Environmental analysis - final

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Advanced, Efficient and Green Intermodal Systems

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Executive Summary

The present report is deliverable D7.7, Environmental analysis-final, in the context of WP7, Cost benefit analysis, and specifically Task 7.3, Environmental analysis. It is an evolution of an earlier, preliminary report on the economic analysis, report which the present document supersedes. It is also the continuation of the work done in Task 7.1, Identification of KPIs, and presented in deliverable D7.2 (Report on KPIs) [1]. Task 7.3 runs parallel to Tasks 7.2 and 7.4, which are the economic analysis and the social analysis, respectively. All three use cases, A, B, and C are covered in this report.

The most important data for the estimation of the environmental KPIs pertain to the sailing route (sea distance, voyage duration, ports of call) and the deployed vessels (fuel consumption at service speed, operating costs). From these, most of the KPIs can be calculated. The methodological framework and set of equations developed to calculate the environmental KPIs are described. These are further grouped into air emissions KPIs, waste emissions KPIs, acoustic emissions KPIs, light pollution KPIs, and other environmental KPIs.

It should be noted that there are two types of air emissions, named Tank to Wake (TTW) (or Tank to Wheel for road or rail vehicles) and Well to Tank (WTT). TTW concerns the operational emissions of the vessel or vehicle. WTT concerns upstream emissions, those associated with the production of the fuel to the vessel or vehicle. If the fuels are produced using renewable energy sources their WTT emissions are also zero, however if the energy sources to produce these fuels are non-renewable (for instance, use of a coal plant to produce electricity), then the WTT emissions are nonzero and need to be accounted for. The same is the case with batteries. There is also the term WTW (Well to Wake or Well to Wheel) which is the sum of WTT+TTW. Even though in the AEGIS Grant Agreement no delineation between these two types of emissions was made and the main focus of the emissions calculation was by default assumed to be TTW, due to the increased emphasis of policy makers, particularly in the EU, but also in the IMO, on WTW emissions, in this report we have also selectively calculated WTT (and WTW) emissions for some KPIs.

Generally, and from the analysis conducted for all three use cases, we can say that the AEGIS solutions are far better in all use cases than the non-AEGIS baseline solutions in terms of environmental KPIs.

The rest of this report explains this result in detail.

Definitions and abbreviations

AG: Advisory Group

CBA: Cost Benefit Analysis

CEMT: European Conference of Ministers of Transport

EU: European Union

FEU: Forty-foot Equivalent Unit

IWW: Inland Water Way

KPI: Key Performance Indicator

LCA: Life Cycle Assessment

LoLo: Lift-on Lift-off

RoRo: Roll-on Roll-off

SSS: Short Sea Shipping

TEU: Twenty-foot Equivalent Unit

TTW: Tank to Wake or Tank to Wheel

UC: Use Case

WP: Work Package

WTT: Well to Tank

WTW: Well to Wake or Well to Wheel

1 Purpose and structure of this report

Whatever solutions are contemplated in AEGIS, it is imperative to assess them holistically so as to capture the effects of all conceivable cross-linkages and interdependencies and hopefully obtain what we call "win-win" solutions. For that purpose, the main objectives of Work Package 7 (WP7) are to:

- Define Key Performance Indicators (KPIs) to do a quantitative Cost-Benefit Analysis (CBA)
- Perform analyses of economic, environmental, and social effects of AEGIS proposals
- Combine to overall CBA, covering all three factors, and compare it with today's solutions
- Identify "win-win" solutions that give the best overall benefits at the lowest possible cost

The present report is deliverable D7.7, Environmental analysis-final. It is the context of Task 7.3 (environmental analysis) and is an evolution of an earlier, preliminary report on the environmental analysis, report which the present document supersedes. It is also the continuation of the work done in Task 7.1, Identification of KPIs, and presented in deliverable D7.2 (Report on KPIs) [1]. Task 7.3 runs parallel to Tasks 7.2 and 7.4, which are the economic analysis and the social analysis, respectively. All three use cases, A, B, and C are covered in this report.

The rest of this document is organized as follows. Section 2 presents and describes each of the three AEGIS use cases which serve to conduct the CBA. Section 3 presents the methodology for the evaluation of the environmental KPIs. Section 4 presents the results of the CBA for the three use cases, and Section 5 presents the conclusions. Finally, Annex A shows the data templates circulated to the AEGIS partners.

A clarifying note is due on other AEGIS deliverables, some of which are cited in this report. Some of these deliverables are classified as "public", hence the reader of this deliverable (which is also public) will have full access to them. For those AEGIS deliverables that are classified as "confidential", a public executive summary will be available, which will also be accessible to the reader of this deliverable.

2 Description of the three use cases

The three AEGIS use cases serve here to compute the predefined KPIs, which represent the criteria under which the set of solutions developed under AEGIS will be evaluated and carry out the cost-benefit analysis (CBA) to assess any solutions further contemplated in AEGIS. The three use cases, including their scenarios and base cases, are presented and described in this section.

An important note is that all three scenarios of use cases (baseline and AEGIS) were continuously evolving during the course of this analysis. The same can be said regarding the data for these scenarios. This section describes the use cases, and associated data, as these were known at the time of the analysis.

A related note is that the degree of completeness of the associated data in the three use cases is by no means uniform as regards the availability of data in these scenarios for the purposes of WP7. Some use cases are more developed than others use cases. In cases data to compute some KPIs were missing, some assumptions and approximations were made, and these are stated in this report.

2.1 Use Case A

This section heavily draws from deliverable D8.2 (Transport system specification– Case A) [2].

Use Case A (UCA) covers transport from the large port of Rotterdam to smaller destinations along a less populated coast of Norway. It will focus on short sea and rural terminals mainly based on a LoLo service. The objectives of UCA are depicted in Figure 1.

The results from the initial cargo volume analysis presented in deliverable D8.1 (Cargo Volume Analysis – Case A) [3] indicate a potential for implementing the AEGIS concepts. Trends that will be important to follow, such as it seems like the volume of 45-feet containers are increasing compared to 40 feet, which again will pose requirements to the vessel design and cargo handling equipment, have been identified. This report points to some of those trends. Based on the results from logistics studies, the concept has estimated available cargo from the Trondheimsfjord region. The calculations in the report are based on volumes from existing transport routes from the west coast of Norway to the Netherlands, with data from statistics, previous projects, port statistics, and direct input from transporters and cargo owners. The container transport to international regions outside Europe, 60 - 70 % of NCL's international cargo, is mainly carried out by shipping to the big European ports, such as Rotterdam, where it is transshipped to deep-sea vessels. Hence, the NCL sailings are vulnerable to delays in the deep-sea sailing schedules. On average, eight vessels sail out of Rotterdam to the west coast of Norway weekly. The average capacity for the fleet is estimated to be about 750 TEUs per vessel, hence a total weekly capacity of about 6,000 TEUs. The cargo volume for bigger terminals is quite stable, but it varies significantly for the smaller ports. The Trøndelag region in Norway can be served on a weekly basis and include Rørvik and the inner ports of the fjords if introducing feeder lines, such as daughter vessels.

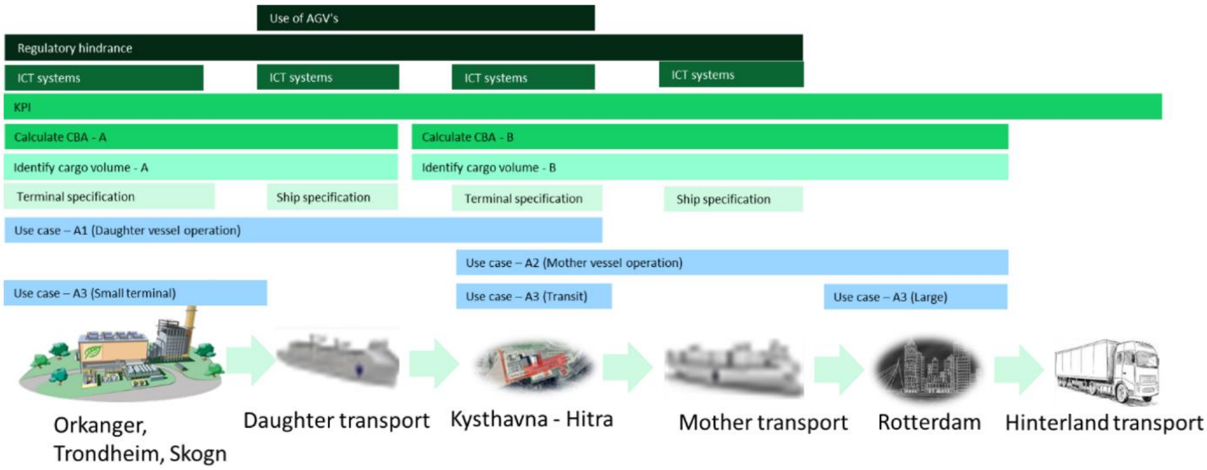


Figure 1: UCA objectives and transport systems (source: Deliverable D8.2 (Transport system specification– Case A) [2].)

According to the cargo analysis carried out in deliverable D8.1 (Cargo Volume Analysis – Case A) [3] has defined two scenarios:

1. The transport between Rotterdam (The Netherlands) and Hitra Kysthavn, Sandstad (Norway). Seen in Figure 1 as region 1.
2. The transport within the Trondheimsfjorden region (Norway). Seen in Figure 2 as region 2.

Figure 2: Use Case A, International and domestic trade.

Furthermore, the use case A transport system will, as indicated in Figure 1 and deliverable D8.2 (Transport system specification– Case A) [2], consist of mother and daughter vessels exchanging cargo at a transshipment terminal and be divided into three segments, A1, A2, and A3:

A1: Transport within the Trondheimsfjorden region, Norway

A2: The transport between Rotterdam, Netherlands, and Hitra Kysthavn (Sandstad), Norway

A3: The terminal activities at the port of Hitra Kysthavn (and Orkanger, Trondheim, Skogn), Norway

The AEGIS concept requires a different operating method than today's practice. The idea behind the concept is to have one or several mother vessels sailing between Rotterdam and Norway with large cargo volumes and a higher level of automation to achieve benefits due to economy of scale. When the mother vessels travel along the west coast of Norway, a number of daughters can accommodate the transport of cargo between a set of regional ports and the mother vessel. In this project, we will focus on the Trondheimsfjord, but the concept can be adapted to other parts of the further route south on the west coast of Norway down to Rotterdam, as well as other regions worldwide. There are several reasons for introducing the mother–daughter concept. The distance between Rotterdam and the Trondheimsfjord and further north will not allow operation by only one vessel with a fixed, regular weekly schedule. The distance is significant, about 800 nm between Rotterdam and Trondheim, which is estimated to be more than two days of sailing one way with a speed of 15 knots. The average loading speed of containers is 30 per hour. The distance from Hitra to Trondheim is 48 nm, which means it takes an extra three hours to sail the distance, and to Skogn, it will be about 72 extra nm which means 5 hours extra sailing time with a speed of 15 knots in one direction out of Hitra. This means that the utilization of a mother will be much better if the cargo can be picked up in Hitra, at the same time as it will take too long time to visit smaller and remote ports to pick up a small number of containers.

Additional to the sailing and cargo handling time, we should also consider mooring time, which will be significant. A roundtrip between Hitra Kysthavn and Skogn via Orkanger and Trondheim takes 16 hours at a speed of 12 knots. Mooring, loading, and discharging time will come on top of this. The daily operational cost of a mother is higher than for a daughter, as a larger vessel consumes more energy (among other things). A daughter vessel will be significantly smaller and allowed to operate at a lower speed, which reduces energy consumption. The daughter vessel will not have the same time constraints as the mother, as it only operates within the fjord and transports cargo between the local ports in the region. In the studies, we are also simulating the possibility of having more than one daughter in operation.

A mother vessel must operate with a higher speed due to time and transport constraints with respect to requirements in Rotterdam, such as reaching the deep-sea schedules. Another factor is that some of the smaller ports are too small for a mother vessel, and the quay capacities or infrastructure cannot allow port calls by a bigger vessel. To secure a successful transport system with a mother and daughter vessel, cargo transshipment must be efficient, cost control, and optimized. This requires an efficient transshipment terminal that can provide services for both mothers and daughters, and not least to the cargo owners.

In the rest of this section, the baseline scenario and AEGIS scenario for mother and daughter ships will be explained. Finally, the specification of new ships for both scenarios will be introduced.

2.1.1 Mother vessel case

The mother vessel route is defined as the existing NCL route from Rotterdam along the Norwegian coastline and finally ends in Orkanger, which visits many ports (up to 22). As baseline, Use Case A uses existing vessels operated by NCL for studies regarding the continental transport, region 1 in Figure 2. These are LoLo vessels with a capacity of around 800 TEUs. On the other hand, for this use case, In the AEGIS scenario, the focus is on the limited part of the existing route: Rotterdam – Hitra Kysthavn, as illustrated in Figure 3. The route is 800 nm, and with an average sailing speed of 15 knots, it will take 53.4 hours. The distance from Hitra Kysthavn to Orkanger is 48 nm, and an average sailing speed of 15 knots takes 3.2 hours. If the mother vessel can drop the sailing to Orkanger, it can save around 6.5 hours of sailing. The total saved time can be significant if the mother-daughter concept is implemented in several regions of the coast, resulting in either shorter turnover time for the route or the possibility of sailing further north for more cargo.

Figure 3: The mother ship route (only Rotterdam - Hitra Kysthavn).

The mother vessel use case (A2) is listed in Table 1. It should be noted that in the AEGIS scenario the vessel fleet will consist of four ships, two new concept vessels, and two of the existing (NCL) vessels. On the other hand, the non-AEGIS scenario consists of four NCL vessels that voyage during the week between the route mentioned.

Table 1: Scenario Rotterdam – Hitra Kysthavn (mother vessel).

Element	Description
Scenario title	Rotterdam – Hitra Kysthavn
Distance and sailing time	Rotterdam – Hitra Kysthavn: 800 nm, average sailing speed: 15 knots Sailing time: 800 nm /15 knots = 53.4 hours
Cargo Type (containerized)	Abrasive grain Silicon carbide Hydrogen Peroxide Wastepaper General cargo Paper, silicone, alloys for the foundry industry, carbon and micro silica.
Transport Requirements	Container vessel, LoLo, with own cranes (two), used at Norwegian terminals (in this case, Hitra Kysthavn) Terminals/quays • No cranes or other container handling equipment in Norwegian terminals • For port of Rotterdam, shipboard cranes cannot be used Dependent on deep-sea schedule for carriers out of Rotterdam

2.1.2 Daughter vessel case

The scenario is shown in Figure 4 and is a route that serves the terminals with the biggest cargo volume potential in the Trondheimsfjord. The route goes from Hitra Kysthavn via Orkanger and Trondheim and completes its journey in Skogn. The transport distance is about 100 nm one way. The daughter vessel can serve the mother vessel(s) with cargo originating from ports in the region and, of course, supply the ports in the area with cargo from the mother vessel(s). If, for instance, containers from rail transport are unloaded in Trondheim or Skogn, the containers can be transported by the daughter's vessel to Hitra Kysthavn, where they will be further transported by the mother vessel.

Figure 4: Skog n Trondheim Orkanger Hitra Kysthavn (incl. Holla), map and route from Logistics Analysis tool.

The route in Figure 4 has been further divided into four different routes, as shown in Figures 5 to 8.

It is anticipated that some of the smaller terminals along the route will have to offer self-service, which means that the daughter vessel autonomy level must enable moving a container from the quayside onto the vessel without human involvement at the quayside. It is therefore necessary with a geared daughter vessel that can handle containers at any terminal in the fjord.

In summary, the fleet and corresponding routes have been chosen as follows for the AEGIS scenario:

1. 2 vessels with a capacity of 60 TEUs
2. Daughter vessel 1 sailing route 2 and 3 with corresponding cargo volume
3. Daughter vessel 2 sailing route 1 and 4 (to Orkanger and Holla from Hitra Kysthavn)
4. Sailing speeds: 8 knots for vessel 1 and 5 knots for vessel 2
5. Frequency of sailings: Twice a week for vessel one and three times a week for vessel 2

Figure 5: Route 1: Hitra Kysthavn - Orkanger- Hitra Kysthavn.

Figure 6: Route 2: Hitra Kysthavn – Orkanger – Trondheim – Skogn- Hitra Kysthavn.

Figure 7: Route 3: Hitra Kysthavn – Trondheim - Skogn- Hitra Kysthavn.

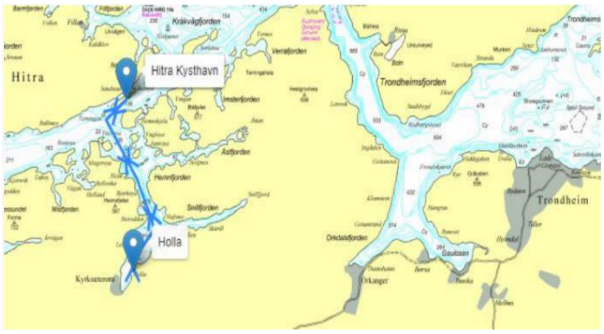


Figure 8: Route 4: Hitra Kysthavn – Holla- Hitra Kysthavn.

It should be mentioned that the baseline scenario in this case (region 2 in Figure 2) is trucks that serve the region today. Based on deliverable D8.2 (Transport system specification– Case A) [2], the (round trip) distance for these four routes in both scenarios is addressed in Table 2.

Table 2: Distances for the daughter case (sea and road).

Number of routes	AEGIS (vessels)	Baseline (trucks)
Route 1	96 nm	138 km
Route 2	183 nm	368 km
Route 3	162 nm	361 km
Route 4	28 nm	154 km

2.1.3 Ships specification

In WP4 (Green advanced vessels), low-energy, low-emission, and logistics-adapted advanced vessel concepts are investigated and developed with the aim of enabling more efficient and green waterborne transport. Its most recent deliverable is D4.2 (Specification of vessel types for use cases) [4]. Its main objective is the development of advanced green vessel concepts which fulfill the requirements of the three different use cases. For the report state of concept development, several vessel types for each use case are presented in detail, for example, in propulsion specification and onboard handling systems.

The actual envisioned vessel concepts for Use Case A are presented in Tables 3 and 4. A mother-daughter concept was identified as a feasible solution for this use case. Hitra, an island outside the

Trondheim fjord, was chosen as the hub for the transshipment between the mother and the daughter vessels.

For the mother vessels, we considered a new short-sea shipping from Rotterdam to the Trondheim region with a capacity of approx. 1100 TEU. Also, the propulsion system of this conceptual ship would be a hybrid of methanol and battery (the main fuel is methanol).

For the daughter vessel in use case A, we considered a self-propelled (fully electric) shuttle with a capacity of approx. 60 TEU. For this case we have two ships that can run inside the Trondheim fjord, collecting cargo at different smaller ports or industry sites.

