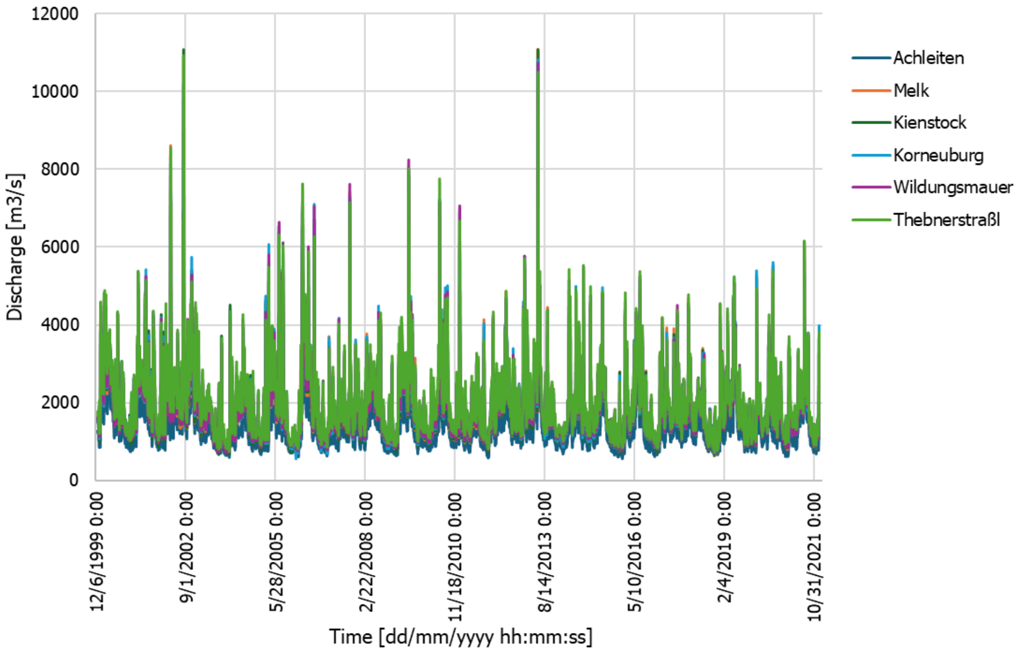

Figure 5-4: Time series of the average daily discharge at the gauge stations of the Austrian Danube.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

5.3 Results

Voyage simulations were carried out for the route and operation described in section 5.1. The simulations are set to meet as much as possible for each leg the target speed over ground from Table 5-2. If to meet the target speed the maximum available shaft power is reached, the ship will sail at 100%MCR and the attained speed over ground will be reduced. The results from the simulations are propulsive and environmental data as function of time, similar to the example shown in Figure 5-5 and Figure 5-6.

