Hybrid Propulsion Unit, Energy Storage and Controls

Final Version of 30/06/2021

Deliverable Number D.3.1.1.

Project Acronym	METRO
Project ID Number	10044221
Project Title	Maritime Environment-friendly TranspOrt systems
Priority Axis	4
Specific objective	4.1
Work Package Number	WP3
Work Package Title	Hybrid vessels study and demonstrators
Activity Number	3.1
Activity Title	Hybrid propulsion unit, energy storage and controls
Partner in Charge	Wärtsilä Italia Spa
Partners involved	University of Trieste, Dept. of Engineering and Architecture Tehnomont Shipyard Pula Ltd University of Rijeka - Faculty of Engineering
Status	Final
Distribution	Public

Contents

1 INTRODUCTION

The aim of this report is to evaluate the best machinery configuration for vessels sailing on two different route types in the Adriatic Sea, based on economical, technical and environmental considerations. To perform this task the starting point was the collection of data from the field, that has been analysed through dedicated software developed in house by Wärtsilä, making possible then to compare several machinery concepts and therefore to tailor the solution on the actual need of the operator (optimizing the overall system). This approach is called *Data Driven Design* and it is particularly suitable for the sizing of hybrid propulsion system, since it depends upon both the actual operating modes of the ship and their sequence.

Based on initial evaluations on the Norther Adriatic Sea area the project focused on two different types of routes for the transportations of goods and people:

- **Short range route:** local route with the heaviest traffic during the year sailed by double ended ferries.
- **Long range route:** crossing the Adriatic Sea and sailing between Italy and Croatia by Ro-Pax vessels.

For both routes the report describes how the different profiles were extracted from AIS data, what machinery configuration were evaluated and the results of the simulation.

1.1 Data Driven Design approach

The developed methodology, outlined in Figure 1, is composed by the following stages:

- *Input data collection*, composed by *historical navigation data* (latitude, longitude, heading and speed as timeseries) and technical *installation data* (e.g. engine installed, trial and service speed) of existing vessels on the selected route.
- *Data cleaning and enrichment*: raw input data is cleaned from possible errors and additional information is added (such as sailing condition or mission/legs information).
- *Average mission selection*: the input data are split into several *missions*. An average operating profile is derived for each mission group/cluster identified using Machine Learning techniques.
- *Operating mode extraction*: for each mission the sequence of the operating modes during sailing condition is extracted using Machine Learning algorithms, in order to identify average duration and power in these conditions. Moreover, the time spent in port is assessed by means of statistical analyses and compared with the available timetables.
- *Simulation*: a simulation tool, developed by Wärtsilä, makes it possible to evaluate the fuel consumption, the pollutant emissions, the OpEx (Operational Expenditure) and the TCO (Total Cost of Ownership) per each tested configuration.

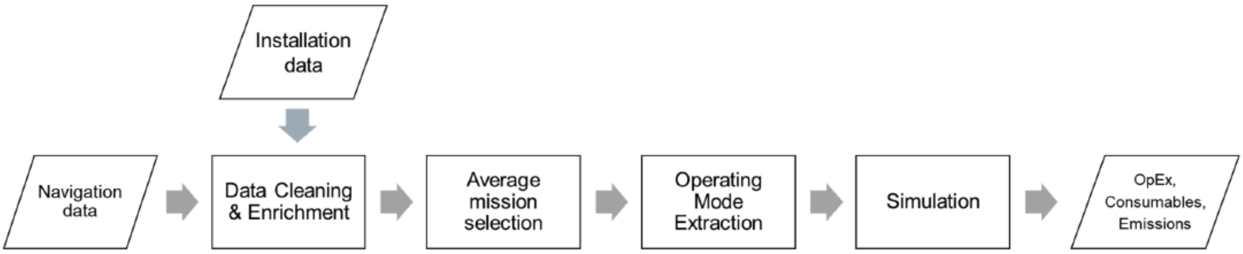

Figure 1: Data Driven Design logical sequence.

This method is directly applicable for the evaluation of retrofit projects, but, using some design parameters, it is possible to apply this approach also to a new build vessel that is following the same route.