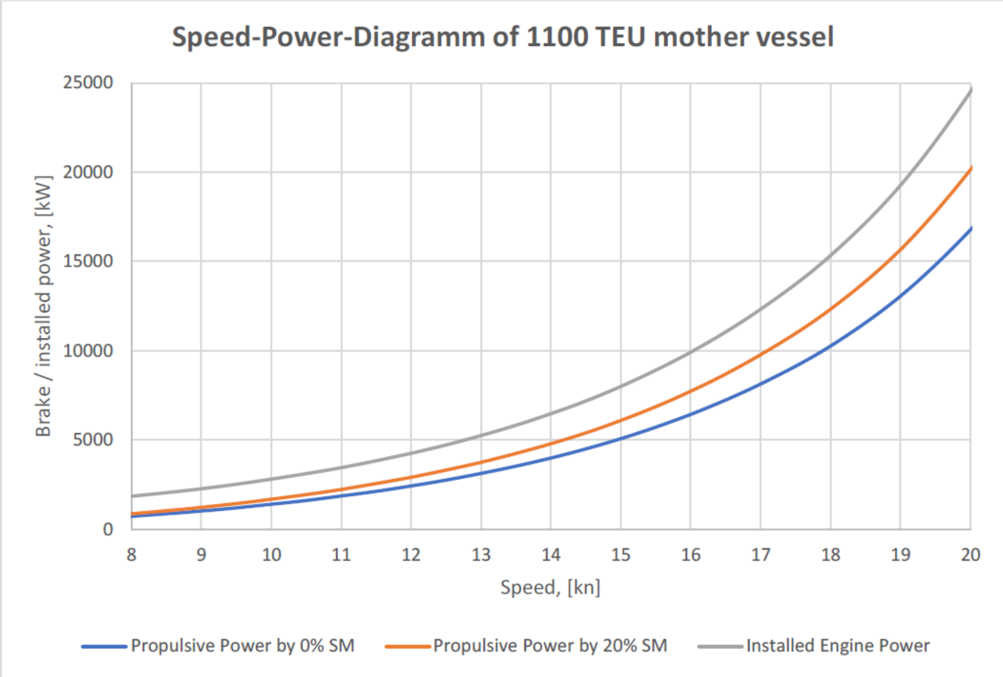
Table 3: Use Case A mother vessels.

Data	Mother Vessel
Vessel Description	1100 TEU Container Ship, incl. places for 20, 40, 45 foot and reefer containers
Vessel Type	Container SSS vessel
Route deployed in	Rotterdam - Hitra
Length Overall, Loa	143.90 m
Length Waterline, Lwl	142.20 m
Length between perpendiculars, Lbp	133.20 m
Beam Overall, Boa	25.50 m
Beam Waterline, Bwl	25.50 m
Design Draft, T	8.16 m
Depth to main deck, D	14.10 m
Displacement	18,997 tonnes
Gross Tonnage	10,890 GT
Wetted Surface	4422.50 m^2
Waterplane Area	2797 m^2
Bulb Area	15.40 m^2
Half Entrance Angle	19.76°
Stern Type Coefficient	-25
Main Engine Type	Methanol combustion engine (“methanol ready”) and battery support for Norwegian Fjords
Main Engine Fuel Type	Methanol and battery
Design Speed	15 knots
Vessel capacity	1100 TEU
Cargo Handling Equipment	2 triple-joint cranes (CT/MCG), reach 32m and SWL of 45t
Autonomy Level	Medium autonomy level (2)

Table 4: Use Case A daughter vessels.

Data	Daughter Vessel
Vessel Description	60 TEU, incl. places for 20, 40 feet containers
Vessel Type	Container vessel for TA1-2, maybe up to TA3
Route deployed in	Daughter 1: Hitra Kysthavn – Orkanger – Trondheim – Skogn & Kysthavn – Trondheim - Skogn Daughter 2: Hitra Kysthavn – Orkanger & Hitra Kysthavn – Holla
Length Overall, Loa	65.00 m
Length Waterline, Lwl	65.00 m
Length between perpendiculars, Lbp	62.70 m
Beam Overall, Boa	11.45 m
Beam Waterline, Bwl	11.45 m
Design Draft, T	2.20 m
Depth to main deck, D	5.00 m
Displacement	1,270 tonnes
Gross Tonnage	895 GT
Wetted Surface	843 m^2
Waterplane Area	670 m^2
Half Entrance Angle	30.8°
Stern Type Coefficient	-22
Main Engine Type	Fully electric
Main Engine Fuel Type	Battery
Design Speed	Daughter 1: 8 knots Daughter 2: 5 knots
Vessel capacity	60 TEU
Cargo Handling Equipment	On-board Reach Stacker (placed on lift + ramp)
Autonomy Level	High autonomy level (3-4)

Furthermore, based on information provided by ISE, the speed-power diagram for the mother and daughter vessels is shown in Figures 9 and 10, respectively.



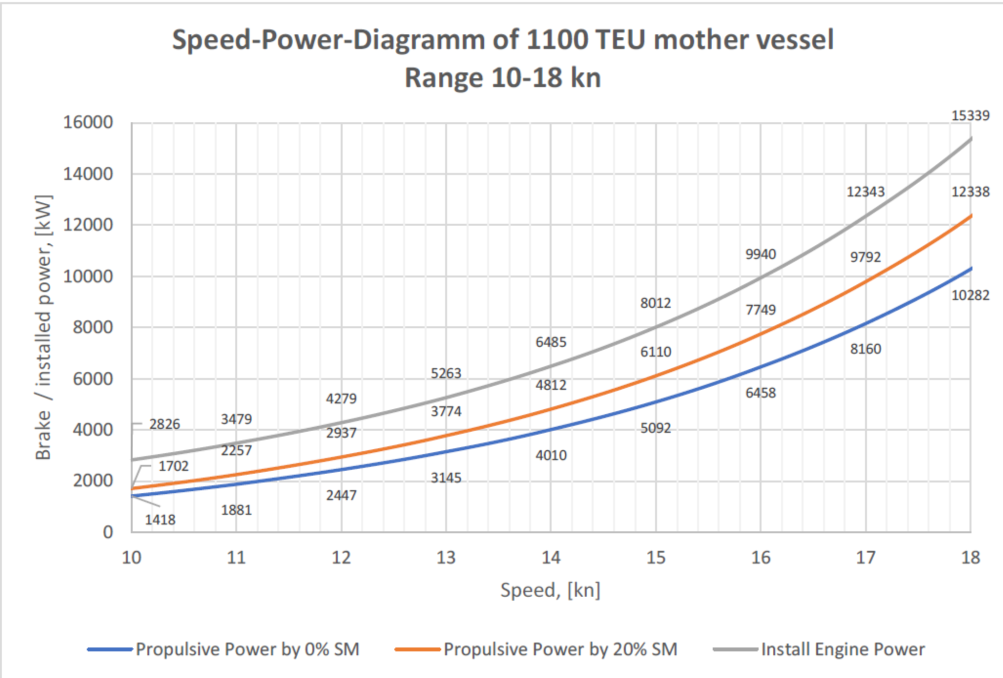
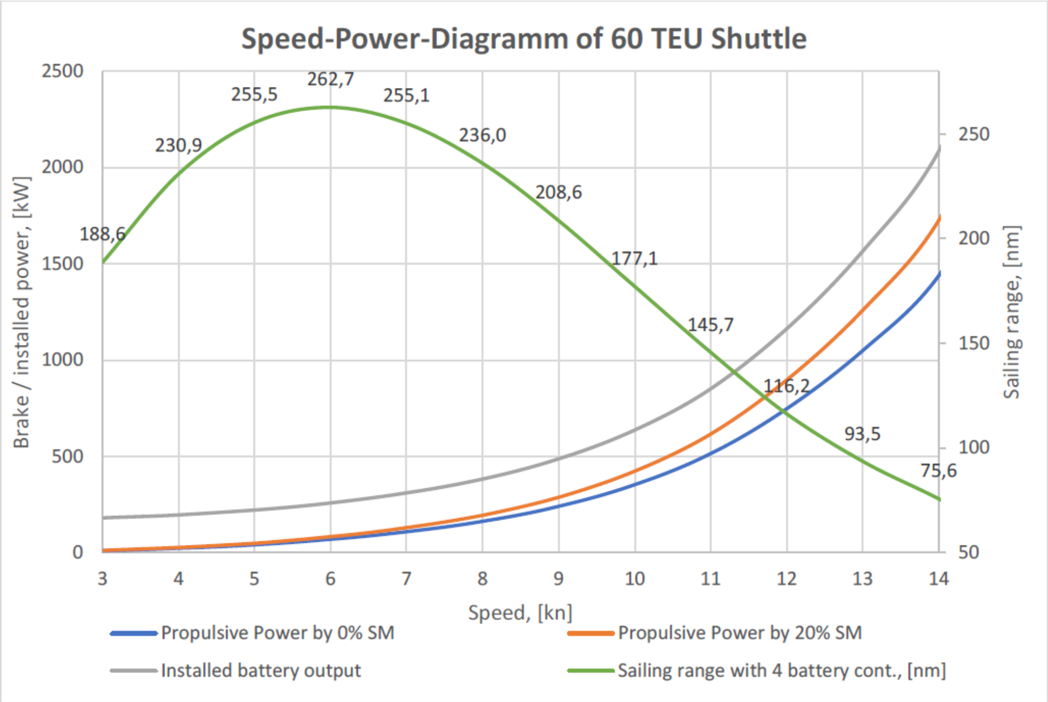


Figure 9: Use Case A, speed-power diagram of mother vessel. Source: ISE.



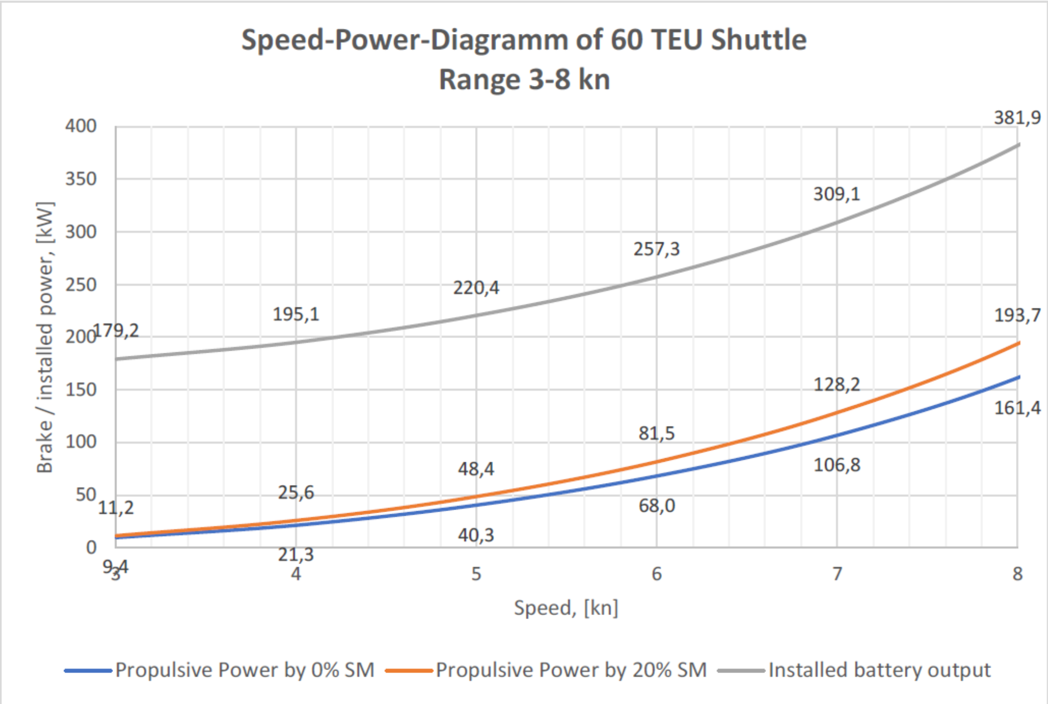


Figure 10: Use Case A, speed-power diagram of daughter vessel. Source: ISE.

2.2 Use Case B

Use Case B examines Belgium and Netherlands's short sea and inland interface. The two countries are significant hubs for cargo transportation from and to Europe. Rotterdam, located in the Netherlands, is the largest port in Europe and one of the largest ports in the world, with shipping lines established to all corners of the globe. Everything from dry bulk to liquid bulk, containers, and breakbulk, in which category one finds RoRo cargo, is passing through the port, constituting a total of 436,800,000 tonnes of cargo in 2020. The second busiest European port is Antwerp, in Belgium. Furthermore, the port of Ghent is part of the so-called North Sea Port – a conglomeration of Vlissingen, Terneuzen, and Ghent (see Figure 11). Consequently, the port extends over 60 kilometers, 9.100 hectares (ha), across two countries: Belgium and the Netherlands. It is ranked number 9 of all European seaports measured in the volume of goods and number 6 of seaports in the Hamburg – Le Havre range also measured in the volume of goods. Freight transportation through the inland waterways is already well developed, but there is still space for more cargo to be distributed via waterways. This region is ideal for the purposes of AEGIS, and this is why it was chosen for this Use Case B.

Figure 11: The ports within North Sea Port (Source: Deliverable D9.1 (Analysis of transport needs – Case B) [5]).

In summary, the objectives of UCB are to:

- Apply and validate the results from WPs 2-7 into use-case B, which examines the short sea and inland interface in Belgium and Netherlands, with partner DFDS being involved as a WP leader. The area under examination involves the ports of Rotterdam, Antwerp, Ghent, and Zeebrugge.
- Use the above results to bring cargo as close to the end destination as possible with small vessels with zero emission propulsion (battery, fuel cells, etc.).
- Address possible administrative and regulatory challenges and bottlenecks that should be tackled for efficient and environment-friendly solutions.

The main objective of the transport system for use case B is to shift cargo from the road to an inland waterway barge service, as illustrated in Figure 12. With this goal in mind, the transport system for use case B was understood as an interaction of advanced inland navigation vessels serving two specific flows in the region of Belgium and the Netherlands, of routes within these flows, of the ports along these routes, and of the transshipment from vessel to port.

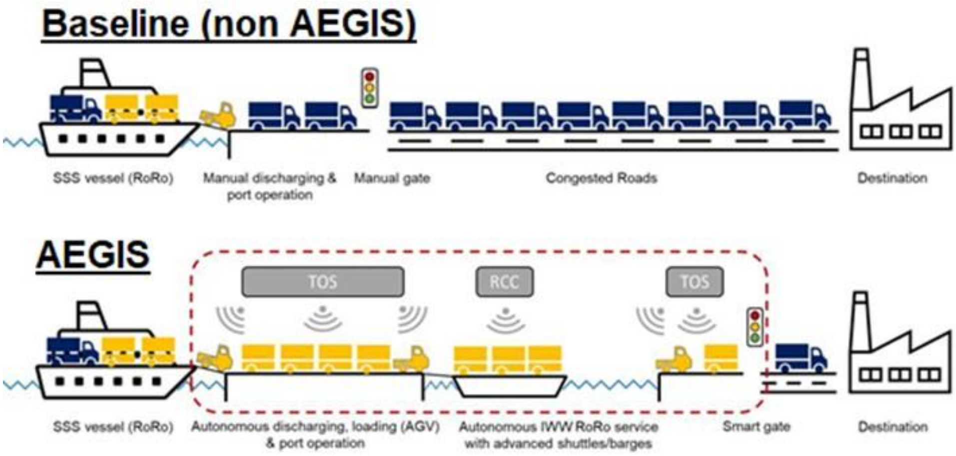


Figure 12: Baseline vs AEGIS scenarios. Source: DFDS.

Use case B involves two scenarios (Figure 12):

a) The baseline (non-AEGIS) scenario, which involves shipping cargo from Ghent to Rotterdam (and vice versa) by truck.

b) The AEGIS scenario, in which cargo is moved from Ghent to Rotterdam (and vice versa) via a canal onboard an AEGIS vessel (Figure 13).

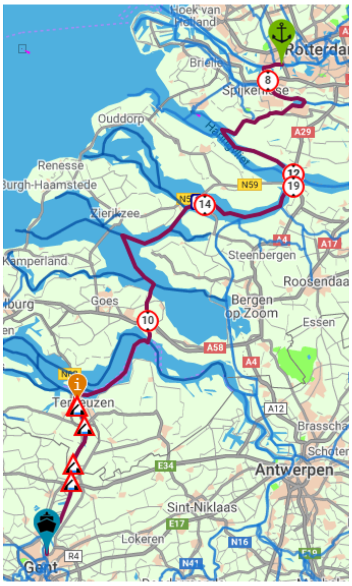


Figure 13: Rotterdam – Ghent route scenario for UCB

A main reason for selecting this route is because DFDS has terminals both in Rotterdam and Ghent – terminals which both are experiencing increasing cargo volumes and expansion projects in order to keep up with this cargo volume. Therefore, potentially redirecting cargo between the terminals into the short sea shipping, especially from Rotterdam to Ghent, would help alleviate these issues and could potentially have a broader, positive influence on the general flow overseas of cargo in and out of the terminals.

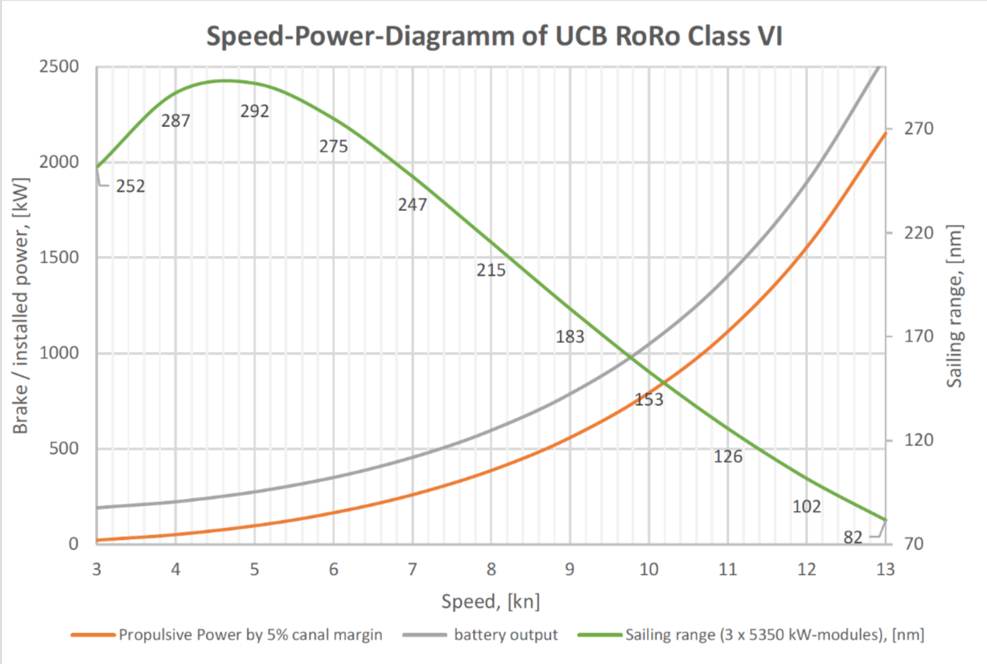
2.2.1 Ships specification

The envisioned vessel concepts for Use Case B are presented in Table 5. RoRo vessel concepts, i.e. for trucks, trailers, or other "rollable" cargo units, of the CEMT class VI concept w/transversal loading (double deck) was developed for this use case. It was tried to keep the draught as low as possible (in the range of 4.5 m) to be able to sail even on low water levels during summer periods. For CEMT class IV+, a transversal loading of trucks or trailers can be realized. Therefore, a RoRo concept with a capacity of 69 trucks/trailers was designed with a resulting vessel breadth of 18.1 and 15 m for trucks and trailers, respectively.

Table 5: Use Case B vessel.

Data	Vessel
Vessel Description	IWW CEMT Class VI
Vessel Type	RoRo IWW vessel
Route deployed in	Rotterdam - Ghent
Length Overall, Loa	139.20 m
Length Waterline, Lwl	125.50 m
Length between perpendiculars, Lbp	124.30 m
Beam Overall, Boa	15.00 m
Beam Waterline, Bwl	15.00 m
Design Draft, T	4.50 m
Depth to main deck, D	9.35 m
Displacement	6,716 tonnes
Gross Tonnage	4,630 GT
Wetted Surface	2,569 m^2
Waterplane Area	1794 m^2
Half Entrance Angle	43.60°
Stern Type Coefficient	-23
Main Engine Type	Fully electric, swappable batteries
Main Engine Fuel Type	battery
Design Speed	7- 8 knots
Vessel capacity	69 trailers/trucks (incl. 2–3 battery trailers/containers)
Cargo Handling Equipment	Lift and ramp; optional AGV (if only trailer)
Autonomy Level	high autonomy level (3-4)

Furthermore, based on information provided by ISE, the speed-power diagram for the vessel is shown in Figure 14.