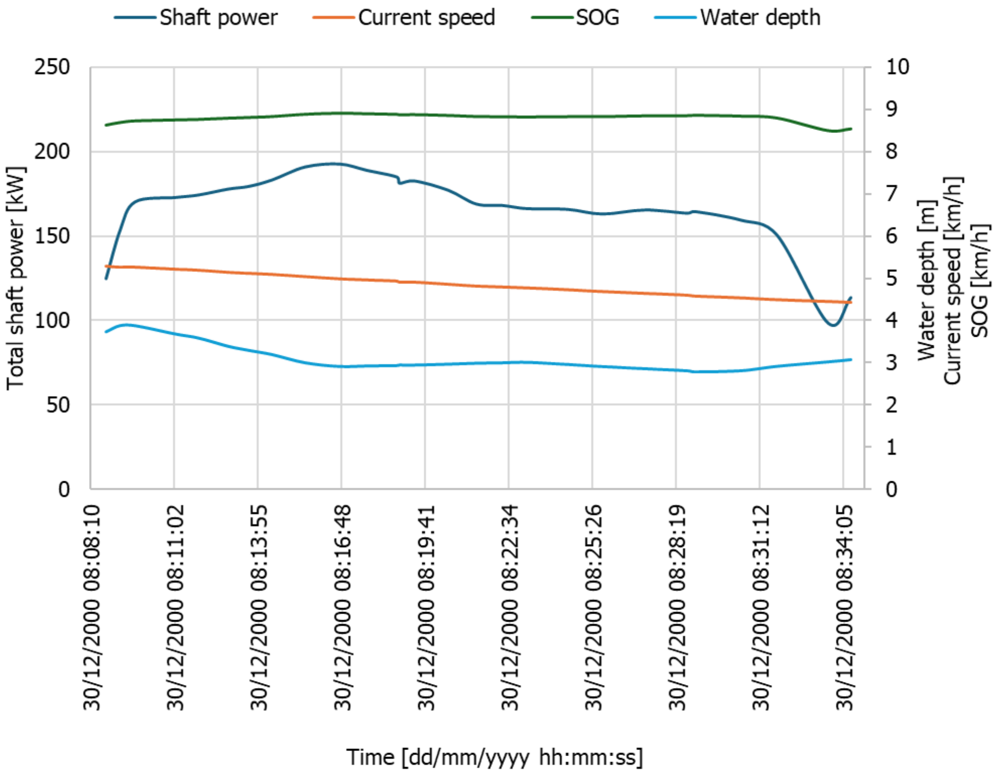

Figure 5-5: Example of output from the voyage simulations of Demo 6 when sailing leg 1

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

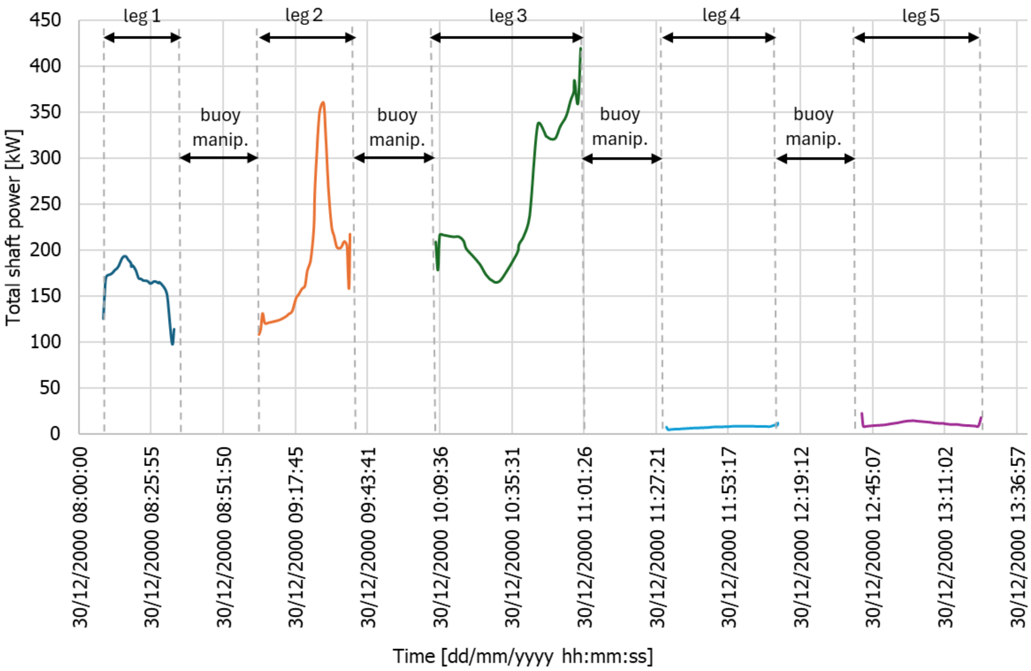

Figure 5-6: Example of required shaft power from the voyage simulations of Demo 6 when sailing a whole trip.

In order to build statistics, the simulations have been run for a period of several years. Within a year, the ship sails a number of trips, each consisting of the legs from Table 5-2.

For each time step within the legs the required engine brake power is known, which is used to calculate the fuel consumption using a mathematical model of the engines. The fuel consumption is used to calculate the energy consumed which is then converted into Tank-To-Wake (TTW) CO_2 equivalent emissions using a TTW conversion factor. In a similar way, a conversion factor is used to calculate the Well-To-Tank (WTT) CO2eq emissions. In Table 5-4, Table 5-5 and Table 5-6 the conversion factors used for this demo are presented, which were taken from deliverable D1.2 [3]. These values correspond to the best guess scenario pathways M1/41 and 61.

Table 5-4: Well-To-Tank (WTT) and Tank-To-Wake (TTW) emission factors for the CO2eq emissions used for Demo 6.

	Pathway	WTT		TTW	
		gCO2/kWh	gCO2/MJ	gCO2/kWh	gCO2/MJ
Diesel EN590		84.00	23.33	266.00	73.89
e-Methanol	M1/41	106.00	29.44	0.00	0.00
HVO	61	12.75	3.54	0.00	0.00

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 5-5: Well-To-Tank (WTT) and Tank-To-Wake (TTW) emission factors for the NOx emissions used for Demo 6

	Pathway	WTT		TTW	
		gNOx/kWh	gNOx/MJ	gNOx/kWh	gNOx/MJ
Diesel EN590		0.10	0.03	3.91	1.09
e-Methanol	M1/41	0.15	0.04	1.53	0.43
HVO	61	0.04	0.01	1.53	0.43

Table 5-6: Well-To-Tank (WTT) and Tank-To-Wake (TTW) emission factors for the particulate matter emissions used for Demo 6.