1.2 Design Inputs

As above mentioned, the data driven design approach requires data input for being performed. Thus, in this section the main hypotheses used in defining such data for the work here presented is summarized. The following topics are addressed: routes, ship types, propulsion, electric power generation, fuel, energy storage systems, shore connection, rules and regulations.

In the METRO project the **routes** that have been taken as case study are two: Brestova-Porozina and Ancona-Split. These two routes call for different **ship types**, which are a double ended ferry for the first route and a Ro-Pax vessel for the second one. More information regarding the rationale for selecting the routes and the ship types can be found in the document "*Identification of research area, referent lines and referent ships*", included in Act. 5.2 documentation.

Regarding the **propulsion** system, different solutions have been considered during the design in order to find the best combination for each ship. Particularly, the propellers can be powered by Diesel Engines, electrical motors, or both.

Onboard **electric power generation** can be provided by dedicated Diesel generators, fuel cells, shaft generators (or equivalently electric motor in Power Take Off – PTO – mode), or a combination of these solutions.

The *fuel* used for the Diesel engines and/or generators is Light Fuel Oil (LFO), but the option of using Dual Fuel motors with Liquified Natural Gas (LNG) is also taken into account.

The onboard installation of **energy storage systems** (ESS) is considered for both ships. Information about energy storage systems technologies that are suitable for marine applications can be found in the project deliverables of Act. 4.1. It is relevant to notice that in the analyses depicted in this document, the ESS is assumed to be charged and discharged keeping at a less than 2C rate. Considering the need of keeping the ESS weight and volume as low as possible (to avoid reducing the ships payload) and the performance required, it is assumed that Li-ion technology is the best option. Thus, in the data driven design activity specific data for these kinds of batteries has been used.

It is hypothesized that all the ports have a **shore connection system** available, with a power reaching up to 2 MW. Information about shore connection technology can be found in the project deliverables related to Act. 4.1 and Act. 4.2. While for big ports such a powerful system may be installable with limited intervention on their power infrastructure, on the smaller ones this can be an issue. Indeed, as discussed in Act. 4.2 documents in both Brestova and Porozina ports the actual power system can support only up to 1 MW loads with limited intervention on existing infrastructure. Although such power can still be suitable for supplying the onboard loads when the ferry is at berth and for providing onboard ESS recharge at night, it is surely insufficient for providing fast charge to the ship during the berthing periods between routes. The installation of a higher power shore connection is however possible, by applying one of the solutions presented in Act. 4.1 documents. This requires a significant investment on local electric power infrastructure, but will enable fast charge of the onboard ESS during stops, as well as the integration of local renewables in the energy mix of the port (thus boosting the environmental-friendliness of the ship).

A final remark is to be made regarding **rules and regulations**. In particular, different rules may apply to each solution presented in the following, due to the presence of different technologies integrated onboard. As an example, the installation of energy storage systems calls for specific rules and regulations. The same happens when using shore connection systems. Due to that, in Act. 4.3 deliverable documents a collection of the most relevant regulation in force and certification regarding ships with hybrid power systems is presented.

2 Short range vessel

2.1 Ferry Operating Profile

The selected route, shown in Figure 2, takes place in Croatia between the berths of Brestova and Porozina, with a nautical distance of about 2.7 NM and a crossing time of approximately 10 minutes.

A preliminary evaluation identified the two reference vessels for this route: MV Bol and MV Brestova, whose details are in Table 1.

In order to attain the reference data for designing the propulsion system, an analysis on the navigation data has been done. This has been achieved by collecting the position and the speed of the selected vessels with an average sampling rate of 5 minutes, in a period from 1 January 2016 to 1 June 2019.

The final dataset amount to nearly 300 thousand samples, allowing to define the real ship speed profile with a good accuracy.

For the speed profile during crossing the data were processed to obtain an average profile using a non-dimensional distance as main parameter, as shown in Figure 3.