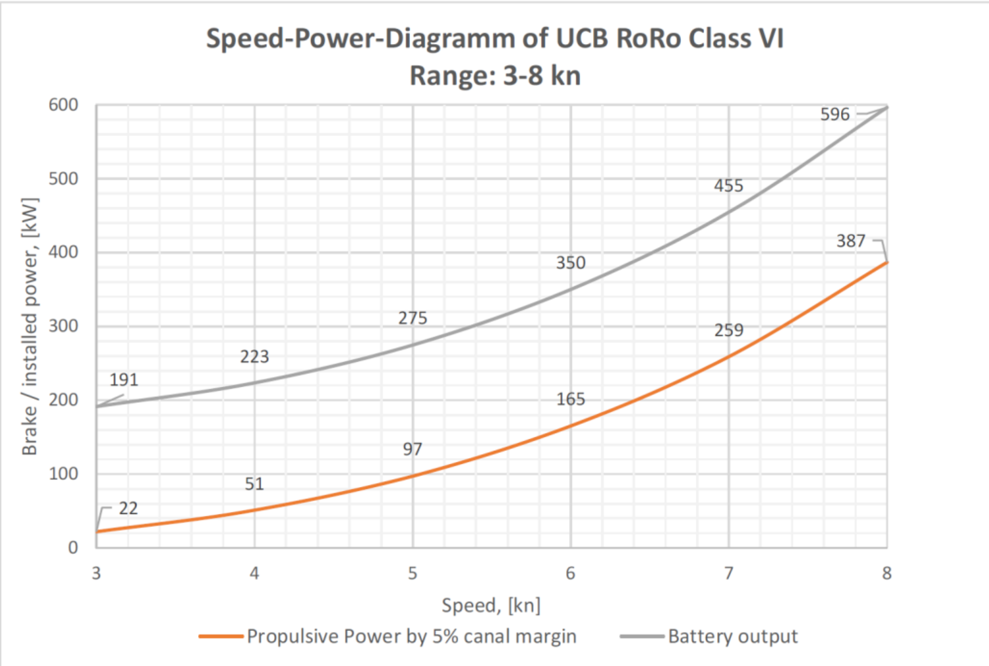


Figure 14: Use Case B, speed-power diagram of CEMT class VI vessel. Source: ISE.

2.3 Use Case C

Use Case C examines cargo traffic in the areas around Vordingborg and Aalborg and looks at possibilities to increase the use of waterborne transport by increasing automation of cargo handling and some types of ships. It will also look at possibilities for restructuring the terminal network and also increase inbound and outbound transport to the rest of Europe, in particular, Germany and possibly the Baltic states.

The objectives of UCC are to:

- To validate outputs from WPs 2-7 in two Danish ports, the Port of Vordingborg and the Port of Aalborg.

- To use the ports of Vordingborg and Aalborg as practical test sites for the application of the technical developments of AEGIS in redesigning logistic systems, developing new terminal concepts, applying automatic cargo handling, and improving digital connectivity.
- To use the ports of Vordingborg and Aalborg to address regulatory challenges and constraints to enhance new waterborne logistics solutions.

In the first Use Case C deliverable D10.1 (Potential transfer from road transport to short-sea-shipping in Denmark) [6], the potential gross volume that can be shifted from road transport to short-sea shipping in Denmark, categorized by different goods types, was examined. This encompasses analyses of the price structure for transportation of the goods by both road transport and short-sea shipping, including an analysis of last mile delivery. The report analyses all relevant goods in Denmark, including national and international goods. To have a comparable price structure baseline, it was found that any road transport would need to be more than 150 km in order for a shift to short-sea shipping would be economically viable. This included a last-mile analysis. For national goods, emphasis is put on the region of Northern Jutland as well as the Capital Region and Zealand, due to the case focus of the ports of Aalborg and Vordingborg, as well as the distance between these regions. Approximately 1 million tonnes of goods are transported to/from Northern Jutland (mostly of relevance to Port of Aalborg) and Zealand (mostly of relevance to Port of Vordingborg). Applying a scenario-based analysis, it was estimated that 177,540 tonnes of national goods, covered by 9,899 truck movements, could be shifted to sea yearly in Denmark.

Moreover, it was estimated that the potential gross volume of goods that can be shifted from road transport to short sea shipping (SSS) in Denmark is approximately 5 million tonnes yearly, or about 18% of the relevant goods by truck. It is again important to note that any short-sea shipping solution would be on par or cheaper than a competing direct road solution.

Deliverable D10.2 (SWOT analysis for Port of Vordingborg and Aalborg) [7] conducted a SWOT analysis for the Port of Aalborg and the Port of Vordingborg. The report concluded that Port of Aalborg has a strong financial position compared to the closest competitors. This provides great long-term opportunities to invest in new, autonomous port solutions. Short-term, it can be expected that the closest geographical competitors (the Port of Hirtshals and the Port of Frederikshavn) on RoRo would have a solid counter-reaction for a potential RoRo route. However, due to the CAPEX bindings of these two ports, it is assessed that the Port of Aalborg would have better long-term maneuverability for RoRo and overall terminal investments. Furthermore, the Port of Vordingborg has recently undergone vast development, including a large port expansion. This provides great opportunities yet simultaneously gives financial constraints in terms of investment capacity in the coming years. Possible short-term solutions would be to capitalize on goods that can be overtaken by decommissioned ports in the vicinity and carefully analyze a “virtual terminal» concept for possible RoRo activities.

After several discussions with the partners of this project and examination of several scenarios, the following scenarios for both ports were considered.

<u>For Aalborg:</u>

a) The baseline (non-AEGIS) scenario involves shipping cargo from the port of Gothenburg to the port of Hamburg (and vice versa) by truck. Specifically, this route consists of Gothenburg to Malmö, Malmö to Copenhagen, and Copenhagen to Hamburg and would be around 644 km.

b) In the AEGIS scenario, cargo is moved from the port of Gothenburg to the port of Aalborg (and vice versa) via an AEGIS vessel and then from the port of Aalborg to the port of Hamburg by trucks. The distance of the sea route is 160 km, and the land-based route is nearly 458 km.

For Vordingborg:

a) The baseline (non-AEGIS) scenario involves shipping cargo from the port of Vordingborg to the port of Rostock in Poland by ships and then from the port of Rostock to the port of Elblag in Poland (and vice versa) by trucks. The distance of the sea route is around 49 km, and the land-based route is 750 km.

b) In the AEGIS scenario, cargo is moved from the port of Vordingborg to the port of Elbląg (and vice versa) via an AEGIS vessel (the one specified for use case C- Vordingborg scenario). The distance of the route is 573 km.

2.3.1 Ships specification

According to deliverable D4.2 (Logistics analysis tool initial version) [4], the envisioned vessel concepts for Use Case C are presented in Tables 6 and 7. The diverse cargo and route options lead to the development of different vessel concepts for Use Case C. For the Aalborg case, a RoRo short-sea shipping vessel was studied using Use Case B synergies. A truck/trailer vessel can be adopted from a design for inland waterway conditions to be feasible for short-sea shipping between Denmark and South Sweden. As for use case B, a double-decker solution (combined with a lift system) is used to achieve a capacity of 50 – 60 trucks or trailers. For the Vordingborg case, a mixed container and bulk vessel concept with approx. 3500 tonnes were considered.

Table 6: Use Case C Aalborg case vessels.

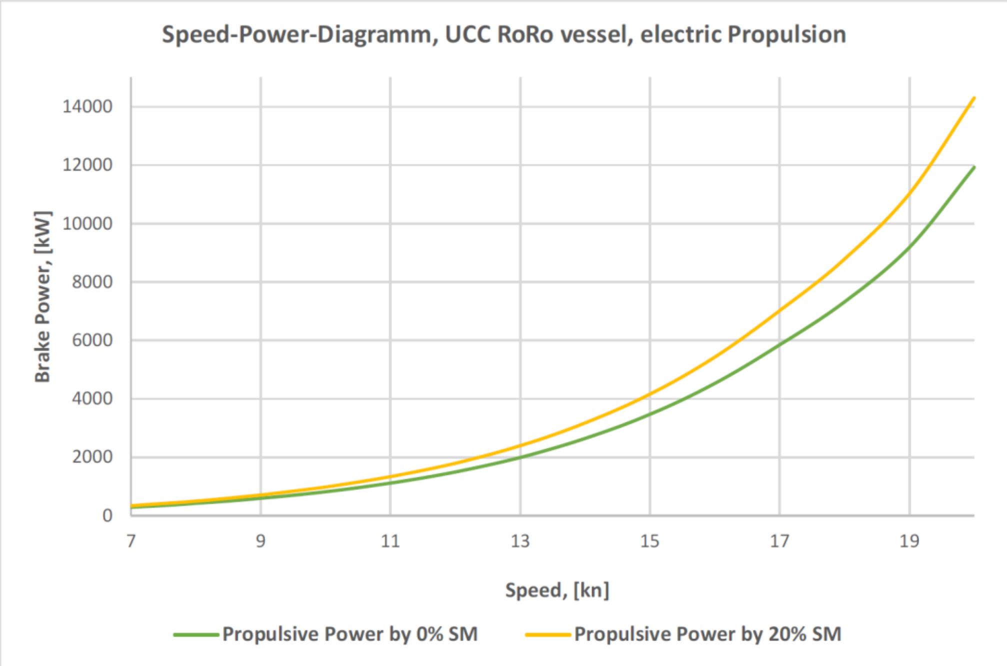
Data	Vessel
Vessel description	AHL-case: 55 units SSS RoRo vessel
Vessel Type	SSS RoRo
Route deployed in	Aalborg - Hamburg
Length Overall, Loa	127.47 m
Length Waterline, Lwl	127.42 m
Length between perpendiculars, Lbp	123.40 m
Beam Overall, Boa	16.90 m
Beam Waterline, Bwl	16.90 m
Design Draft, T	4.50 m
Depth to main deck, D	6.35 m
Displacement	8,394 tonnes
Gross Tonnage	5,700 GT
Wetted Surface	2876.21 m^2
Waterplane Area	1919.48 m^2
Half Entrance Angle	19.76°

Stern Type Coefficient	-25
Main Engine Type	Fully electric or Methanol propulsion system
Main Engine Fuel Type	Battery or Methanol
Design Speed	8 knots
Vessel capacity	55 trailers/trucks (37 main deck + 18 tank top)
Cargo Handling Equipment	Lift and ramp; optional AGV (if only trailer)
Autonomy Level	Medium autonomy level (2-3)

Table 7: Use Case C Vordingborg case vessels.

Data	Vessel
Vessel Name	VH-case: Combined SSS/IWW LoLo concepts for bulk & containers
Vessel Type	SSS/IWW LoLo
Route deployed in	Vordingborg - Elbląg
Length (max)	99.00 m
Breadth	15.00 m
Design Draft, T	3.90 m
Max airdraft	9.10 m
Main Engine Type	Methanol propulsion system
Main Engine Fuel Type	Methanol
Design Speed	10 knots
Vessel capacity	3500 tonnes (170 containers)
Cargo Handling Equipment	crane
Autonomy Level	2

Furthermore, based on information provided by ISE, the speed-power diagram for the vessels of Aalborg case for battery and methanol are shown in 15 and 16, respectively. For the Vordingborg case this is shown in Figure 17.



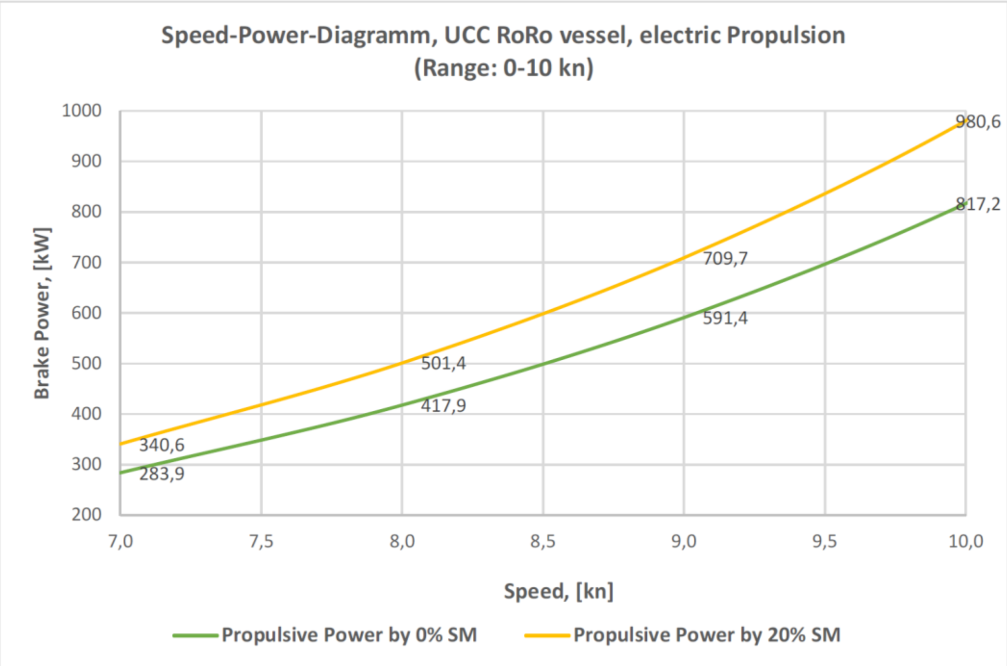


Figure 15: Use Case C, speed-power diagram of Aalborg case vessels (Electric system). Source: ISE.

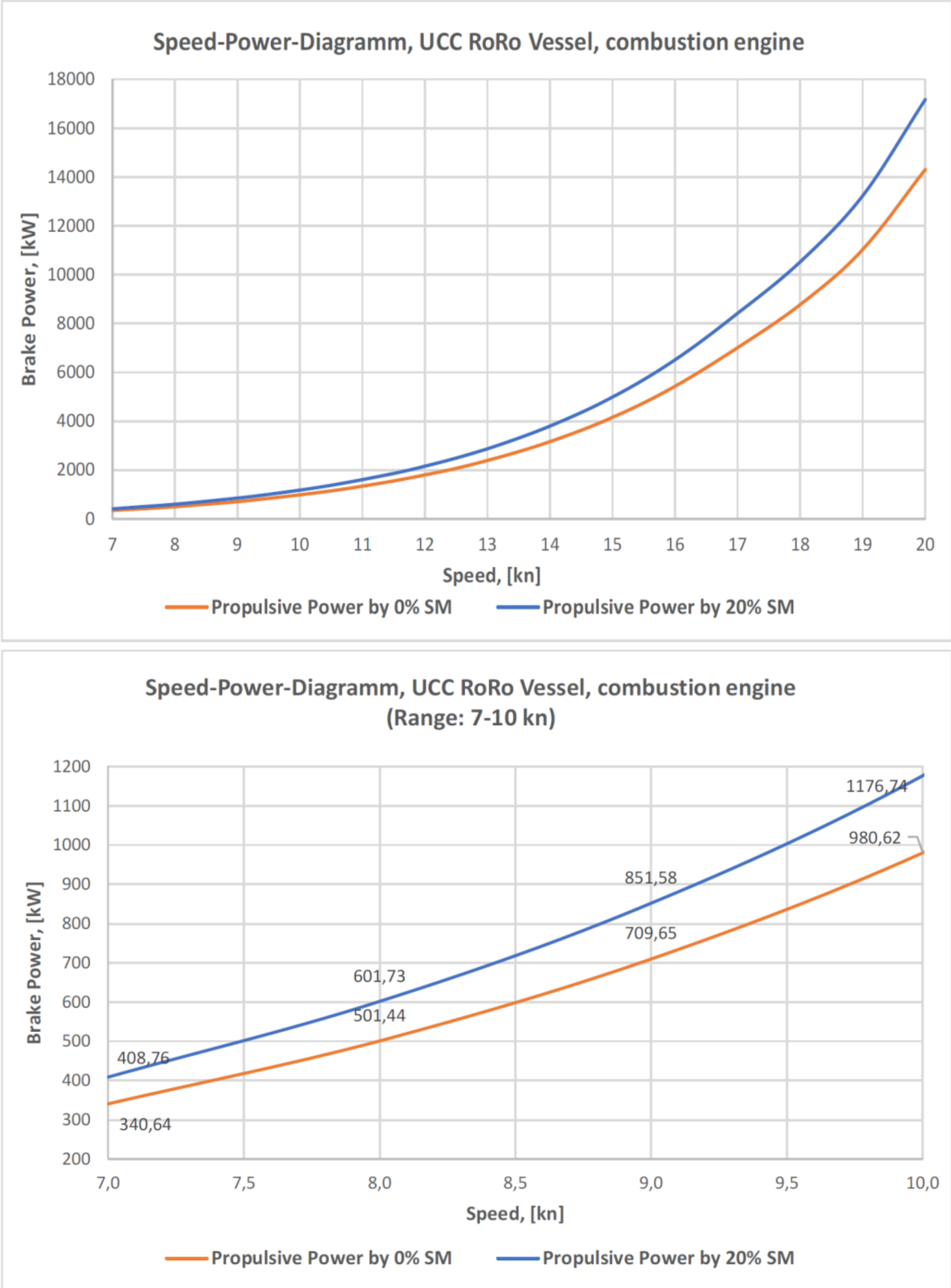


Figure 16: Use Case C, speed-power diagram of Aalborg case vessels (Methanol system). Source: ISE.

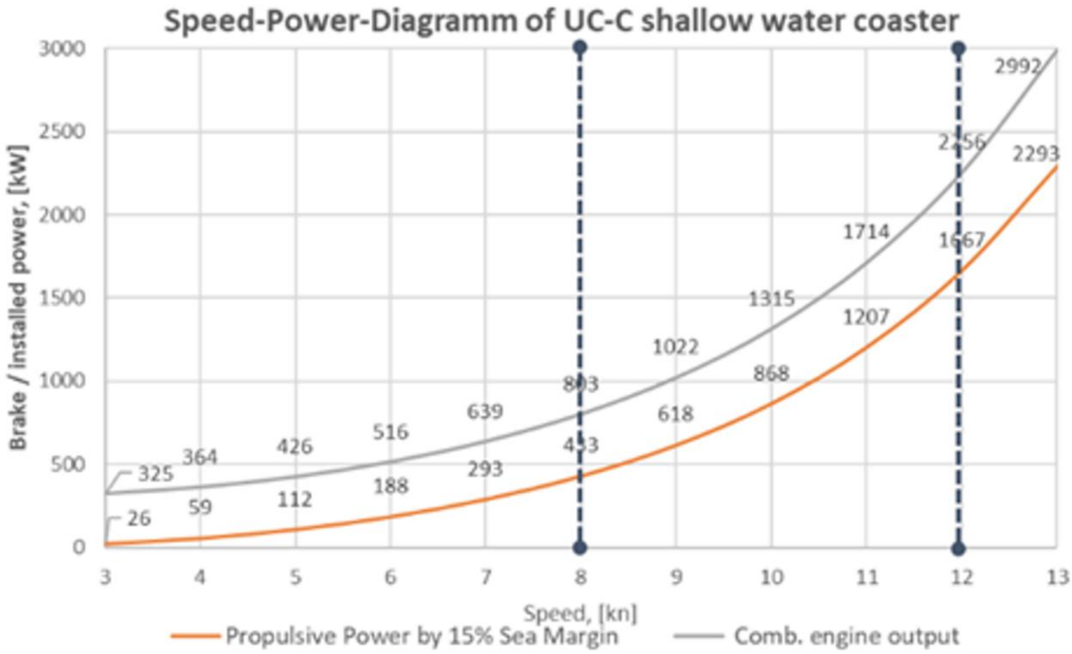


Figure 17: Use Case C, speed-power diagram of Vordingborg case vessel. Source: ISE.