	Pathway	WTT		TTW	
		gPM10/kWh	gPM10/MJ	gPM10/kWh	gPM10/MJ
Diesel EN590		0.00	0.00	0.08	0.02
e-Methanol	M1/41	0.67	0.19	0.04	0.01
HVO	61	0.27	0.08	0.04	0.01

For this demo, the following concepts were compared:

1. **Diesel (EN590) CI ICE [Diesel (EN590)]**: Diesel direct propulsion with compression-ignited engines. This concept was selected as reference benchmark as this is currently the most implemented on this type of ship.

2. **Diesel (HVO100) CI ICE [Diesel (HVO100)]**: Diesel direct propulsion with compression-ignited engines running on HVO100. This concept was selected as the current push boat Bad Deutsch Altenburg is also sailing using this fuel.

3. **e-CH_3OH (M1/41) CI ICE [e-CH_3OH (M1/41)]:** Methanol electric propulsion with compression-ignited single fuel engines running on methanol synthesized using electricity from renewable source. This concept represents the retrofitted vessel resulting from the initial concept design performed in deliverable D3.13 [5].

The results from the voyage simulations for Demo 6 are presented in Table 5-7 and in graphical form in Figure 2-5, Figure 2-6, and Figure 2-7. In addition, in Table 2-7 the average annual emissions are presented. The following section contains the conclusions derived from the results.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

Table 5-7: Comparison of annual emissions between the reference diesel direct concept [Diesel (EN590)], the diesel direct concept running with HVO100 [Diesel (HVO100) (61)] and the methanol electric concept with single fuel methanol engines [e-CH$_3$OH (M1/41)]. Figures are the average values for the 15 year voyage simulations.

Parameter	**Unit**	**Diesel (EN590)**		**Diesel (HVO100) (61)**		**e-CH$_3$OH (M1/41)**	
Fuel consumed	t	33.67	100%	33.67	100%	78.63	234%
	m3	39.15	100%	39.15	100%	99.29	254%
CO2eq emissions (T2W)	tCO2eq	106.22	100%	0.00	0%	0.00	0%
CO2eq emissions (W2T)	tCO2eq	33.54	100%	5.09	15%	46.07	137%
Total CO2eq emissions (WTW)	**tCO2eq**	**139.76**	**100%**	**5.09**	**4%**	**46.07**	**33%**
NOx emissions (TTW)	tNOx	1.57	100%	0.62	39%	0.67	43%
NOx emissions (WTT)	tNOx	0.04	100%	0.01	33%	0.06	145%
Total NOx emissions (WTW)	**tNOx**	**1.61**	**100%**	**0.63**	**39%**	**0.74**	**46%**
PM10 emissions (TTW)	kgPM10	31.63	100%	15.81	50%	17.21	54%
PM10 emissions (WTT)	kgPM10	1.44	100%	115.00	8000%	0.30	21%
Total PM10 emissions (WTW)	**kgPM10**	**33.06**	**100%**	**130.82**	**396%**	**17.51**	**53%**

Figure 5-7: Annual Well-To-Wake (WTW) CO2eq emissions for the reference diesel concept , the concept with HVO100, and the methanol electric concept e-CH$_3$OH, resulting from the voyage simulations for Demo 6.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