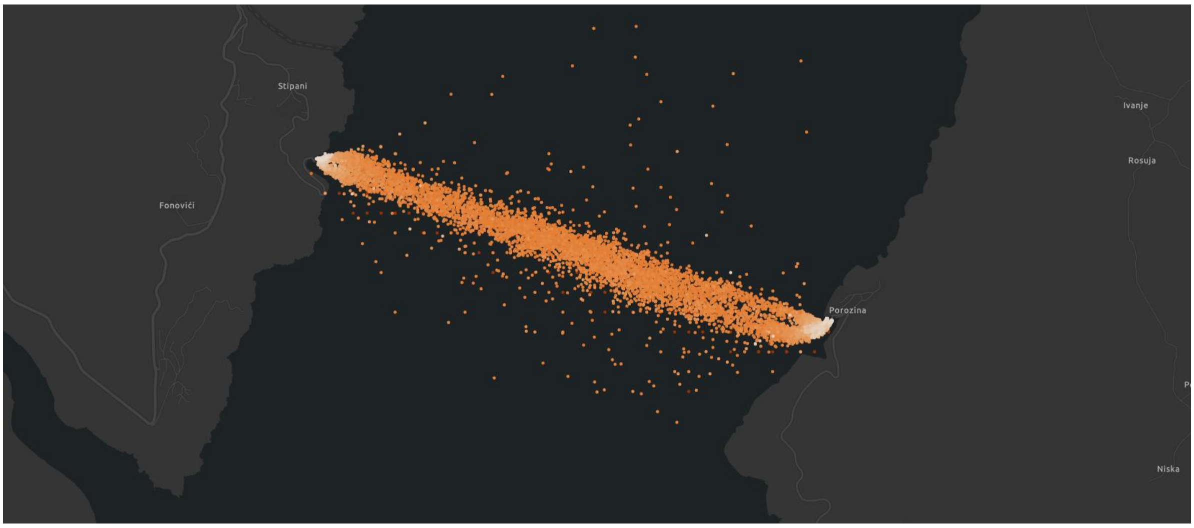

Figure 2: Ferry route between the berth of Brestova and Porozina

Table 1: Double ended ferry's main particulars, M/V Bol and M/V Brestova

Main Particulars	***M/V Bol***	***M/V Brestova***
LOA	95.4 m	58.17 m
Breadth	20 m	16.8 m
Draught	2,3 m	2,7 m
GT	2330	2315
DWT	1.000 t	482 t
IMO	8736344	8625090
MMSI	238810440	238154000
Build	2006	1985
Capacity vehicles/passengers	176 / 600	70 / 338
Engines	4 x MAN D28482LE402 TSP F240 total: 1.412 kW	2 x YANMAR T 260 ET total: 2.200 kW
Speed	12 kts	12 kts

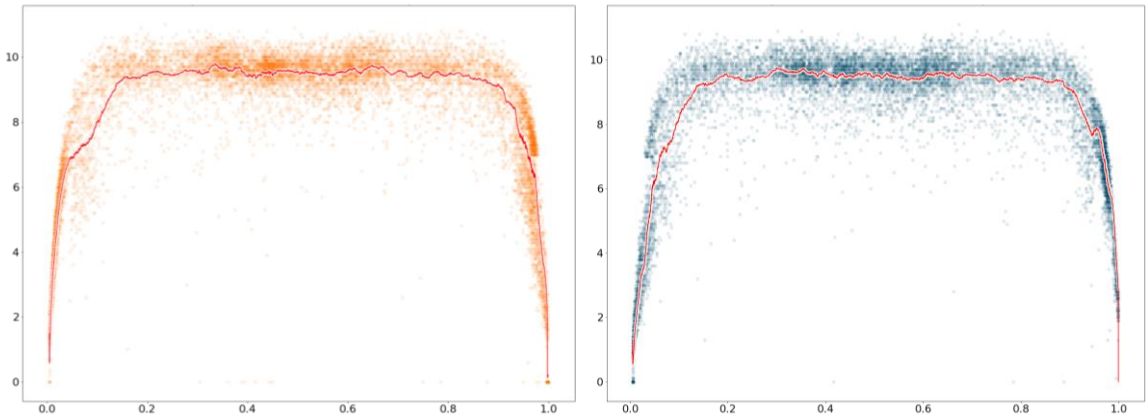

Figure 3: Speed profile from Brestova to Porozina and return

Since data shows a seasonal change (as shown in Figure 4), the yearly operation can be aggregate into three groups:

- ❖ **Type 1:** corresponding to July – August
- ❖ **Type 2:** corresponding to April – May – June – September
  - ➢ Type 1
  - ➢ Type 2
- ❖ **Type 3:** corresponding to October – November – December – March
  - ➢ Type 1
  - ➢ Type 2

Each mission starts with the departure from Porozina's harbour for all these routes, that differ from each other for the time spent in port, the sequence of transits and repetitions of the missions.