3 Methodolody: evaluation of environmental KPIs

3.1 Preamble

The purpose of this section is to present the methodology for evaluating environmental KPIs. The methodology describes how the data assembled for each use case scenario are used to perform the economic CBA and assess the economic KPIs.

It is to be understood that any such methodology has two main components or parts:

(a) A general part, which is more or less independent of the use case under consideration.

(b) A specific part, which depends on the use case under consideration.

The above distinction is important, as it is conceivable that the data that is assembled for each use case may ultimately influence and customize the method to conduct the CBA.

The rest of this section first presents how the environmental KPIs are calculated based on the data template input that we requested from AEGIS partners. We start by introducing the quantitative modelling framework and the equations that link data input with the required KPIs.

It should be noted that, although in this research a maximum effort has been given to collect as much data as possible, some data were still unavailable by the time this report was being finalized. Also, for some KPIs, precise data would only be available after the real-world implementation of the AEGIS project. For several data, where uncertain, we have made some assumptions and approximations on the missing values and data.

3.2 General framework for the estimation of environmental KPIs

Deliverable D7.2 (Report on KPIs) [1] pertaining to the outcome of Task 7.1, presented the different KPIs for evaluating the AEGIS solutions and their comparison with existing transportation options. The process concerned several rounds of discussions, work between the consortium partners and Advisory Group (AG) members, and prioritization of retrieved KPIs. Table 8 is adapted from the above deliverable and presents the finalized environmental KPIs that we aim to analyze in this document. It is recalled that the above deliverable stated that these KPIs might be adjusted in the CBA, depending on the availability and quality of data.

In addition, it should be noted that there are two types of emissions, named Tank to Wake (TTW) (or Tank to Wheel for road or rail vehicles) and Well to Tank (WTT). TTW concerns the operational emissions of the vessel or vehicle. WTT concerns upstream emissions, those associated with the production of the fuel to the vessel or vehicle. Thus, a vessel burning hydrogen or ammonia has zero TTW GHG emissions, whereas the associated WTT emissions depend on how these fuels are produced[1]. If the fuels are produced using renewable energy sources their WTT emissions are also zero, however if the energy sources to produce these fuels are non-renewable (for instance, use of a coal plant to produce electricity), then the WTT emissions are nonzero and need to be accounted for. The same is the case with batteries. Battery electric propulsion has zero TTW emissions, however the WTT

[1] No hydrogen or ammonia is considered for AEGIS vessels, however this argument is valid for any kind of fuel used, for instance methanol or even using batteries.

emissions depend on how the energy used to power the batteries has been produced. There is also the term WTW (Well to Wake or Well to Wheel) which is the sum of WTT+TTW.

We note that in the project plan (and Grant Agreement) no delineation between these two types of emissions was made, and the main focus of the emissions calculation was by default assumed to be TTW. The same has been the case with deliverable D7.2 (Report on KPIs) [1]. However, due to the increased emphasis of policymakers, particularly in the EU, but also at the IMO, on WTW GHG emissions, in this report we have also calculated WTT (and WTW) emissions, but for CO_2 only. These concern both the baseline (non-AEGIS) solution and the AEGIS solution. No WTT/WTW emissions have been calculated for SO_x, NO_x and PM_{10} emissions, due to the uncertainty in the related data (for some insights into this subject see Zis et al. [16]). So all reported emissions KPIs for SO_x, NO_x and PM_{10} are only on a TTW basis.

It should also be clarified that the WTT analysis reported here is by necessity incomplete, being confined only to emissions produced during the production of the alternative fuel, or of the electrical energy to charge the batteries, as appropriate. Emissions associated with the transportation of the fuel, of the production of the batteries, or of the recycling of batteries have not been considered, being outside the scope of this report.

Table 8: Environmental KPIs (adapted from Table 6 of deliverable D7.2 (Report on KPIs) [1]).

KPI Level	KPI Sublevel	KPI Name	KPI Measurement	KPI Description
Environmental	Emissions	CO_2	g of CO_2/tkm	CO_2 emissions (TTW &WTT)
Environmental	Emissions	SO_x	g of SO_x/tkm	SO_x emissions (TTW only)
Environmental	Emissions	NO_x	g of NO_x/tkm	NO_x emissions (TTW only)
Environmental	Emissions	Particulate matter	g of PM_{10}/tkm	PM_{10} emissions (TTW only)
Environmental	Emissions	Waste emissions	kg	Amount of waste produced
Environmental	Emissions	Acoustic emissions - Noise	dB/per ship or truck	Noise emitted
Environmental	Emissions	Light pollution	Lumens/shipment	Brightening of the night sky
Environmental	Others	Terminal area per cargo unit	m^2/cargo unit	Amount of square meters of land needed to perform AEGIS operations as function of the cargo moved
Environmental	Others	Energy consumption	KW/cargo unit	Total energy needed for each AEGIS proposal
Environmental	Others	Use of renewable energy sources	%	Percentage of energy consumed that comes from environmental-friendly energy sources
Environmental	Others	Sustainability factor		Shows how environmental-friendly the AEGIS vessels are with respect to ecological footprint, recyclability and life cycle of the vessel and port equipment.

3.3 Data templates

As with the economic KPIs in deliverable D7.6, the environmental KPIs are linked with the fuel consumption data and information on the actual energy sources powering the vessels. Therefore, in order to estimate the KPIs values, data were solicited from the AEGIS partners. The data template circulated in the spring of 2021 to WP7 partners, which included the leaders of all other technical WPs and the leaders of all three use cases, requested the relevant information for the estimation of the environmental KPIs. The template contained 75 fields to be filled by AEGIS partners, but only the fields on the fuel consumption from each machinery onboard the vessel is required to estimate the environmental KPIs. A snapshot of the template is shown in Figure 18, where we highlight (in yellow) the data input necessary for calculating environmental KPIs. Annex A presents the rest of the data template. After this stage, to collect data during this research, we provided several questionnaires and sent them to our partners, to get more information. To do this, we also had several meetings to get more precise data.

Data	Units	ENTER INPUT HERE	COMMENT
Vessel Name	Name		
Vessel Type	Name		
Route deployed in	Name		
Geometric Characteristics (LPP, LOA, B, T)	meters		
Main Engine Power (MCR)	kW		
Main Engine Type/Model			
Main Engine Fuel Type			
Main Engine Fuel Consumption at 75% MCR	tonnes/day		
Auxiliary Engine & Boiler Power (MCR)	kW		
Auxiliary Engine & Boiler Type/Model			
Auxiliary Engine & Boiler Fuel Type			
Auxiliary Engine & Boiler Fuel Consumption at 75% MCR	tonnes/day		
Design speed	knots		
Vessel capacity	TEU/lane meters		
Vessel cargo handling equipment (if any): name	Name		
Vessel cargo handling equipment; number	#		
Cargo handling rate (per cargo handling unit)	TEUs/hour, LM/hour		
CAPEX-Price New Vessel	€		
OPEX- crew	€/year		
OPEX-maintenance	€/year		
OPEX-other (no fuel)	€/year		
Crew size (non-hotel)	#		
Autonomy Level	Fully manual/Operator Controlled/Automatic/Partial Autonomy/ Constrained Autonomous/ Fully Autonomous		
Load factor	%		
Any other relevant info.			

Figure 18: The data template circulated to the AEGIS use case leaders (“Route” component).

3.4 Mapping KPIs in terms of use case relevance and context

The complete list of environmental KPIs, as seen in Table 8, should be seen as generic for the overall AEGIS project. Some of the KPIs may be more or less relevant for each use case, depending on the overall objective of the use case and the involved stakeholders (and potential decision makers). In addition, the required input data needed to calculate each KPI may not be available in all use cases. This is because we are working with concepts and not actual operations. The latter is most evident when assessing the «to-be solutions» but also for the various «as-is solutions» A lack of reliable and valid input data may pose a challenge. Figure 19 shows this procedure.

For each use case, the stakeholders assessed each KPI in terms of validity. In addition, all KPIs were evaluated in terms of overall AEGIS validity by AEGIS partners and the AEGIS advisory group. In addition, for each use case, the KPIs were assessed in terms of data availability and accuracy. Finally, for each use case, the KPIs were assessed in terms of interested stakeholders, data input source, and required assumptions (KPI context). Hence, in addition to the previously presented Table 8, three extra columns were added:

- Data availability/accuracy was categorized as “yes,” “no,” and “maybe.”
- Prioritization by the AEGIS partners, the AEGIS advisory group, and the specific use case.
- KPIs capture and usage include the interested stakeholder, KPI usage, required data input, input data source, and required assumptions.

In section 4, where the KPIs are applied to each use case, we present the final list of KPIs that are relevant and obtainable for the specific use case.

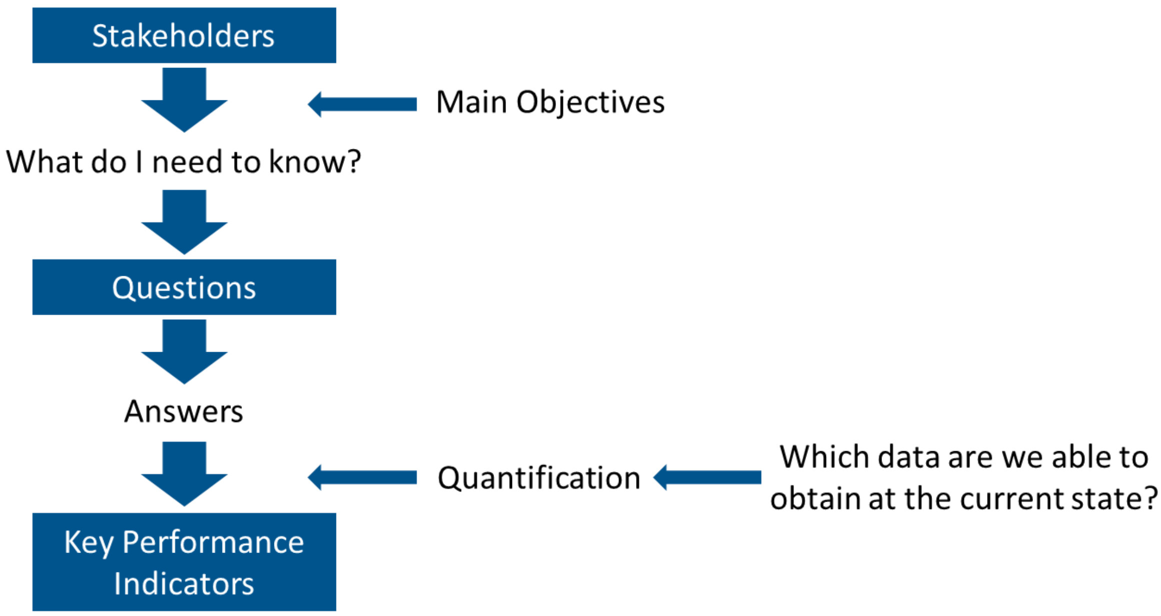


Figure 19: Mapping KPIs in terms of use case relevance and context.

3.5 KPIs calculation

As shown in Figure 18, the critical data for the environmental KPIs are the consumption of each engine at its design operating levels and the route information (distance, sailing time, and time spent at the port where auxiliaries are running). With this information, the calculation of each KPI is possible. The equations linking these input data will be explained in the next section.

3.5.1 Emissions KPIs

The first KPIs refer to the emissions generated during the transportation of cargo. As seen in Table 5, the KPIs have been defined as grams of emissions per tonne-kilometer. This would facilitate comparisons with the emissions intensity of other transportation modes. McKinnon (2007) [8] has produced a set of average carbon emission factors for 40-44 tonne trucks assuming different levels of payload and levels of running empty. The emissions intensity ranges from 0.01511 to 0.0397, depending on how loaded the truck was, although since 2007, there have been improvements in the fuel efficiency of diesel engines for trucks. However, it might not always be easy to retrieve information on the actual payload of the AEGIS solutions, which in turn would affect the vessel's fuel consumption. Therefore, this section will describe a few equations that can link these KPIs with the input from the data template. As with the majority of the economic KPIs, the key input here is the actual fuel consumption during each voyage. This fuel consumption can be multiplied with an appropriate emissions factor so as to calculate the emissions generated during the voyage. Dividing these emissions by the transport work will return the first four KPIs. Transport work in the AEGIS solutions can also be described in terms of TEU-NM, TEU-km, tonne-NM, or tonne-km, depending on how the information on the actual cargo onboard the vessels is given. Mathematically, these are shown below, taking the fuel consumption either as input from the ship operator or through calculation, as shown in deliverable D7.6.

We start with equation 1, which shows the estimation of the CO_2 KPI that expresses the grams of CO_2 emitted per tonne-kilometer of transport work.

$$CO_2 = \frac{\left(EF_{CO2} * FC_{sailing}\right) + \left(EF_{CO2} * FC_{port}\right)}{(Number\ of\ Cargo\ Units * Weight\ of\ one\ Cargo\ Unit) \cdot (Voyage\ distance * 1.852)} \tag{1}$$

Where EF_{CO2} is the CO_2 emission factor. This is a fuel-specific factor that is dimensionless and represents the mass of CO_2 emissions over the mass of fuel consumed. For conventional engines running on HFO, a typical EF_{CO2} is 3.114 , whereas if the engine runs on MDO, the factor is 3.206 (see also Table 9). $FC_{sailing}$ represents the total fuel consumption per voyage and is expressed in tonnes of fuel. Similarly, FC_{port} is the port fuel consumption, again in tonnes. We multiply the voyage distance (expressed in Nautical Miles – NM) with 1.852 to convert nautical miles into kilometers. We then divide the estimated grams of CO_2 per km by the total number of containers, or lane meters of cargo moved (depending on whether the ship is carrying containers or trailers as in the case of Ro-Ro ships). To convert the number of loaded containers or trailers into the mass of cargo carried, we define Unit weight as the average weight in tonnes per TEU or tonnes per lane meter (lm) of each container or lane meter of cargo transported onboard the vessels, respectively. This KPI can easily be expressed in different units (e.g., grams per NM-TEU, grams per voyage, grams per TEU, grams per week, per year, etc.) with simple algebraic manipulations.

A similar expression can be used for all other emissions KPIs so long as the appropriate emission factor is used. Therefore, for Sulphur oxides emissions (in grams of SO_x per tonne-km of cargo) we get equation 2:

$$SO_x = \frac{\left(EF_{SO_x} * FC_{sailing}\right) + \left(EF_{SO_x} * FC_{port}\right)}{(Number\ of\ Cargo\ Units * Weight\ of\ one\ Cargo\ Unit) \cdot (Voyage\ distance * 1.852)} \tag{2}$$

Where $EF_{SO_x}$is the SO_x emission factor. The value of EF_{SOx} depends on the Sulphur content in the combustion fuel. Typically, it is assumed that this is fully combusted; thus, the emission factor is equal to 2 multiplied by the % of the Sulphur content. For example, when MGO is burned with 0.1 % Sulphur content, EF_{SO2} is equal to 0.0002 grams of SO_x per gram of fuel. However, in the fourth IMO GHG study (2020) [9], this value has slightly changed as there are indications that the combustion is not full. Thus, that value is multiplied by 0.97753 to reflect the incomplete combustion of the Sulphur present in the fuel.

Similarly, for nitrogen emissions, the calculation of the relevant NO_x KPI is shown in equation 3:

$$NO_x = \frac{(EF_{NO_x} * FC_{sailing}) + (EF_{NO_x} * FC_{port})}{(Number\ of\ Cargo\ Units * Weight\ of\ one\ Cargo\ Unit) \cdot (Voyage\ distance * 1.852)} \quad (3)$$

Where EF_{NO_x} is the NO_x emission factor. For nitrogen emissions, in previous years a simplistic method assumed an emission factor of 0.000057 grams of NO_x per gram of fuel burned for slow-speed engines and a factor of 0.087 for medium-speed engines (for example, auxiliary engines). However, considering the requirements for reduced NO_x emissions per IMO regulations (Tier II and III engines), the fourth IMO GHG study suggests fuel-based emissions factors. In 2018, a value of 0.0000759 was used for HFO, 0.00005671 for MDO, and 0.00001344 for LNG.

For the particulate matter (PM) KPI that is also expressed in grams of pollutant per tonne-km, equation 4 provides the means for its calculation.

$$PM_{10} = \frac{(EF_{PM_{10}} * FC_{sailing}) + (EF_{PM_{10}} * FC_{port})}{(Number\ of\ Cargo\ Units * Weight\ of\ one\ Cargo\ Unit) \cdot (Voyage\ distance * 1.852)} \quad (4)$$

Where EF_{PM} is the PM emission factor.

All emissions KPIs are expressed in this unit (grams per tonne-km), which facilitates comparisons across different transportation modes. At the same time, important policy metrics such as the EEDI of the IMO are expressed in grams per tonne-mile. However, since in AEGIS we will also compare with road transportation modes, the decision to use grams of pollutant per tonne-km was made. On the discussion with emission factors, we note that there are also emission factors expressed in terms of grams of pollutant per energy used (g/kWh). These can also be useful when considering robust data on the actual energy consumption during a voyage.

Finally, we present a summary of the fuel-based emission factors that have been used so far in this WP. Again, these are TTW emissions.

Table 9: Fuel based emission factors for key pollutants (g of pollutant/kg of fuel). Source: IMO (2020) [9]

Fuel	CO_2	SO_x	NO_x	PM_{10}
HFO	3,114	0.1	75.9-78.6	6.96-7.53
MDO	3,206	0.02	52.1-57,6	0.92-0.97
LNG	2,749-2,753	0.03	5.6-10.9	0.11
Methanol	1,375	0	10.54	0.000736

3.5.2 Waste emissions

Waste emissions are expressed in kg and have been loosely defined in the context of WP7. In essence, waste emissions refer to any disposal of waste streams during a voyage. Traditionally these include sewage, greywater, hazardous waste, bilge water, ballast water, and solid waste. Some of these streams will be minimized or even eliminated due to the absence of crew in the transition to a fully autonomous ship. However, some streams will still remain (for example, ballast water). This is a KPI that may not be feasible to assess quantitatively before the actual deployment of the vessels, but it would be a ”nice to have” indicator once these ships are operational.

3.5.3 Acoustic emissions

These emissions can be measured in decibels (dB), and we can consider two main areas of attention. The first and rather obvious concern is for noise near the shore and at ports, and the sources can be both the ship’s engine during approach/departure as well as during berth. At the same time, cargo handling operations and intermodal transport operations (for example, hinterland connections) are also sources of noise. The second concern is underwater noise, which can significantly affect marine life. This is an essential concern for marine mammals [[10], with significant research efforts mainly targeting the West Coast of the Americas [11]. Moving to autonomous shipping and autonomous port operations can result in some reductions in noise levels, particularly in the case of using electricity as a power source. However, marine engines and diesel engines powering cargo handling equipment tend to create additional noise due to the vibrations during fuel combustion. Like waste emissions, measuring the acoustic emissions would be a “nice to have” indicator later in the project.

3.5.4 Light pollution

The last KPI that falls under the category of emissions KPI is light pollution (to be measured in lumens). This is a concern during nighttime for nearby community ports and residents near shores with nearby ship traffic. Lighting requirements would be reduced for fully autonomous operations at a port, although even in such cases, there would still be staff monitoring the operations on the spot. Regarding shipping operations, even a fully autonomous vessel would still be emitting light, as it should still be clearly visible.