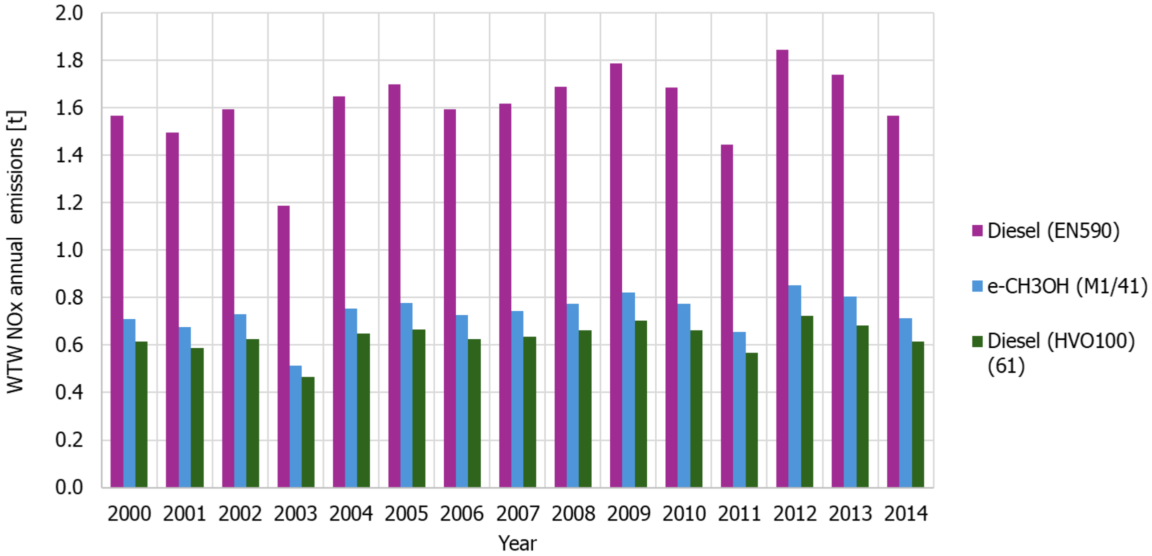

Figure 5-8: Annual Well-To-Wake (WTW) NOx emissions for the reference diesel concept , the concept with HVO100, and the methanol electric concept e-CH3OH, resulting from the voyage simulations for Demo 6.

Figure 5-9: Annual Well-To-Wake (WTW) particulate matter PM10 emissions for the reference diesel concept , the concept with HVO100, and the methanol electric concept e-CH3OH, resulting from the voyage simulations for Demo 6.

Funded by the Horizon Europe Programme of the European Union under grant agreement No 101096809
Funded by the Horizon Europe guarantee of the United Kingdom, under project No 10068310
Funded by the Swiss State Secretariat for Education, Research and Innovation

5.4 Conclusions for Demo 6

Based on the results of the voyage simulations conducted for Demo 6 summarised in Table 5-7, the following conclusions summarise the findings of this work:

- Concept Diesel (HVO100) (61) consisting of diesel direct propulsion running on HVO100, gives the largest reduction in CO2eq and NOx emissions with respect to the reference concept Diesel (EN590). Concept e-CH_3OH (M1/41), consisting of methanol electric propulsion with single fuel methanol engines achieves a significant reduction in CO2eq emissions, namely about 70%. Therefore both Diesel (HVO100) (61) and e-CH_3OH (M1/41) concepts achieve amply the emission reduction targets for 2035 of 35% less GHG emissions, as defined in CCNR [1].

- Concept e-CH_3OH (M1/41), consisting of methanol electric propulsion with single fuel methanol engines results in a reduction of Well-To-Wake particulate matter of about 46% with respect to the reference concept Diesel (EN590). On the other hand, despite the concept Diesel (HVO100) gives a reduction of 50% in particulate matter Tank-To-Wake emissions compared to the reference concept Diesel (EN590), it also produces approximately 4 times the amount of Well-To-Wake particulate matter emissions, mainly caused by the large Well-To-Tank emission factor of this concept.

6. Bibliography

[1] Zentralkommission für die Rheinschifffahrt (ZKR), „Mannheimer Erklärung „150 Jahre Mannheimer Akte - Motor für eine dynamische Rhein- und Binnenschifffahrt,“ 18 October 2018. [Online]. Available: https://www.ccr-zkr.org/files/documents/dmannheim/Mannheimer_Erklaerung_en.pdf.

[2] H. C. Raven, „A New Correction Procedure for Shallow-Water Effects in Ship Speed Trials,“ in *PRADS2016*, Copenhagen, 2016.

[3] F. Thalmann, F. Elimar, M.-S. Cornelia und S. Almut , „SYNERGETICS D1.2 Report on suitability of identified technical solutions,“ 2024.

[4] I. Bačkalov, “Greening of Inland and Coastal Ships in Europe by Means of Retrofitting: State of the Art and Scenarios,” *Sustainability,* vol. 17, no. 11, p. 5154, Jun 2025.

[5] P. Garcia Barrena and G. Giurco, “SYNERGETICS D3.13 Evaluation report viadonau push boat,” 2025.

[6] P. Garcia Barrena and G. Giurco, “SYNERGETICS D3.1 SPEC analyses of full scale and model scale demonstrators,” 2024.

[7] International Maritime Organization, Code of safety for ships using gases or other low-flashpoint fuels (IGF Code), 2016.

[8] International Maritime Organization, International Convention for the Safety of Life at Sea (SOLAS), 1974.

[9] International Maritime Organization, Technical Code on Control of Emission of Nitrous Oxides from Marine Diesel Engines (NOx Technical Code), 2008.