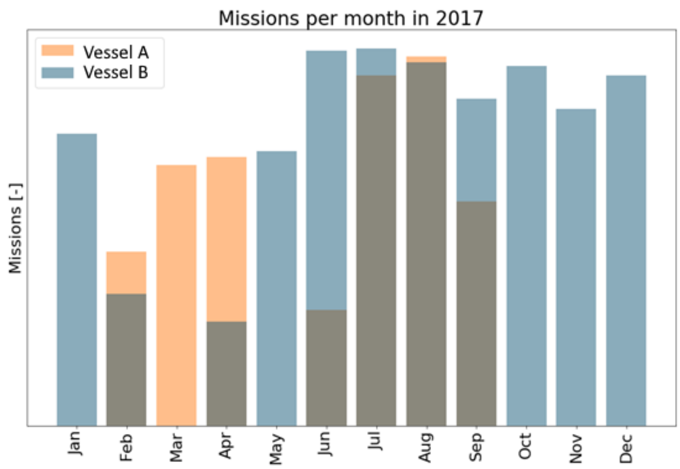

Figure 4: Number of missions for each vessel.

2.2 Power Assumptions

The diagram in Figure 5 shows the break power according to speed from 3 to 14 knots for this vessel: this curve has been used in our tool to get the power profile from the speed profile. For the simulations performed on the configuration at section *Machinery Configurations* a 15% sea margin on the speed power estimation was selected (dotted line). This curve is the output of the deliverable *Act 3.2 Hull modelling and design*.

The hotel load has been estimated to be around 80 kWe and, given the reference propulsion setup for this kind of installation (4 azimuthal thrusters), no additional bow and stern thrusters have been included.

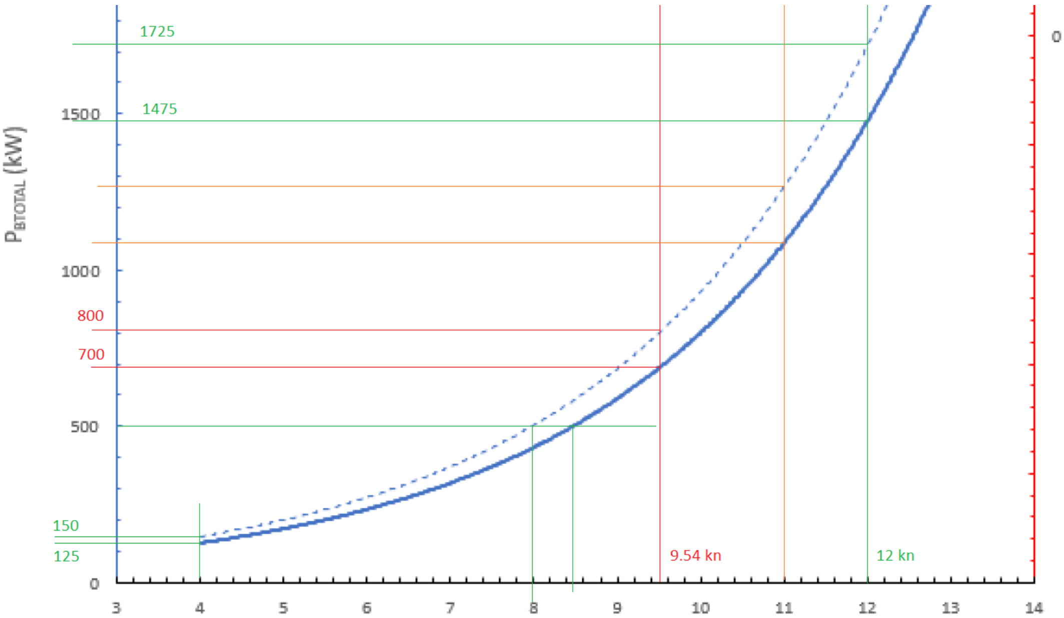

Figure 5: speed-power curve for the double ended ferry.