3.5.5 Other Environmental KPIs

The last group contains somewhat more diverse KPIs that have some environmental repercussions but are not directly translated into quantifiable emissions. The first KPI is the terminal area for cargo operations (measured in m^2 per cargo unit – TEU or lane meters). The second KPI is also related to cargo units and expresses the energy consumption of kW per cargo unit. The third KPI refers to the % use of renewable energy sources (RES). It can again be perceived as a separate KPI for the AEGIS vessel (when it uses either alternative fuels or is partly powered by electricity) but also for the cargo handling operations at the port. Finally, the last environmental KPI refers to the sustainability factor, which has not been fine-tuned yet in the context of the AEGIS project.

4 Application of environmental KPIs on Use Cases

In this section we have calculated the KPIs relevant to each Use Case in baseline and AEGIS scenarios. Also, we have compared these scenarios to investigate the advantages of each of them.

4.1 Use Case A

The final list of relevant and obtainable KPIs for the specific UCA for the mother and daughter cases are presented in Table 10. This is the end result of the Mapping of the KPIs in terms of use case relevance and context, as previously described.

Table 10: Environmental KPIs for Use Case A (adapted from Table 6 of deliverable D7.2 (Report on KPIs) [1]).

KPI Level	KPI Sublevel	KPI Name	KPI Measurement	KPI Description
Environmental	Emissions	CO_2	g of CO_2/tkm	CO_2 emissions
Environmental	Emissions	SO_x	g of SO_x/tkm	SO_x emissions
Environmental	Emissions	NO_x	g of NO_x/tkm	NO_x emissions
Environmental	Emissions	Particulate matter	g of PM_{10}/tkm	PM_{10} emissions
Environmental	Emissions	Acoustic emissions - Noise	dB/per ship or truck	Noise emitted
Environmental	Others	Terminal area per cargo unit	m^2/cargo unit	Amount of square meters of land needed to perform AEGIS operations as function of the cargo moved
Environmental	Others	Use of renewable energy sources	%	Percentage of energy consumed that comes from environmental-friendly energy sources

Based on the questionnaires shown in Annex A, we have made efforts to collect data from our partners and stakeholders. However, some data in the mother and daughter case were still unavailable. These KPIs and the associated approximations are explained in Table 11.

Table 11: Lack of data and associated approximations in UCA.

KPIS	Explanation
Acoustic emissions - Noise	The lack of data for this KPI was for mother vessels. Unfortunately, we do not have enough data to measure noise pollution of combustion systems with methanol fuel. According to data from ISE, conventional ships will have pollution equivalent to 65 to 85 dB. In the worst case, if we assume that the sound pollution with methanol fuel is equal to that of MDO, since ten percent of AEGIS ships' power is from electricity and the batteries have sound pollution equivalent to 11 dB. It is important to mention that the methanol propulsion section will use new and updated systems, and the level of acoustic emissions will also be reduced in this way as well.

Light pollution	The lack of this KPI was for both types of ships. But it is anticipated that light pollution will be lower. For the mother ship, since both are sea routes, on the other hand, the autonomy level of AEGIS ships is not high (level 2), and we still need staff on board. Therefore, we cannot expect noticeable improvement and even noticeable changes in the level of pollution in this part. But on the other side, in daughter ships, we expect significant improvements because autonomous vessels will replace many trucks on the roads without needing a crew. Therefore, there will definitely be created less light pollution.

In the following, according to the routes explained in section 2.1, the results obtained in both scenarios (baseline and AEGIS) for the mother, daughter 1 and daughter 2 vessels are respectively in Tables 12 to 14.

For the mother vessel, the calculation has been done for one way route (Rotterdam to Hitra and Rotterdam to Orkanger) in a week. Also, calculations have been done based on four conventional ships for the base scenario and four ships for the AEGIS scenario, two of which have a new design. In addition, according to the data we have received from ISE, two cranes have been considered for loading and unloading the ship. The types of these cranes and their energy consumption are shown in Table 15.

In addition, since the propulsion system of the mother vessel is a hybrid fuel system of methanol and battery, we need the percentage of each of them. After holding a meeting with SINTEF and since methanol fuel will be the ship's main fuel, 90 % of the consumed energy is allocated to methanol and 10 % to the battery.

For the daughter vessels, the AEGIS solution will compete mainly with existing road infrastructure, as the expected shipments in both cases are on-demand services. In Tables 13 and 14 the calculation has been done for round trip and considered the frequency of services in a week. Also, to compare the baseline scenario with the AEGIS, the number of trucks/trips required to equal the shipload is considered. In addition, we assumed the speed of the first daughter vessel as 8 knots, and for the second daughter vessel as 5 knots.

Table 12: Results of mother vessel in UCA.

<table>
<tr><th rowspan="3">KPI</th><th rowspan="3">KPI Name</th><th rowspan="3">KPI Measurement</th><th colspan="3">Result</th><th rowspan="3">Description</th></tr>
<tr><th colspan="2">AEGIS (Rotterdam-Hitra)</th><th rowspan="2">Baseline (Rotterdam-Orkanger)</th></tr>
<tr><th>New Vessel (Methanol + Battery)</th><th>NCL</th></tr>
<tr><td>Emissions</td><td>CO_2-WTT</td><td>g of CO_2/tkm</td><td>0.27</td><td>1.06</td><td>1.06</td><td></td></tr>
<tr><td>Emissions</td><td>CO_2-TTW</td><td>g of CO_2/tkm</td><td>3.32</td><td>5.68</td><td>5.67</td><td></td></tr>
<tr><td>Emissions</td><td>NO_x-TTW</td><td>g of NO_x/tkm</td><td>0.0104</td><td>0.14</td><td>0.14</td><td></td></tr>
<tr><td>Emissions</td><td>SO_x-TTW</td><td>g of SO_x/tkm</td><td>0</td><td>0.006</td><td>0.006</td><td></td></tr>
<tr><td>Emissions</td><td>Particulate Matter (PM_{10})-TTW</td><td>g of PM_{10}/tkm</td><td>$1.8X10^{-9}$</td><td>0.0016</td><td>0.0016</td><td></td></tr>
<tr><td>Emissions</td><td>Acoustic Emmissions-Noise</td><td>dB/per ship or truck</td><td>11</td><td>65-85</td><td>65-85</td><td></td></tr>
<tr><td>Others</td><td>Terminal Area Per Cargo Unit</td><td>m^2/cargo unit</td><td>(205;69)</td><td>(261;88)</td><td>(261;232)</td><td>The first figure is for Rotterdam. The second is relevant to Hitra or Orkanger.</td></tr>
<tr><td>Others</td><td>Use of Renewable Energy Sources</td><td>%</td><td colspan="3">(17.29; 98)</td><td>The first figure is for the Netherlands and the second is for Norway.</td></tr>
</table>

Table 13: Result of daughter vessel 1 in UCA.

<table>
<tr><th rowspan="2">KPI</th><th rowspan="2">KPI Name</th><th rowspan="2">KPI Measurement</th><th colspan="2">Result</th><th rowspan="2">Description</th></tr>
<tr><th>AEGIS</th><th>Baseline-Truck</th></tr>
<tr><td>Emissions</td><td>CO_2-WTT</td><td>g of CO_2/tkm</td><td>0.123</td><td>4.4</td><td></td></tr>
<tr><td>Emissions</td><td>CO_2-TTW</td><td>g of CO_2/tkm</td><td>0</td><td>22.5</td><td></td></tr>
<tr><td>Emissions</td><td>NO_x</td><td>g of NO_x/tkm</td><td>0</td><td>$7.8X10^{-3}$</td><td></td></tr>
<tr><td>Emissions</td><td>SO_x</td><td>g of SO_x/tkm</td><td>0</td><td>$8.7X10^{-5}$</td><td></td></tr>
<tr><td>Emissions</td><td>Particulate Matter (PM_{10})</td><td>g of PM_{10}/tkm</td><td>0</td><td>$8.7X10^{-5}$</td><td></td></tr>
<tr><td>Emissions</td><td>Acoustic Emmissions- Noise</td><td>dB/per ship or truck</td><td>11</td><td>80</td><td></td></tr>
<tr><td>Others</td><td>Terminal Area Per Cargo Unit</td><td>m^2/cargo unit</td><td>630</td><td>---</td><td>Calculated for Hitra</td></tr>
<tr><td>Others</td><td>Use of Renewable Energy Sources</td><td>%</td><td colspan="2">98</td><td></td></tr>
</table>

Table 14: Result of daughter vessel 2 in UCA.

KPI	KPI Name	KPI Measurement	Result		Description
			AEGIS	Baseline-Truck	
Emissions	***CO_2-WTT***	g of CO_2/tkm	0.071	4.4	
Emissions	***CO_2-TTW***	g of CO_2/tkm	0	22.5	
Emissions	***NO_x-TTW***	g of NO_x/tkm	0	$7.8X10^{-3}$	
Emissions	***SO_x-TTW***	g of SO_x/tkm	0	$8.7X10^{-5}$	
Emissions	***Particulate Matter (PM_{10})***	g of PM_{10}/tkm	0	$8.7X10^{-5}$	
Emissions	***Acoustic Emmissions-Noise***	dB/per ship or truck	11	80	
Others	***Terminal Area Per Cargo Unit***	m^2/cargo unit	467	---	Calculated for Hitra
Others	***Use of Renewable Energy Sources***	%	98		

Table 15 – Power consumption of crane

Type of drive system	Crane type	Average power
Closed-loop hydraulic	LC45 Cylinder	137 KW
Closed-loop hydraulic	GL45 Rope	126 KW
VFD new generation	GLE45 Rope	62 KW

As one can see for the KPI of use of renewable energy sources, the data for the Netherlands is that 17.29 percent of the electricity production comes from renewable energy sources [12]. Also, for Norway, 98 percent of the electricity production comes from renewable energy sources[2].

For the KPI of terminal area per cargo unit, the Rotterdam terminal is currently undergoing a larger extension, increasing the present 135,000 m^2 with an approximately additional 90,000 m^2 (Deliverable D9.2 (Transport system specification case B) [13]). For the Hitra this space is around 75,589 m^2 [3], and for the Orkanger the zoning plan provides a baking area of about 200,000 m^2 for freight handling, logistics and port-related industry. The areas will be sufficient to handle a future cargo volume of 100,000 TEUs (deliverable D8.2 (Transport system specification– Case A) [2]).

As one can generally see in Table 12, there is a noticeable advantage for the AEGIS solution compared to the baseline solution in terms of the amount of GHG emissions. For example, in CO_2 TTW, according to the equation below, we see a decrease of approximately 21% in g /tkm.

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[2] https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/

[3] https://en.wikipedia.org/wiki/Hitra

$$100 \times \frac{(5.67) - ((3.32 + 5.68)/2)}{5.67} \sim 21\% \quad (5)$$

In the mother case, for the emission rate of greenhouse gases (gr/kWh), we have three fuel types: Battery, methanol, and diesel ship oil (MDO). This number is equal to zero for the battery in the TTW section, and for other fuels, we have used Table 16.

Table 16: Fuel based emission factors for key pollutants (g of pollutant/kWh). Source: Balcombe et al. (2021) [14]

Fuel	CO_2	SO_x	NO_x	PM_{10}
HFO	579.4	5.7	13.4	0.63
MDO	557.5	0.57	14	0.16
Methanol	541.4	0	1.7	$29X10^{-6}$

For example, to calculate the CO_2 TTW emission for the new mother AEGIS ship, we use equation 6. In expression 6, we multiplied the energy consumption of one ship in the emission factor according to the percentage use of methanol and battery fuels. Also, in the denominator, we have calculated the amount of weight moved in the distance traveled.

$$CO_2\ emission - TTW: \frac{(0.9 * (333410.3 * 541.4)) + (0.1 * (333410.3 * 0))}{(1482 * (1100 * 30))} \sim 3.32 \quad (6)$$

To calculate the CO_2 WTT for new mother vessels, we have used Table 17 in the battery calculation section. As one can see in Table 17, compared with the existing solution, it is expected that the emissions will be much lower for the AEGIS solution, particularly due to the Norwegian grid that is far cleaner (only 16 grams of CO_2 per kWh). In the Netherlands, the grid is not as clean (441 grams of CO_2 per kWh), but the charging will be done in both countries, and thus an average value should be used for comparison. In addition, For the methanol part, an IMO report [15] on methanol as marine fuel shows the WTT emissions from methanol produced with biomass vary largely based on electricity source and the amount of biomass deficit. The report suggests an approximate 25 g CO_2 eq/MJ life cycle WTT emission using the Finnish electricity mix, accounting for both methanol and wood transport emissions. If, in addition, there is a 15 % biomass deficit, and this deficit is covered by burning residual fuel oil, the life cycle GHG emissions rise to around 70 g CO_2 eq/MJ. It should be mentioned that one MJ is equivalent to 0.27 kWh. Furthermore, we used 104 g/kWh for WTT of CO_2 emissions for conventional mother ships.

Like the mother case, as one can see in Tables 13 and 14, the greenhouse gas TTW emissions in the AEGIS scenario are significantly lower for both daughter ships. Indeed, because of the battery propulsion system for AEGIS ships, these KPIs are equal to zero.

Table 17: UCA-Mother case when powered by batteries.

Country	Ship Energy Consumption (kWh/km)	Payload (Tonnes)	Grid Emission Factor	Emissions intensity (g CO_2/tkm)
Norway	224.97	33000	16	0.1091
Netherlands			441	3.01
Average				1.56

For the truck, we used the Volvo brand, which characteristics of this type of truck are shown in Table 18 [12]. Table 18 summarizes the characteristics of the Volvo Trucks. Knowing the fuel's contents, the fuel consumption (0,26 l/km), and the Euro 6 engine emission standards, it is possible to calculate the emissions per tonne-kilometer for a fully loaded trailer. Hence, as one see in Table 19, according to emissions factors that come from Podiotis and Daskalaki (2021) [12], we calculated TTW emissions for one truck in Table 19.

Table 18: The specification and energy consumption of selected truck (Podiotis and Daskalaki, 2021 [12]).

Volvo truck name	Volvo FH
Engine	D13k500 Euro 6 Diesel Engine
Max power output at 1530-1800 r/min	500 hp (368 kw)
Fuel	Diesel EN590
Consumption	26 Liters/100 km
Emission standards	Euro 6

Table 19: UCA-Daughter case for baseline scenario-one truck (Podiotis and Daskalaki, 2021 [12]).

Emission	Emissions Factor (g/l)	Fuel Consumption per tonne transported (l/tKm)	Emissions (g/tKm)
CO_2	2600	0.009	22.5
NO_x	0.9		7.8X10-3
SO_x	0.01		$8.7X10^{-5}$
PM_{10}	0.01		$8.7X10^{-5}$

On the other hand, by calculating the amount of CO_2 emissions on a WTT basis, it can be seen that the absolute advantage is still with the AEGIS solution. For this matter, Table 20 shows these emissions for both ships.

Table 20: UCA-Daughter case, powered by batteries.

Ship	Ship Energy Consumption (kWh/Km)	Payload (Tonnes)	Grid Emission Factor	Emissions intensity (g CO_2/tkm)
Daughter 1	13.84	1800	16	0.123
Daughter 2	7.17	1620		0.071

Also, for the baseline scenario to calculate the CO_2 emissions for the WTT, we used the data that comes from Holland et al., (2009) [18]. In fact, according to it, the EN 590 diesel well-to-tank GHG emissions are 14.2 grCO_2eq/MJ diesel. To calculate the CO_2 emissions for the WTT of the trucks (based on g/tkm), we have used equation 7 that the conversion coefficients 35.49M MJ/l and 0.26 l/Km come from Podiotis and Daskalaki (2021) [12].

$$CO_2\ emission\ of\ daughter\ 1 - WTT: \frac{14.2 * 35.49 * 0.26}{30(t)} \sim 4.4 \quad (7)$$

4.1.1 Analysis of UCA

In this section, we further analyze the results obtained from UCA. First, a simple analysis has been made according to the results obtained for the cases of mother and daughter vessels in Tables 21 and 22, respectively. As seen in these Tables, the green and red cells show the advantages of the AEGIS and baseline scenarios on that KPIs, respectively. Also, orange cells represent there is no significant difference between the two scenarios.

Table 21 – Comparing the baseline scenario and AEGIS in the mother case in UCA.

KPI Name	Mother	
	AEGIS	Baseline
CO_2-WTW		
NO_x-TTW		
SO_x-TTW		
PM_{10}-TTW		
Acoustic Emmissions- Noise		

Table 22 – Comparing the baseline scenario and AEGIS in the daughter cases in UCA.

KPI Name	Daughter 1		Daughter 2	
	AEGIS	Baseline-Truck	AEGIS	Baseline-Truck
CO_2-WTW				
NO_x-TTW				
SO_x-TTW				
PM_{10}-TTW				
Acoustic Emmissions- Noise				

It is expected that after the implementation of AEGIS, we will have a reduction in gas emissions in the case of the mother ship. Also, this improvement reaches nearly significantly in the case of daughter ships. The reason for this is due to the use of electricity in these types of ships.

In the rest of this section, we look at how much gas emissions will be reduced over the years with the implementation of AEGIS.

For the mother ships case, we have depicted all four pollutants under consideration in figures 20 to 23, respectively. As one can see in the figures, if we consider year 2030, according to the equations below, the total reductions of emissions are as follows.

$$CO_2 - WTW: (454{,}960) - (360{,}988) = 93{,}972\ tonnes\ of\ CO_2 \quad (8)$$

$$NO_x: (9{,}464) - (4{,}871) = 4{,}593\ tonnes\ of\ NO_x \quad (9)$$

$$SO_x: (406) - (191) = 215\ tonnes\ of\ SO_x \quad (10)$$

$$PM_{10}: (110) - (51) = 59\ tonnes\ of\ PM_{10} \quad (11)$$

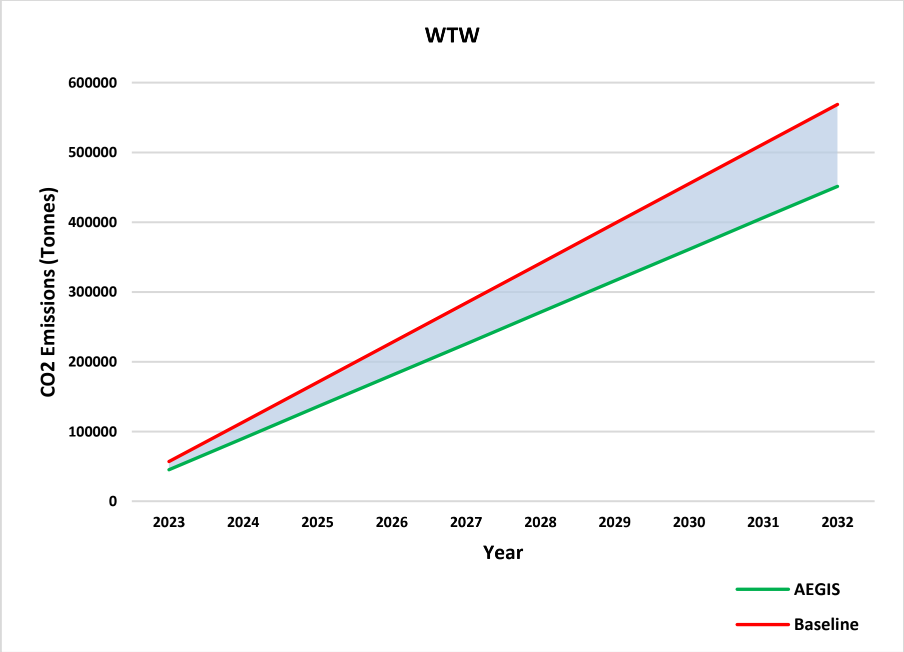


Figure 20: WTW CO_2 emissions for UCA-Mother case.