2.3 Machinery Configurations

For this kind of vessel six machinery concepts shown in Table 2, were evaluated, based on the following assumptions (made as a result of preliminary evaluations):

- Only **Diesel Electrical** configuration, since this concept enable better results with the selected operating profile.
- **No LNG** configuration, due to issue of bunkering in the region.
- **High speed engines**, besides the lower efficiency compared to medium speed engines, the dimensions simplify the design of innovative engine rooms.
- Test new technologies that enable zero local emissions in order to make an initial assessment on future platforms.

Table 2: double ended ferry configuration.

	DM	***HY***	***HY + SC***	***FE***	***FC***
Main Engine	**4 x High speed** 492kW @1800 rpm	**2 x W16V14** 1055kW @ 1800 rpm	**2 x W16V14** 1055kW @ 1800 rpm	**2 x PEMFC** 1000 kW	–
Gensets	**2 x High speed** 135kW @ 50 Hz	–	–	–	–
ESS	–	1 x 625kWh	1 x 625kWh	2 x 625kWh	2 x 1250kWh
Shore connection	–	–	1500kW	1500kW	2000kW

2.3.1 DM (reference configuration)

This configuration in Figure 6 is a standard Diesel Mechanic setup with modern engines, connected via a gearbox to one propeller each (in total 4 small main engines), moreover there are two genset for hotel in all conditions.

The fuel utilized is LFO (Light Fuel Oil) with a 0,2% of Sulphur: all the propulsion engines and one genset are running during crossing, while in harbour mode there is only one active genset.

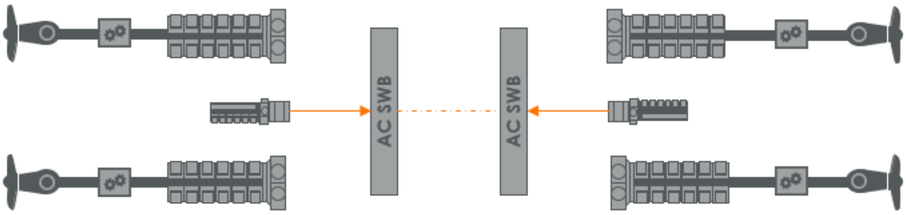

Figure 6: conceptual diagram for double ended ferry's DM configuration (reference).

2.3.2 HY

In the configuration of Figure 7 the change of setup enables to install only 2 small-bore high-speed engines that feed four electric motors moving one propeller each. Moreover, it has an additional ESS (Energy Storage System) with 2C-rate which takes care of hotel load in harbour mode and therefore no harbour genset is required.

During crossing ESS reduces the load peaks, while only one diesel generator is running at full load suppling power to the four electric motors. In harbour the optimization of the engine room is possible using a start & stop operation.

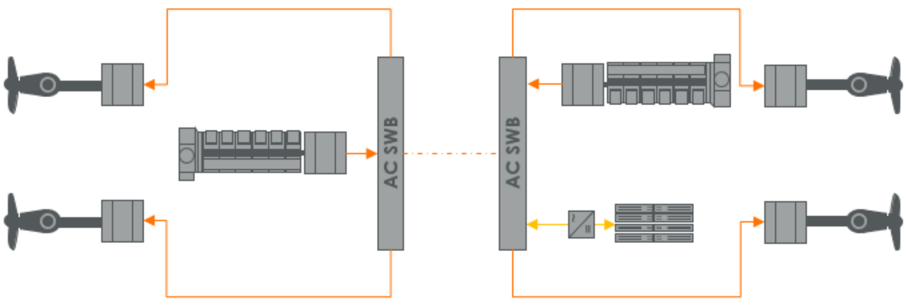

Figure 7: conceptual diagram for double ended ferry's HY configuration.

2.3.3 HY + SC

Based on HY configuration, but, as shown in Figure 8, additionally equipped with shore connection, in order to perform cold ironing when vessel stops at Porozina harbour. With this solution, while the vessel is at berth, all diesel generators are not used and ESS is in charging mode.

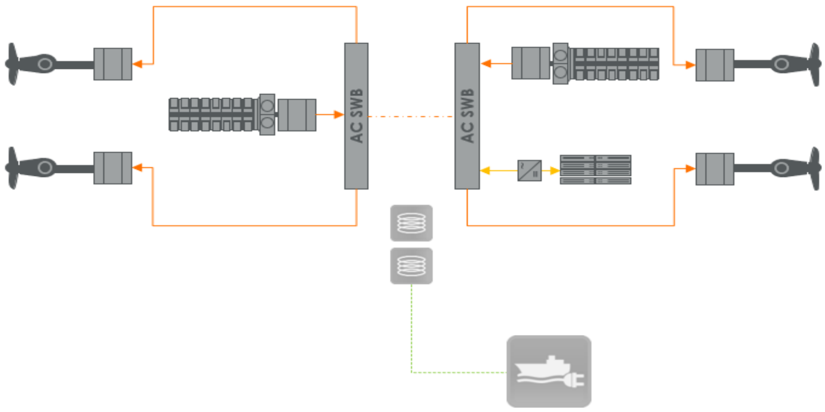

Figure 8: conceptual diagram for double ended ferry's HY+SC configuration.

2.3.4 FC

This concept of Figure 9 aims to replace engines with two fuel cells (PEMFC, hydrogen fuelled in order to sail with zero emissions), supported by ESS and shore connection for the harbour stay. The operation is very similar to HY+SC but with different loads to optimize the FCs.

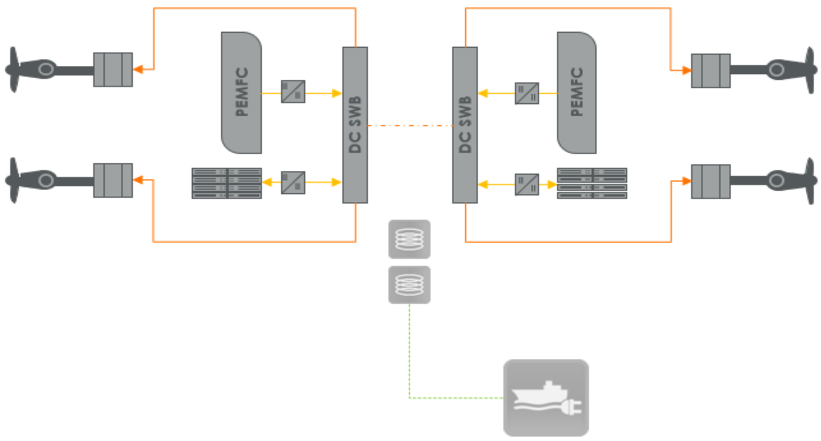

Figure 9: conceptual diagram for double ended ferry's FC configuration.

2.3.5 FE

This concept of Figure 10 aims to replace engines with only batteries, providing a zero-emission alternative to FCs. ESS is in discharging mode when sailing, and it's charging in harbour with different load for all different routes.

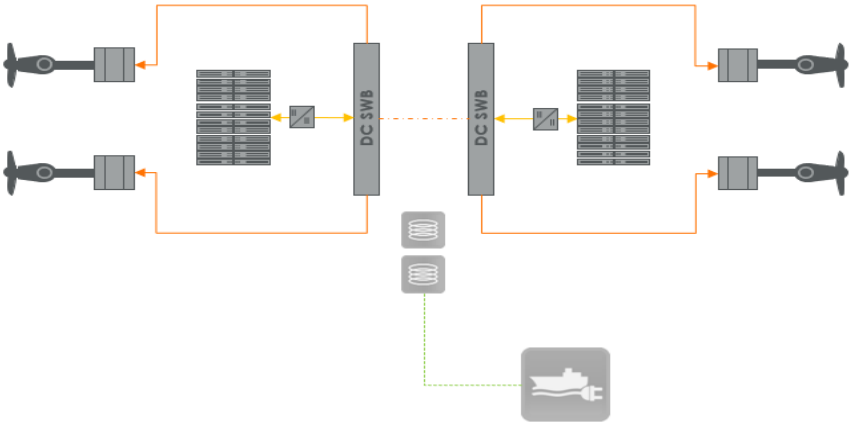

Figure 10: conceptual diagram for double ended ferry's FE configuration.