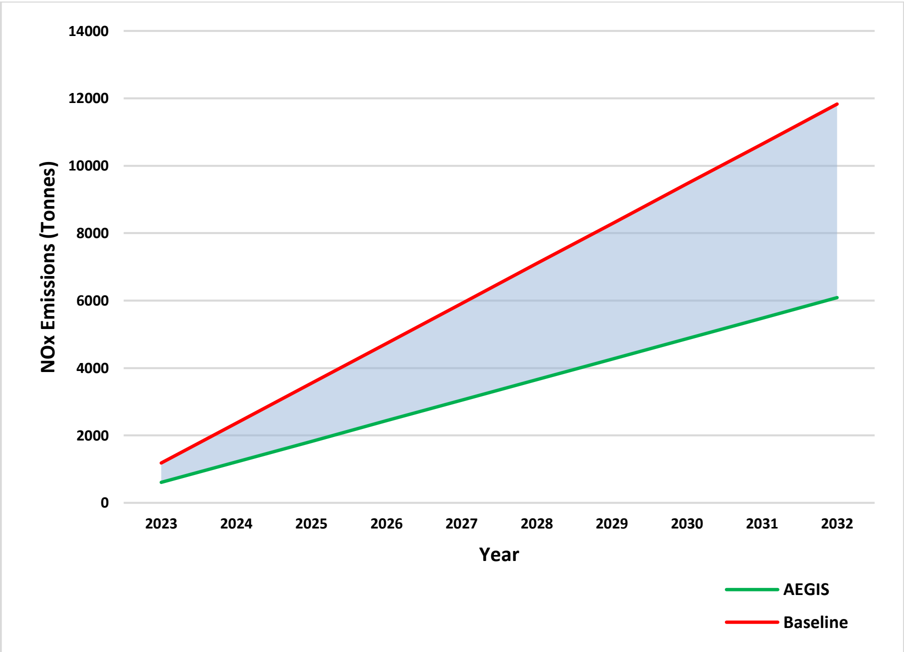


Figure 21: TTW NO_x emissions for UCA-Mother case.

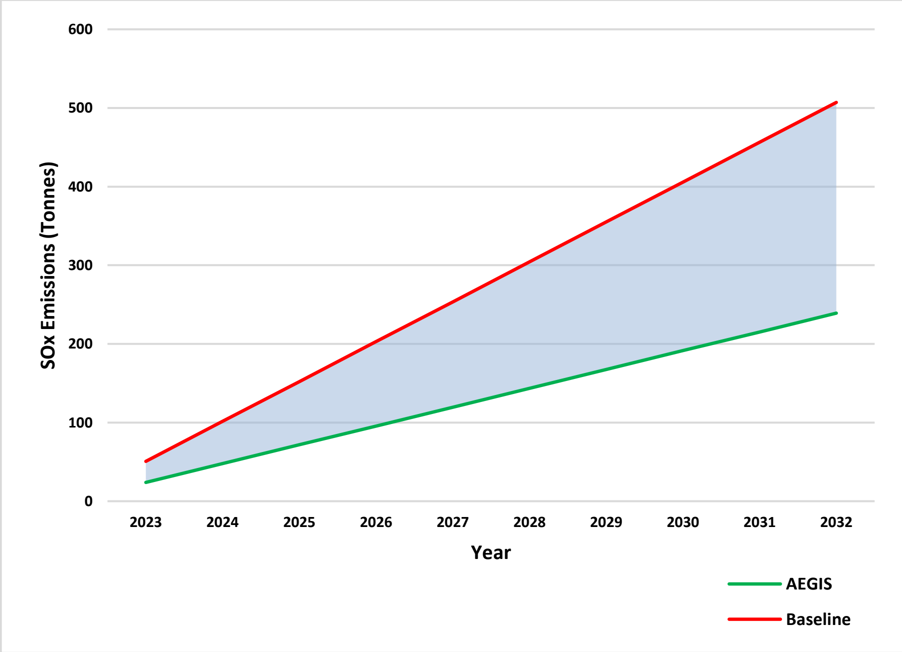


Figure 22: TTW SO_x emissions for UCA-Mother case.

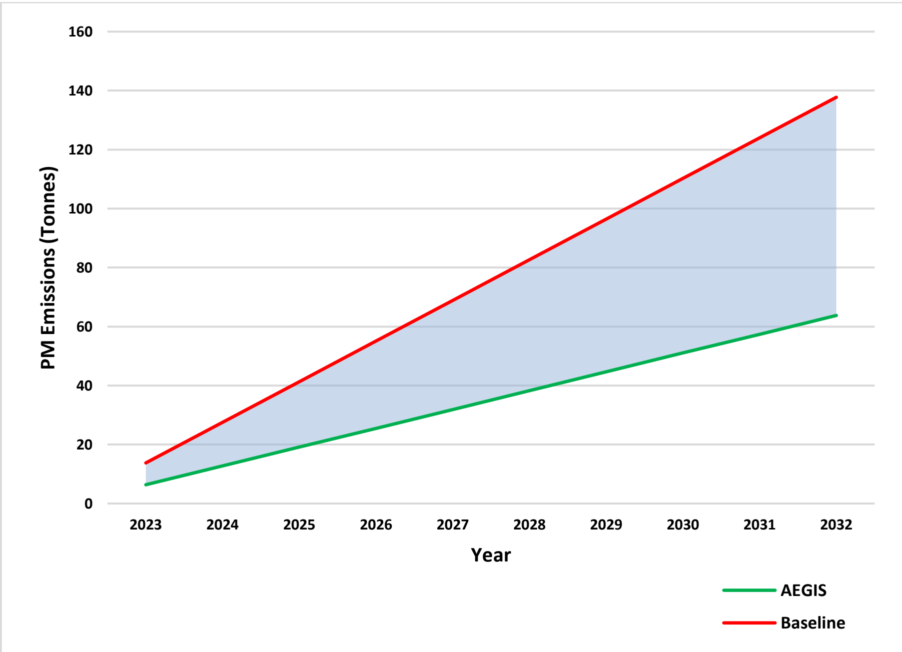


Figure 23: TTW PM_{10} emissions for UCA-Mother case.

Furthermore, for the daughter ships, we calculated the total CO_2 production cycle over ten years (WTT+TTW), shown in figures 24 and 25 for the first and second ships, respectively. As one can see, the absolute superiority is with the AEGIS scenario, and the amount of CO_2 reduction decreases significantly every year that passes. For example, after eight years in 2030, according to the following equations, we will have saved the following emissions for Vessels 1 and 2, respectively.

$$CO_2 - WTW\ (Daughter\ 1): (29{,}335) - (117) = \ 29{,}218\ tonnes\ of\ CO_2 \quad (12)$$

$$CO_2 - WTW\ (Daughter\ 2): (15{,}863) - (33) = \ 15{,}830\ tonnes\ of\ CO_2 \quad (13)$$

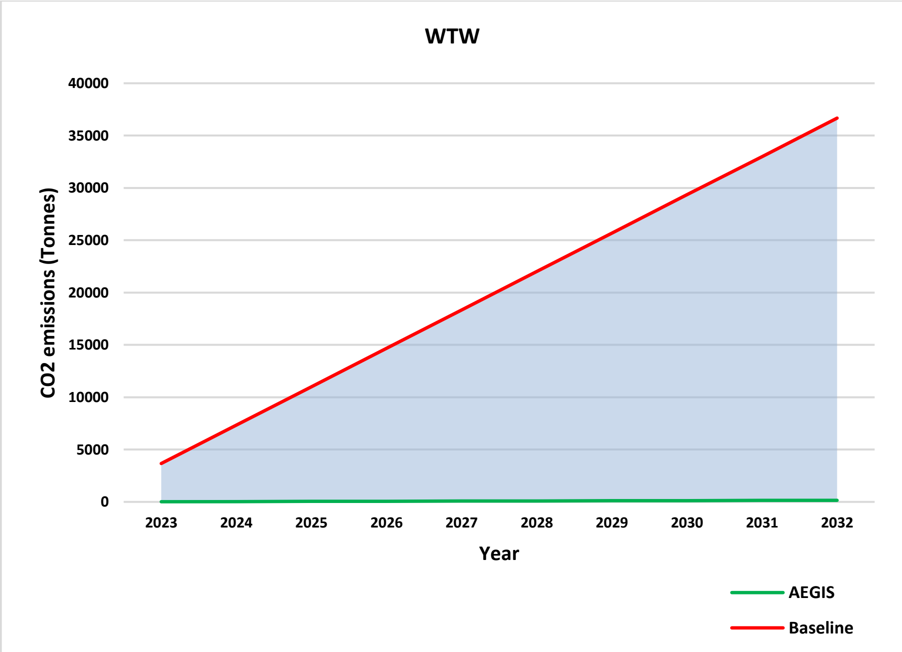


Figure 24: WTW CO_2 emissions for UCA-Daughter vessel 1 case.

Figure 25: WTW CO_2 emissions for UCA-Daughter vessel 2 case.

For the remaining KPIs (terminal area per cargo unit), some minor cargo terminal areas might be required at each port of call. Still, as the daughter vessels will be carrying a small number of containers, it is possible to rely on just-in-time logistics, and thus there will not be as much requirement for terminal space. However, the main issue of concern for Use Case A is that there should be charging facilities for the daughter vessels at the smaller ports along the Norwegian coast and that there should be a suitable ramp when trailers are loaded on the daughter's vessels.

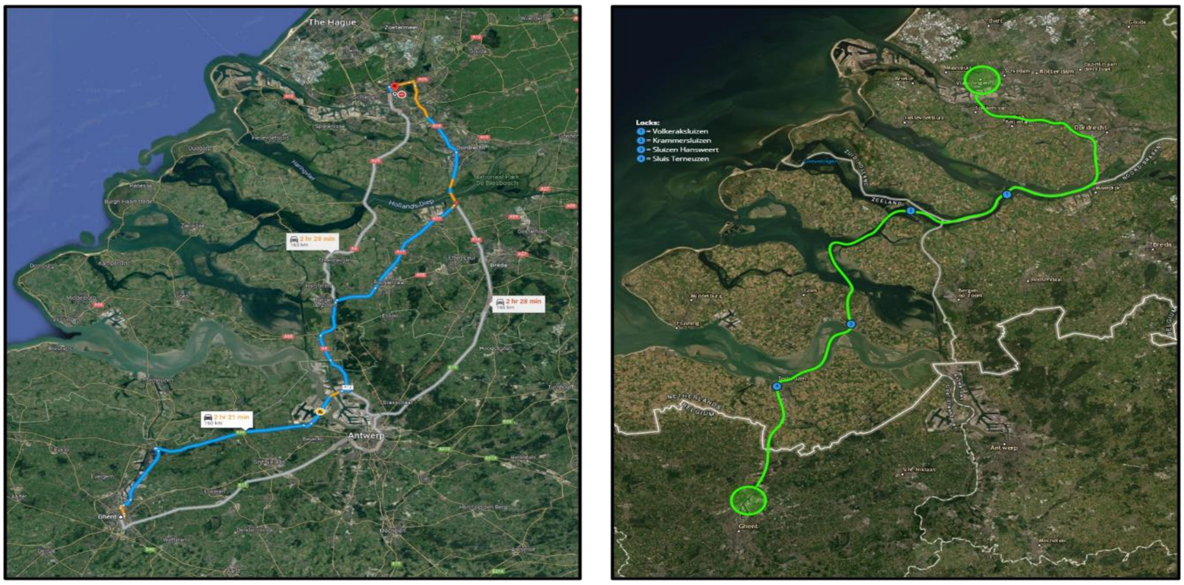
4.2 Use Case B

The final list of relevant and obtainable KPIs for the specific use case is presented in Table 23. This is the result from mapping of the KPIs in terms of use case relevance and context, as previously described in section 3.4.

Table 23: Environmental KPIs for Use Case B (adapted from Table 6 of deliverable D7.2 (Report on KPIs) [1]).

KPI Level	KPI Sublevel	KPI Name	KPI Measurement	KPI Description
Environmental	Emissions	CO_2	g of CO_2/tkm	CO_2 emissions
Environmental	Emissions	SO_x	g of SO_x/tkm	SO_x emissions
Environmental	Emissions	NO_x	g of NO_x/tkm	NO_x emissions
Environmental	Emissions	Particulate matter	g of PM_{10}/tkm	PM_{10} emissions
Environmental	Emissions	Acoustic emissions - Noise	dB per ship or truck	Noise emitted
Environmental	Others	Terminal area per cargo unit	m^2/cargo unit	Amount of square meters of land needed to perform AEGIS operations as function of the cargo moved
Environmental	Others	Use of renewable energy sources	%	Percentage of energy consumed that comes from environmental-friendly energy sources

In the following, according to the use case explained in section 2.2 and seen in more detail for both scenarios (basic and AEGIS) in Figure 26, the results obtained are shown in Table 24.



a) Baseline (land-based system) b) AEGIS (sea transport)

Figure 26: Route details of two scenarios at UCB.

Table 24: Result of UCB.

KPI	KPI Name	KPI Measurement	Result		Description
			AEGIS	Baseline	
Emissions	***CO_2-WTT***	g of CO_2/tkm	9.1	3.97	.
Emissions	***CO_2-TTW***	g of CO_2/tkm	0	20.5	
Emissions	***NO_x-TTW***	g of NO_x/tkm	0	$7.09X10^{-3}$	
Emissions	***SO_x-TTW***	g of SO_x/tkm	0	$7.88X10^{-5}$	
Emissions	***Particulate Matter (PM_{10})***	g of PM_{10}/tkm	0	$7.88X10^{-5}$	
Emissions	***Acoustic Emissions- Noise***	dB/per ship or truck	11	80	
Others	***Terminal Area Per Cargo Unit***	m^2/cargo unit	(679; 724)	---	The first element is related to Rotterdam port and latter is Ghent port.
Others	***Use of Renewable Energy Sources***	%	(17.29;20.55)		Renewable resources for electricity production The first term is for the Netherlands and second is for Belgium.

For the UCB, as one can see in Table 24, the calculation has been made for the round trip in a week. Also, according to the data we have received from the DFDS, three AEGIS ships have been considered at the sea route between Ghent to Rotterdam and vice versa, which works daily and has 7 round trips during the week. To compare the land-based scenario with the AEGIS scenario, the number of trucks/trips required to equal the ship load is considered. Also, we have assumed the average speed of ships and trucks are 8 knots and 65 km/h, respectively.

As one can see for the KPI of use of renewable energy sources, the data for the Netherlands and Belgium is 17.29 and 20.55%, respectively [12].

For the KPI of terminal area per cargo unit, the Rotterdam terminal is undergoing a larger extension, increasing the present 135,000 m^2 by approximately 90,000 m^2 (deliverable D9.2 (Transport system specification case B) [13]). Also, for the Ghent with direct access to the Ghent–Terneuzen Canal, the DFDS-owned Mercatordok Multimodal Terminal is ideally located to connect to the motorways and rail network of Belgium and its hinterlands. A variety of services can be offered at the 240.000m^2 facilities (Deliverable D9.1 (Analysis of transport needs – Case B) [5]).

For acoustic emissions, instead of carrying cargo by truck, we use ships that carry more cargo and produce less noise, we see a significant reduction in noise pollution. In detail, based on the ISE report, using electrically powered ships (slow displacement ships) in the harbor and during the voyage, we can conclude that these ships are really quiet and do not produce more than 11 dB of noise. We think the underwater noise is also low because the electrically driven propulsion has much less vibration than internal combustion engines. The cavitation effect of propeller blades can also be neglected for slower speeds.

It should be noted that due to the availability of sufficient data in UCB, we have managed to calculate the GHG emissions (CO_2) for both TTW and WTT.

As one can see in Table 24, the emissions in the AEGIS scenario are significantly lower in the TTW part. Indeed, because of using the battery propulsion system for AEGIS ships, these KPIs are equal to zero.

For the land-based system, we used the Volvo brand like UCA, which characteristics of this type of truck are shown in Table 18 [12]. Knowing the fuels contents, the fuel consumption (0.26 l/km), and the Euro 6 engine emission standards, it is possible to calculate the emissions per tonne-kilometer for a fully loaded trailer. Hence, according to emissions factors that come from Podiotis and Daskalaki, 2021 [12], we calculated TTW emissions for one truck in Table 25.

Table 25: Emission factors for one truck in UCB (Podiotis and Daskalaki, 2021 [12]).

Emission	Emissions Factor (g/l)	Fuel Consumption per tonne transported (l/tkm)	Emissions (g/tkm)
CO_2	2,600	(0.26/33) = 0.0079	20.5
NO_x	0.9		0.007
SO_x	0.01		7.88X10-5
PM_{10}	0.01		7.88X10-5

To calculate the amount of CO_2 emissions at the WTT level for the ships, we have used Table 26. As shown in Table 26, in the Netherlands, the grid emission factor is 441 grams of CO_2 per kWh, and this factor is 207 grams of CO_2 per kWh in Belgium. Since the battery charging will be done in both countries, thus an average value should be used for the estimation.

Table 26: UCB-AEGIS scenario, powered by batteries.

Country	Ship Energy Consumption (kWh/km)	Payload (Tonnes)	Grid Emission Factor	Emissions intensity (g CO_2/tkm)
Netherlands	51.11	1821.6	441	12.37
Belgium			207	5.81
Average				9.1

For the land-based scenario, to calculate the CO_2 emissions for the WTT we used data that comes from Holland et al., (2009) [18]. In fact, according to that reference, the EN 590 diesel WTT GHG emissions are 14.2 gCO_2eq/MJ diesel. Hence, to calculate the CO_2 emissions for the WTT of the trucks (based on g/tkm), we have applied equation 14, in which that the conversion coefficients 35.4 MJ/l and 0.26 l/Km come from Podiotis and Daskalaki, 2021 [12].

$$CO_2 \; emissions \; for \; UCB - WTT: \frac{(14.2 * 35.49 * 0.26)}{33} \sim 3.97 \tag{14}$$

4.2.1 Analysis of UCB

In this section, we further analyze the result obtained from UCB. In Table 27, the green and red cells show the advantages of the AEGIS and baseline scenarios, respectively.

Table 27 – Comparing the superiority of the base scenario and AEGIS in UCB.

KPI Name	AEGIS	Baseline
CO_2-WTW		
NO_x-TTW		
SO_x-TTW		
PM_{10}-TTW		
Acoustic Emissions- Noise		

As can be seen in Table 27, it is expected that after the implementation of AEGIS, we will have a significant improvement in the reduction of gas emissions in the UCB. The reason for this is due to the use of batteries for the AEGIS ships in this use case.

In the rest of this part, we look to find out how much gas emissions will be reduced over the years with the implementation of AEGIS.

For this purpose, we have represented all four emissions under consideration in figures 27 to 30. As one can see in the figures, if we consider the year 2030, the AEGIS solution will have prevented significant emissions of the examined gases according to the equations of 15 - 18. Also, to compare the GHG emissions (CO_2) for both scenarios, we have used the WTW (=WTT+TTW) approach in order to have a more precise assessment.

$$CO_2 - WTW : (124{,}695) - (46{,}340) = 78{,}355 \; tonnes \; of \; CO_2 \qquad (15)$$
$$NO_x : (36) - (0) = 36 \; tonnes \; of \; NO_x \qquad (16)$$
$$SO_x : (0.40) - (0) = 0.40 \; tonnes \; of \; SO_x \qquad (17)$$
$$PM_{10} : (0.40) - (0) = 0.40 \; tonnes \; of \; PM_{10} \qquad (18)$$

Figure 27: WTW CO_2 emissions for UCB.