2.4 Simulation Results

In this section the results from the simulations of the configurations showed in the previous section are reported. Since for the configuration simulated the fuel is the same (except for the final one which runs on hydrogen) the carbon dioxide emissions and fuel consumption have the same trend only with different scale.

2.4.1 Emissions

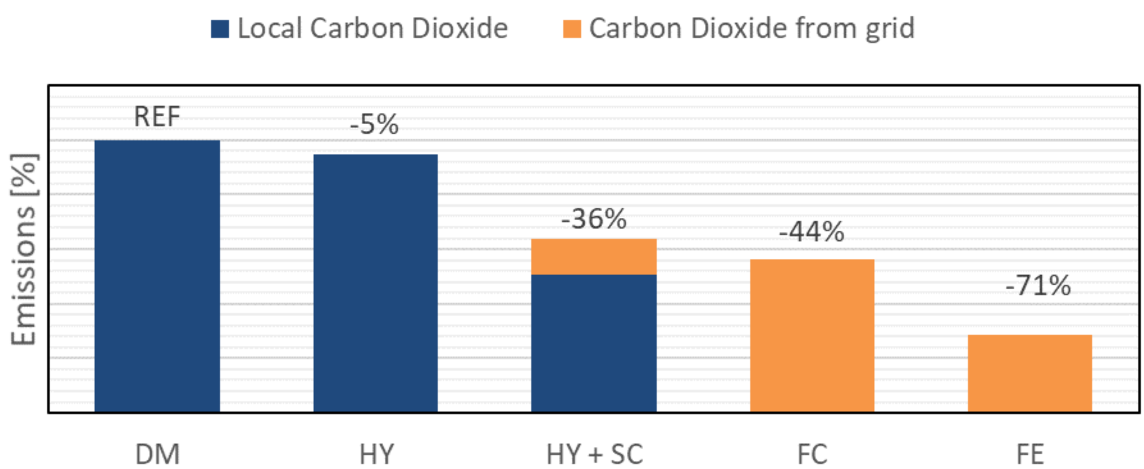

Figure 11: Carbon dioxide emission for the double ended ferry.

In Figure 11 the difference between reference, the Hybrid versions and the full electric concepts is due to presence of battery which makes the engines running less time, thus producing less CO2 emissions, while dioxide emissions attributed to Fuel Cell is only for hydrogen production. The impact of shore connection is remarkable and the equivalent emissions from the grid are very low highlighting the benefits of such solutions.

The local carbon dioxide is related to vessel's emissions, while the carbon dioxide from the grid is related to the production of energy for the shore connection. In this case the electricity carbon intensity for cold ironing is assumed to be *210 gCO2/kWh* and it is quite affected by how it has been generated, in particular the renewables penetration of the local grid.