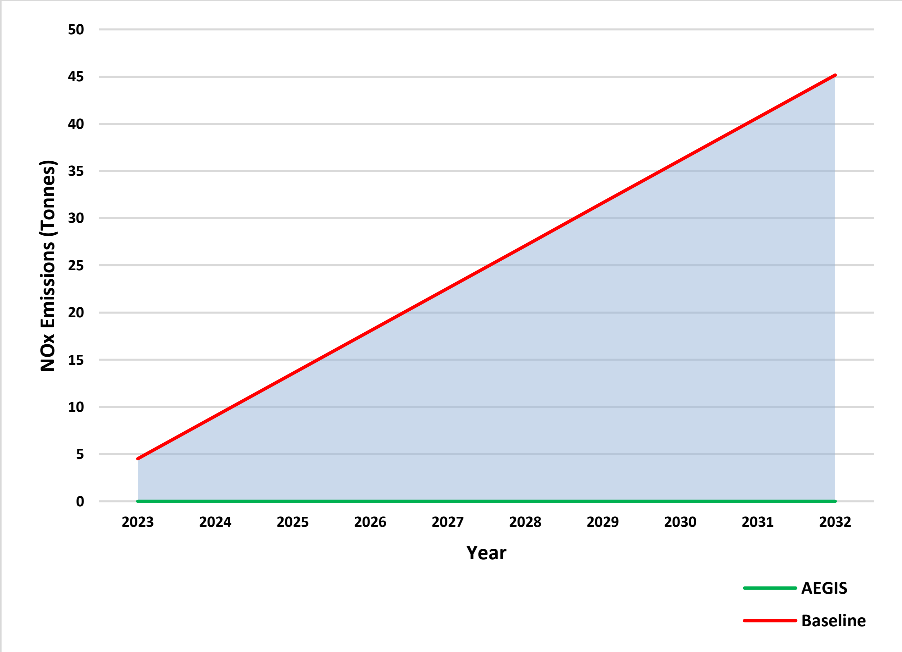


Figure 28: TTW NO_x emissions for UCB.

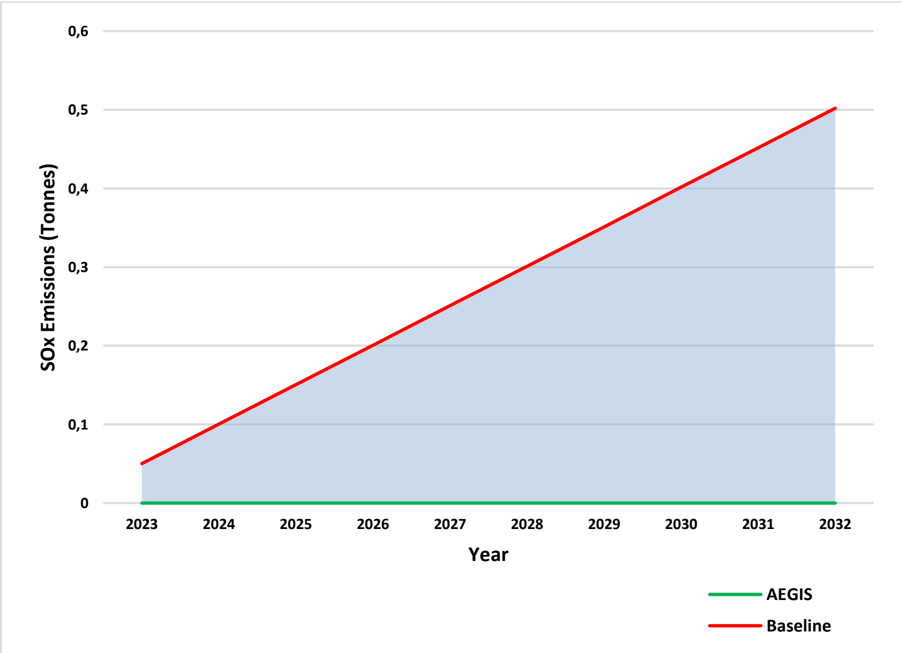


Figure 29: TTW SO_x emissions for UCB.

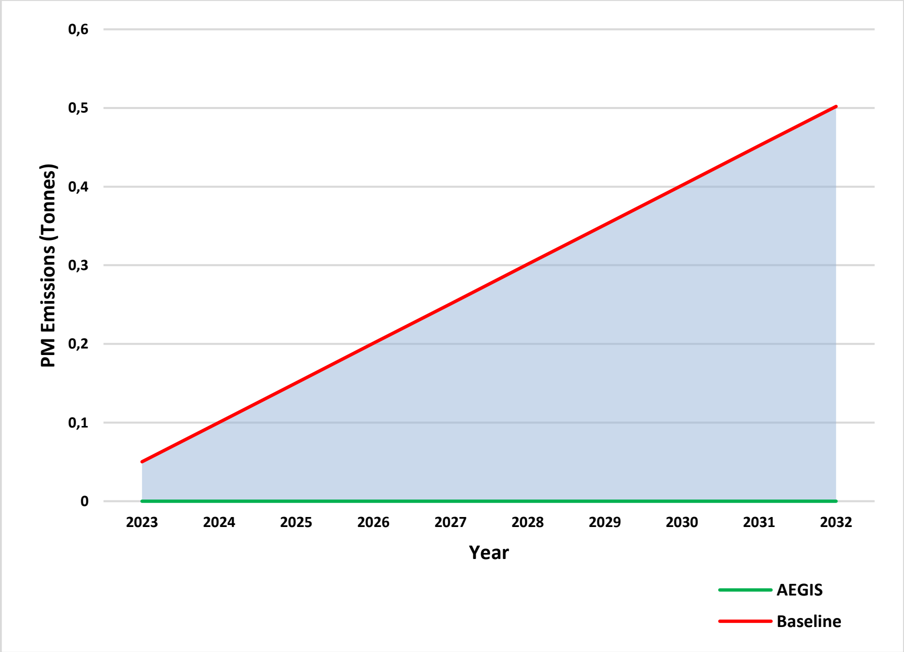


Figure 30: TTW PM_{10} emissions for UCB.

Therefore, as can be seen in the results, it is evident that these four KPIs will be much lower with the AEGIS solution compared to the use of trucks (even if these are EURO 6).

Finally, it has to be noted that as road transportation is also gradually moving to electro-mobility, a similar environmental benefit will be enjoyed if electric trucks are to be used in the future. The analysis of such a scenario is subject to many uncertain parameters and is beyond the scope of the AEGIS project.

4.3 Use Case C

The final list of relevant and obtainable KPIs for the specific UCC for the Aalborg and Vordingborg cases are presented in Table 28. This is the result of the mapping of the KPIs in terms of use case relevance and context, as previously described.

Table 28: Environmental KPIs for Use Case C (adapted from Table 6 of deliverable D7.2 (Report on KPIs) [1]).

KPI Level	KPI Sublevel	KPI Name	KPI Measurement	KPI Description
Environmental	Emissions	CO_2	g of CO_2/tkm	CO_2 emissions
Environmental	Emissions	SO_x	g of SO_x/tkm	SO_x emissions
Environmental	Emissions	NO_x	g of NO_x/tkm	NO_x emissions
Environmental	Emissions	Particulate matter (PM_{10})	g of PM_{10}/tkm	PM_{10} emissions
Environmental	Emissions	Acoustic emissions - Noise	dB/per ship or truck	Noise emitted

Environmental	Others	Terminal area per cargo unit	m^2/cargo unit	Amount of square meters of land needed to perform AEGIS operations as function of the cargo moved
Environmental	Others	Use of renewable energy sources	%	Percentage of energy consumed that comes from environmental-friendly energy sources

Based on the questionnaires shown in Annex A, we have made efforts to collect data from our partners and stakeholders. However, as some data in the Aalborg and Vordingborg cases were unavailable, we made some approximations. These are explained in Table 29. Also, how to deal with these issues are stated.

Table 29: Lack of data and associated approximations in UCC.

KPIS	Explanation
Acoustic emissions - Noise	The lack of data for this KPI is for the AEGIS ship of Aalborg case, which works by methanol, and the AEGIS ship of Vordingborg case. Unfortunately, we do not have enough data to measure the noise pollution of combustion systems with methanol fuel. According to data from ISE, conventional ships have an acoustic pollution equivalent to 65 to 85 dB. Since a methanol propulsion system will use new and updated equipment, the acoustic emissions will be reduced.
Light pollution	The lack of data for this KPI was for both scenarios. But it is anticipated that light pollution will be reduced in the case of Vordingborg, and that there will not be significant changes in the case of Aalborg. Indeed, in the case of Vordingborg, we expect significant improvements because autonomous vessels will replace many trucks on the roads. For the Aalborg case, we cannot expect noticeable improvement and even noticeable changes in the level of light pollution in this part. Although the land path of the AEGIS scenario is less than the base scenario, and a part of that sea path has been replaced, which will have less light pollution, the light pollution related to the activity at night in the ports cannot be ignored.

In the following, according to the routes explained in section 2.3, the results obtained in both scenarios (basic and AEGIS) for Aalborg and Vordingborg are respectively in Tables 30 to 31.

Table 30: Result of the Aalborg case in UCC.

KPI	KPI Name	KPI Measurement	Result				Description
			AEGIS			Baseline (Truck)	
			New Vessel		Truck		
			Battery	Methanol			
Emissions	***CO_2-WTT***	g of CO_2/tkm	5.1	0.94	5.95	5.95	
Emissions	***CO_2-TTW***	g of CO_2/tkm	0	26.9	30.7	30.7	
Emissions	***NO_x-TTW***	g of NO_x/tkm	0	0.084	0.0106	0.0106	
Emissions	***SO_x-TTW***	g of SO_x/tkm	0	0	$1.18X10^{-4}$	$1.18X10^{-4}$	
Emissions	***Particulate Matter (PM_{10})-TTW***	g of PM_{10}/tkm	0	$1.441X10^{-7}$	$1.18X10^{-4}$	$1.18X10^{-4}$	
Emissions	***Acoustic Emmissions-Noise***	dB/per ship or truck	11	Less than 75 dB	80	80	
Others	***Terminal Area Per Cargo Unit***	m^2/cargo unit	125		---	---	Data comes from deliverables D10.3 (Potential for calling the two Danish ports by DFDS) [17]. The figure is related to Aalborg port.
Others	***Use of Renewable Energy Sources***	%	(80; 58)				The first term is for Denmark and second is for Sweden.

Table 31: Result of the Vordingborg case in UCC.

KPI	KPI Name	KPI Measurement	Result			Description
			AEGIS	Baseline		
			New Vessel	Vessel	Truck	
Emissions	***CO_2-WTT***	g of CO_2/tkm	0.31	2.61	3.97	
Emissions	***CO_2-TTW***	g of CO_2/tkm	8.976	13.95	20.5	
Emissions	***NO_x***	g of NO_x/tkm	0.028	0.35	$7.09X10^{-3}$	
Emissions	***SO_x***	g of SO_x/tkm	0	0.014	$7.88X10^{-5}$	
Emissions	***Particulate Matter (PM_{10})***	g of PM_{10}/tkm	$5X10^{-9}$	0.004	$7.88X10^{-5}$	
Emissions	***Acoustic Emmissions-Noise***	dB/per ship or truck	Less than 75 dB	75	80	
Others	***Terminal Area Per Cargo Unit***	m^2/cargo unit	2,000	---	---	
Others	***Use of Renewable Energy Sources***	%	80			Renewable resources for electricity production is for Denmark. Source: Monthly OECD Electricity Statistics

For the Aalborg case (Table 30), the calculation has been done for round trip in a day. Also, according to the data we have received from deliverable D10.1 (Potential transfer from road transport to short-sea-shipping in Denmark) [6], one AEGIS ship has been considered at the sea route between Gothenburg to Aalborg and vice versa, which works daily and has 7 round trips during the week. To compare the land-based scenario with the AEGIS, the number of trucks/trips required to equal the shipload is considered. Also, we have assumed the average speed of ships and trucks are 8 knots and 60 km/h, respectively.

For the Vordingborg case (Table 31), the calculation has been done one way (for example, port of Vordingborg to port of Elblag, Poland) in a week. In this case, we got most of the data from Vordingborg port chiefs, such as the speed of the ship and number of cargo carried. To compare the land-based scenario with the AEGIS, the number of trucks/trips required to equal the shipload is considered. Also, we have assumed the average speed of ships (AEGIS and conventional) and trucks are 10 knots and 60km/h, respectively.

As one can see for the KPI of use of renewable energy sources in Tables 30 and 31, the data for Denmark and Sweden is 80 and 58 percent, respectively (Source: Monthly OECD Electricity Statistics).

In UCC, for the emission rate of gases (g/kWh), we have three fuel types: Battery, methanol, and MDO. These emissions are equal to zero for the battery at the TTW level, and for rest of fuels, the numbers are as per Table 16.

For the calculation of WTT CO_2 emissions, we follow the data of Table 32 in the battery calculation section in the Aalborg case when the AEGIS ships used this type of propulsion system. Indeed, in Denmark, the grid emission factor is 189 grams of CO_2 per kWh and this factor is 13 grams of CO_2 per kWh in Sweden[4]. Since the battery charging will be done in both countries, thus an average value should be used for comparison. Also, for the methanol section in both cases, an IMO report on methanol as marine fuel shows the WTT emissions from methanol produced with biomass vary largely based on electricity source and the amount of biomass deficit. The report suggests an approximate 25 g CO_2 eq/MJ life cycle WTT emission using the Finnish electricity mix, accounting for both methanol and wood transport emissions. If, in addition, there is a 15 % biomass deficit, and this deficit is covered by burning residual fuel oil, the life cycle GHG emissions rise to around 70 g CO_2 eq/MJ. It should be mentioned that each MJ is equivalent to 0.27 kWh. Furthermore, we used 104 g/kWh for WTT of CO_2 emissions for conventional ships in Vordingborg case.

In addition, for the truck side of both cases, we used the Volvo brand like UCB, which characteristics of this type of truck are shown in Table 18 [12]. Knowing the fuel's contents, the fuel consumption (0,26 l/km), and the Euro 6 engine emission standards, it is possible to calculate the emissions per tonne-kilometer for a fully loaded trailer. It should be noted that for the Aalborg case, as can be seen in Table 33, we assumed the full truckloads of each truck is 22 tonnes based on the data that comes from deliverable D10.1 (Potential transfer from road transport to short-sea-shipping in Denmark) [6]. And, for the Vordingborg case, we follow the truck type of UCB (please see Table 25). Hence, Tables 33 and 25 show the TTW emissions of the Aalborg and Vordingborg cases, respectively.

Furthermore, for the land-based scenario to calculate the CO_2 emissions for the WTT, we used the data that comes from Holland et al. (2009) [18]. In fact, according to that reference, the EN 590 diesel well-to-tank GHG emissions are 14.2 g CO_2eq/MJ diesel. Hence, for example, to calculate the CO_2 emissions for the WTT of the AEGIS scenario (based on g/tkm) in the Aalborg case when powered by methanol, we have implemented equation 19. The conversion coefficients 35.4 MJ/l and 0.26 l/Km come from Podiotis and Daskalaki, 2021 [12].

Table 32: UCC-Aalborg case when powered by batteries.

Countrry	Ship Energy Consumption (kWh/Km)	Payload (Tonnes)	Grid Emission Factor	Emissions intensity (g CO_2/tkm)
Sweden	44.43	880	13	0.66
Denmark			189	9.54
Average				5.1

[4] https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment

Table 33: Emission factors for one truck in UCC- Aalborg case.

Emission	Emissions Factor (g/l)	Fuel Consumption per tonne transported (l/tKm)	Emissions (g/tKm)
CO_2	2600	(0.26/22) = 0.0118	30.7
NO_x	0.9		0.01
SO_x	0.01		0.0001
PM_{10}	0.01		0.0001

$$\begin{aligned}&CO_2\ emission\ of\ Aalborg\ case - WTT:\\&For\ the\ vessel\ side: \left\{\frac{6993\ * 70 * 0.27}{160\ * (40 * 22)} = 0.94\right\}\\&For\ the\ truck\ side: \left\{\frac{14.2 * 35.49 * 0.26}{22(t)} = 5.95\right\}\end{aligned} \tag{19}$$

In equation 19 the first term is related to the part of the ship, and the second term is related to the trucks.

4.3.1 Analysis of UCC

In this section, we further analyze the result obtained from UCC. First, a simple analysis has been made according to the results obtained for the cases of Aalborg and Vordingborg in Tables 34 and 35, respectively. In these Tables, the green and red cells show the superiority of the AEGIS and baseline scenarios respectively. Also, orange cells represent there is no significant difference between the two scenarios.

Table 34 – Comparing the AEGIS and baseline solutions in UCC- port of Aalborg.

KPI Name	AEGIS Battery	AEGIS Methanol	Baseline	
			Compare to Battery	Compare to Methanol
CO_2-WTW				
NO_x-TTW				
SO_x-TTW				
PM_{10}-TTW				
Acoustic Emissions- Noise				

Table 35 – Comparing the AEGIS and baseline solutions in UCC- port of Vordingborg.

KPI Name	AEGIS	Baseline
CO_2-WTW		
NO_x-TTW		
SO_x-TTW		
PM_{10}-TTW		
Acoustic Emissions- Noise		

As one can see in Table 34, which compares the solutions on a g/tkm scale, there is generally a (weak) advantage with the baseline scenario in the NO_x emission in the methanol case.

However, it should be noted that this KPI should not mislead us that the AEGIS scenario is weaker than the base scenario from the absolute emissions point of view. As one can see in Figures 31 and 32, in the amount of GHG emissions (CO_2) on a scale of grams emitted during ten years, the superiority belongs to the AEGIS scenario in both modes of ships with batteries and methanol. The reason for this reduction is that although there are trucks in the two scenarios, due to the fact that a part of the route in the baseline scenario would be changed by substituting with the AEGIS ship, which has a much lower emission rate, so the emission of greenhouse gases will be less in total. The land route of the baseline solution is much longer than the land route of the AEGIS solution. Also, Figures 31 and 32 show the entire CO_2 cycle (WTT+TTW) for AEGIS scenarios when using the ship with battery and methanol propulsion systems, respectively. In addition, Figures 33 to 35 show the emission of the rest of the gases.

Another point after examining this case, it can be seen that in the scenario where the energy source is a battery, compared to the methanol fuel, it has an advantage in the number of CO_2 and NO_x emissions.

In order to examine this issue more precisely, equations 20 to 27 have shown savings in emissions in both combustion systems, considering the year 2030.

$$CO_2 - WTW - Battery: (121{,}298) - (90{,}458) = 30{,}840 \ tonnes\ of\ CO_2 \quad (20)$$
$$CO_2 - WTW - Methanol: (121{,}298) - (109{,}157) = 12{,}141\ tonnes\ of\ CO_2 \quad (21)$$
$$NO_x - Battery: (35) - (25) = \ 10\ tonnes\ of\ NO_x \quad (22)$$
$$NO_x - Methanol: (35) - (94) = \ -59\ tonnes\ of\ NOx \quad (23)$$
$$SO_x - Battery: (0.39) - (0.28) = 0.11\ tonnes\ of\ SO_x \quad (24)$$
$$SO_x - Methanol: (0.39) - (0.28) = \ 0.11\ tonnes\ of\ SO_x \quad (25)$$
$$PM_{10} - Battery: (0.39) - (0.28) = \ 0.11\ tonnes\ of\ PM_{10} \quad (26)$$
$$PM_{10} - Methanol: (0.39) - (0.28) = \ 0.11\ tonnes\ of\ PM_{10} \quad (27)$$

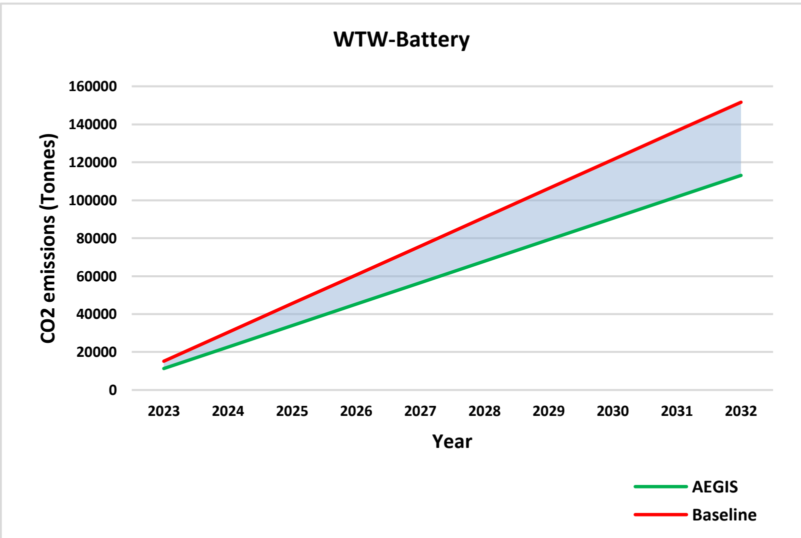


Figure 31: WTW CO_2 emissions for UCC-Aalborg-battery case.

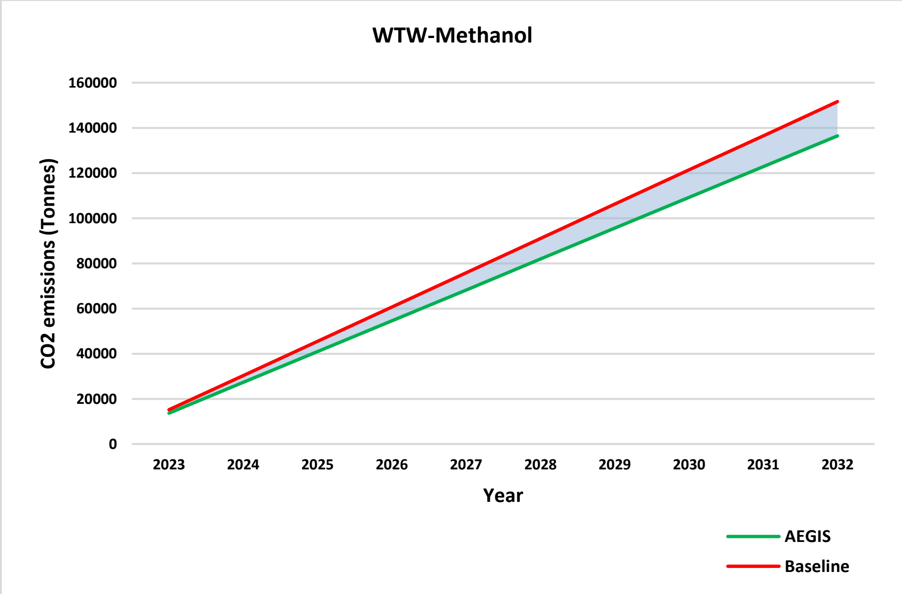


Figure 32: WTW CO_2 emissions for UCC-Aalborg-methanol case.

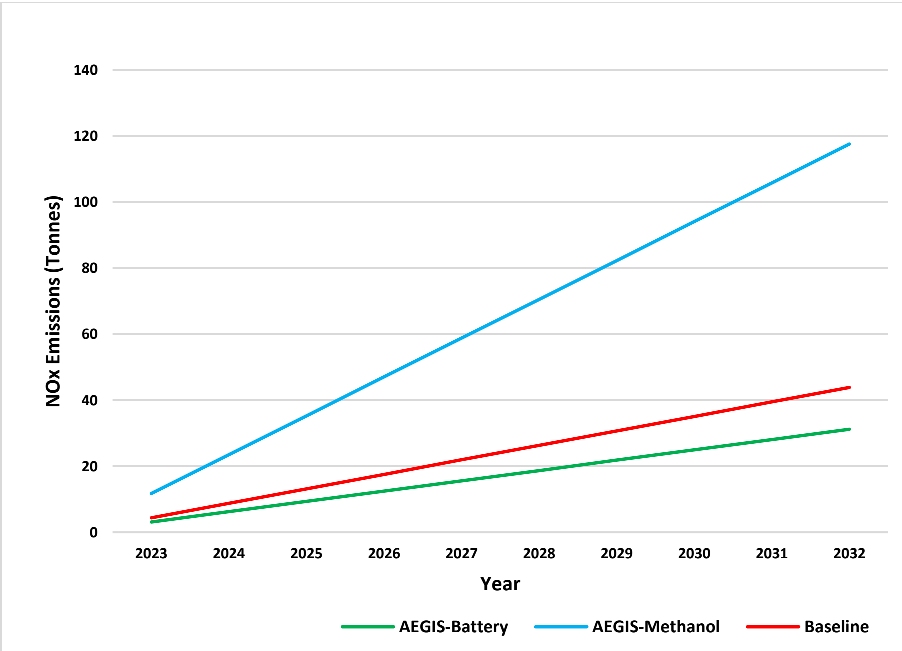


Figure 33: TTW NO_x emission for UCC-Aalborg case.

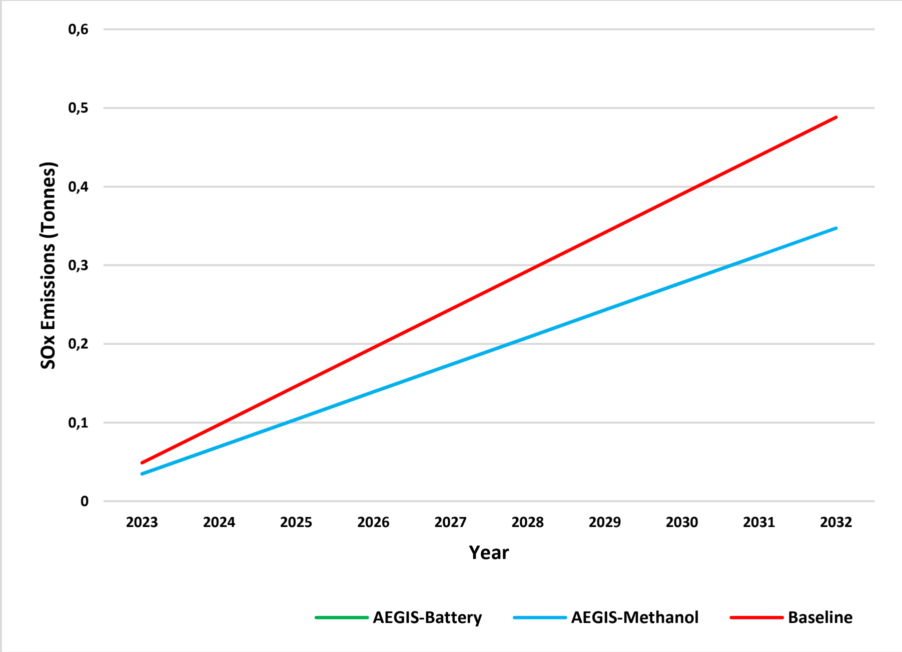


Figure 34: TTW SO_x emissions for UCC-Aalborg case.

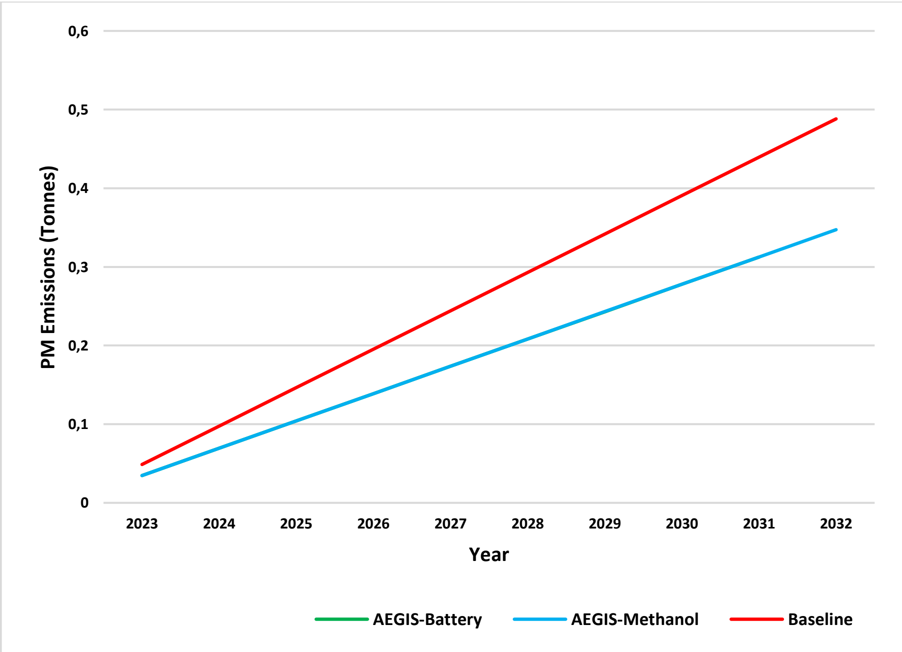


Figure 35: TTW PM_{10} emissions for UCC-Aalborg case.

At Vordingborg case, we estimated the total CO_2 production over ten years, shown in Figure 36. As one can see, the absolute superiority is with the AEGIS scenario. In addition, equation 28 has shown savings in GHG emissions, considering the year 2030.

$$CO_2 - WTW: (26{,}162) - (7{,}747) = 18{,}415 \ tonnes \ of \ CO_2 \quad (28)$$

In addition, Figures 37 to 38 show the amount of reduced emissions by implementing the AEGIS scenario in terms of NO_X and PM_{10}, respectively. Also, the SO_X emissions in the AEGIS scenario are zero.

Figure 36: WTW CO_2 emissions for UCC-Vordingborg case.

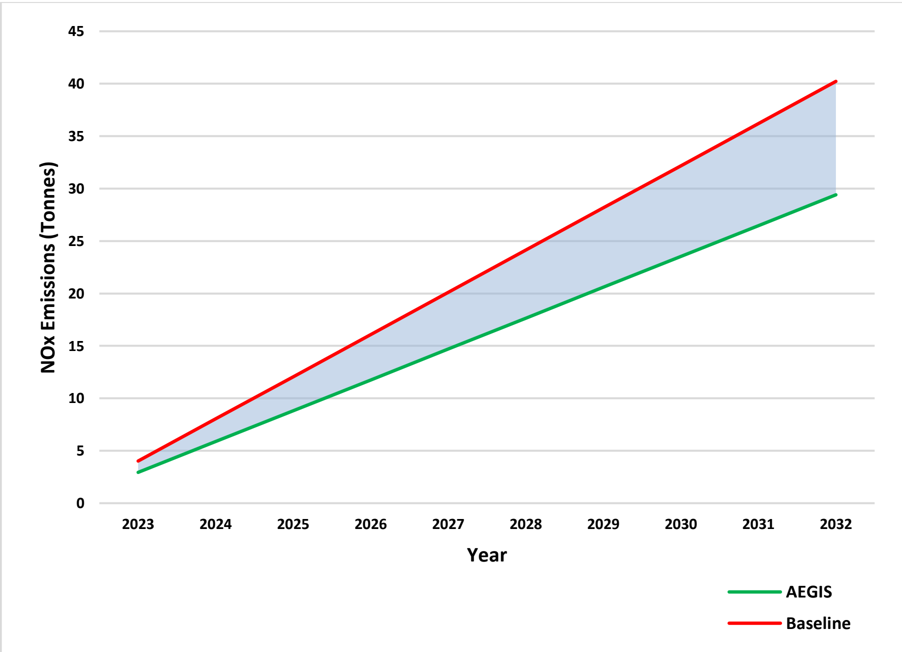


Figure 37: TTW NO_x emissions for UCC-Vordingborg case.

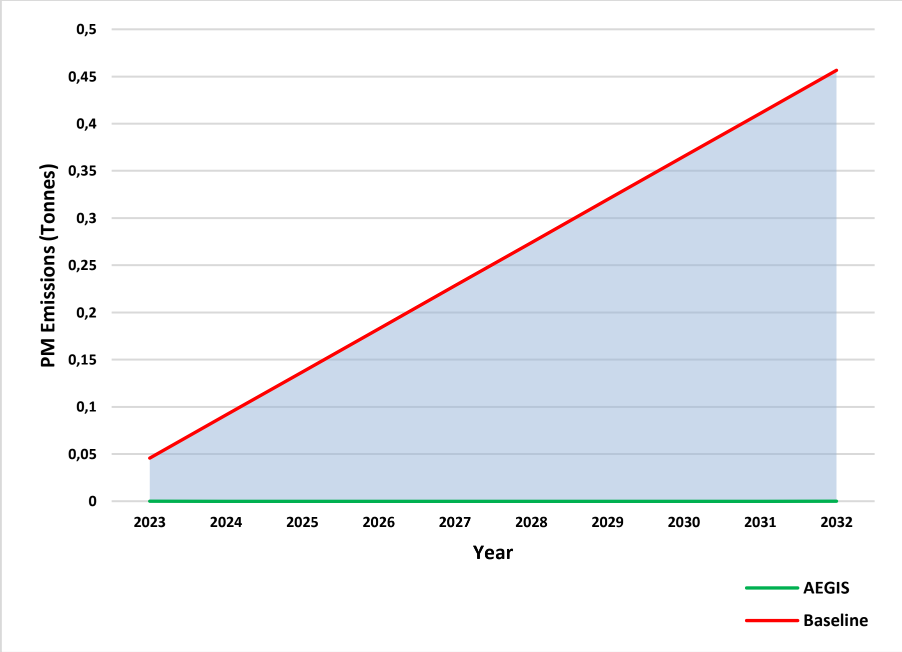


Figure 38: TTW PM_{10} emissions for UCC-Vordingborg case.

5 Conclusions

Generally, from the analysis conducted, the main result is that the AEGIS solutions are significantly better in all use cases than the non-AEGIS baselines in terms of environmental KPIs. In addition, in some cases where ships with batteries are used, this improvement reaches almost 99 - 100 %. It can also be seen that AEGIS scenarios will be increasingly better than basic scenarios after several years and cumulative calculations of greenhouse gas emissions.

It is important to note again that the WTW approach used in this report was by necessity incomplete. However, we believe that it provides additional insights for some comparisons between the alternative solutions examined. For instance, when comparing fossil-fueled powered engines with electric vehicles or alternative fuels, the emissions for the production and transportation of the fuel should also be considered, along with the energy consumed for building each solution. The results indicate a very positive performance of the AEGIS scenario compared to the baseline scenario.

Last but not least, and given the drive for electromobility in the European road sector, the question to what extent converting part of the truck fleet to electric propulsion would reduce the environmental advantage of the AEGIS solution is open and beyond the scope of the AEGIS project. To perform such an analysis, many factors that are currently uncertain should be considered, including the lifecycle emissions of the considerable number of batteries needed for a truck fleet that uses batteries on a large scale. The policy choice between (a) shifting part of the road freight traffic to greener modes and (b) making road freight itself greener is not necessarily an “either-or” choice, as both (a) and (b) make sense from an environmental perspective. It is expected that policies that are adopted and the plans to implement them should be such that both (a) and (b) can be achieved.

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Annex A. Data Template

This annex contains the data template circulated to the AEGIS partners.

Data	Units	ENTER INPUT HERE	COMMENT		Comparison with data
Vessel Name	Name				
Vessel Type	Name				
Route deployed in	Name				
Geometric Characteristics (LPP, LOA, B, T)	meters				
Main Engine Power (MCR)	kW				
Main Engine Type/Model					
Main Engine Fuel Type					
Main Engine Fuel Consumption at 75% MCR	tonnes/day				
Auxiliary Engine & Boiler Power (MCR)	kW				
Auxiliary Engine & Boiler Type/Model					
Auxiliary Engine & Boiler Fuel Type					
Auxiliary Engine & Boiler Fuel Consumption at 75% MCR	tonnes/day				
Design speed	knots				
Vessel capacity	TEU/lane meters				
Vessel cargo handling equipment (if any): name	Name				
Vessel cargo handling equipment; number	#				
Cargo handling rate (per cargo handling unit)	TEUs/hour, LM/hour				
CAPEX-Price New Vessel	€				
OPEX- crew	€/year				
OPEX-maintenance	€/year				
OPEX-other (no fuel)	€/year				
Crew size (non-hotel)	#				
Autonomy Level	Fully manual/Operator Controlled/Automatic/Partial Autonomy/ Constrained Autonomous/ Fully Autonomous				
Load factor	%				
Any other relevant info.					

Figure 39: The "Ship" worksheet

Data	Units	ENTER INPUT HERE	COMMENT
Route Length	NM		
Route description including transshipment nodes (ports, other)	Names		
Number of transshipment nodes	#		
Route Cargo Volume A to B	Lane meters/year or TEUs/year		
Route Cargo Volume B to A	Lane meters/year or TEUs/year		
Ship Speed (average)	Kn		
Total Sailing Time	hours		
Total Loading Time	hours		
Total Unloading Time	hours		
Total Terminal Cargo Residence Time	hours		
Other waiting time	hours		
Number of ships on route	#		
Punctuality	%		
Frequency of Service	shipments/week		
Bunkering Possibilities and Availabilities (LNG, Hydrogen, Battery…)	-		
Competing services on route and their shares			
Non-maritime leg of route- type of vehicle	name		
Non-maritime leg of route- total distance	km		
Non-maritime leg of route- total transit time	hours		
Non-maritime leg of route- total cost (last mile)	€		
Any other relevant info.			

Figure 20: The "Route" worksheeet

Data	Units	ENTER INPUT HERE	COMMENT		CHECK WITH DATA
Volume of Cargo Moved (both loaded and unloaded) per Port Call and type of cargo	#TEUs/port call or #Lane meters/port call				
Type of cargo	name				
Average value of cargo	€/tonne				
Origin of cargo (if known)	name				
Destination of cargo (if known)	name				
Door to door transit time of cargo (if known)	name				
Door to door freight rate	€/tonne				
Any other relevant info.					

Figure 41: The "Cargo" worksheet

Data	Units	ENTER INPUT HERE	COMMENT
Name of port/terminal	Name		
Number of berths	#		
Storage capacity	TEUs, LMs		
Shore cargo handling equipment (if any): name	Name		
Shore cargo handling equipment; number	#		
Cargo handling rate (per cargo handling unit)	TEUs/hour, LM/hour		
People on shore needed to operate cargo handling equipment	#		
Other people on shore needed for operation	#		
Any other relevant info.			

Figure 42: The "Port" worksheet

Data	Data Measurement	ENTER INPUT HERE	COMMENT
Number of successful Cyber-Attacks per Year	#/year		
Number of intended Cyber-Attacks per Year	#/year		
Recovery Time due to Crime (cyber-attack…) from detection to recovery	hours		
Restored Level of Performance after a Cyber-Attack	% of Original Level of Performance		
Education Level Employees Needed	No Degree/BSc/MSc/PhD		
Maximum Noise Emitted Vessel + Port	dB		
Use of Renewable Energy Sources of the total Energy Required	%		
Accident Rate	#/year		
Fatality Rate	#/year		
Fire Incidents	#/year		
Crime (thefts, piracy…)	#/year		
Training time per worker	hours/worker		

Figure 43: The "Other" worksheet