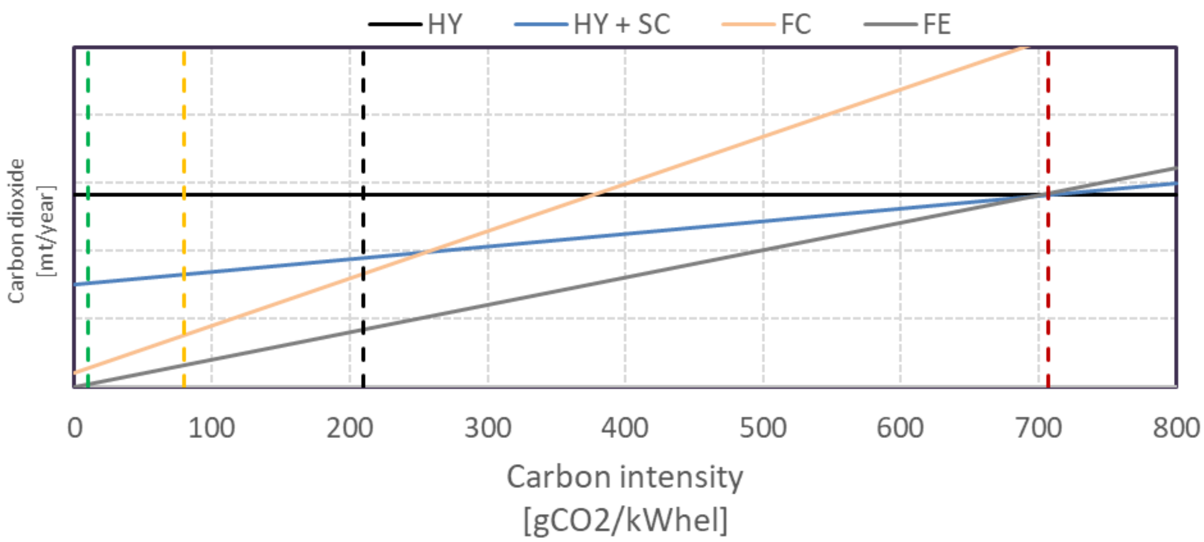

Figure 12: Sensitivity analysis on CO_2 emissions with carbon intensity factor for the double ended ferry.

Figure 12 shows a sensitivity analysis on how the carbon intensity of the grid is impacting the decarbonization of the solution: we can have then different scenarios according to the reported average value for each country. In the picture the Croatian scenario is compared to Austria, Norway and Poland, that has a different pattern of power production: it is clear that the actual and future best configuration are changing according to the level of decarbonisation of the local grid.

2.4.2 Running hours

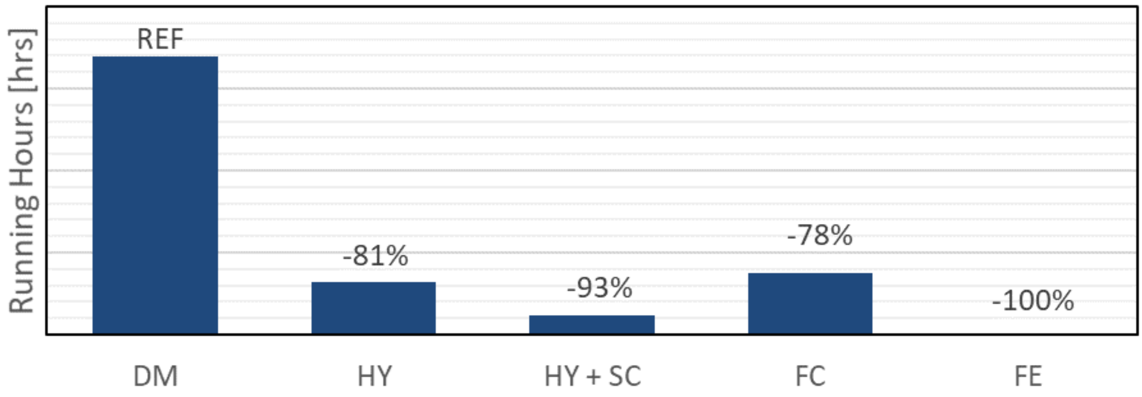

Figure 13: Running hours summary for the double ended ferry.

Figure 13 highlights a huge difference between the DM and the DE concept, that differs from each other for how well they can optimize the usage of batteries. It is interesting to underline that the concept HY and FC are close, while charging batteries and feeding hotel load by shore connection further reduces running hours by 10%.

2.4.3 OpEx

These considerations lead to the economical results showed in Figure 14, which has been calculated using the assumptions on the price of the consumables from Table 3.

Table 3: consumables price assumptions for double ended ferry.

Consumable	Price
Hydrogen	*1000 €/mt*
LFO	*450 €/mt*
Shore energy	*80 €/MWh*
Lube oil	*2300 €/mt.*

In the reference concept is relevant the LFO consumption and cost that is decreased by the other ones thanks to ESS and its combination. Although the relevance of shore connection price, HY+SC is more convenient than both concept DM and HY alone. The futuristic concepts (FC and FE) have a different OpEx's composition and it is interesting to notice that both are better also than hybrid solution on OpEx point of view.

In this overview maintenance cost are not included, but considering the previous discussion on the running hours it is clear that the percentage savings could further increase.

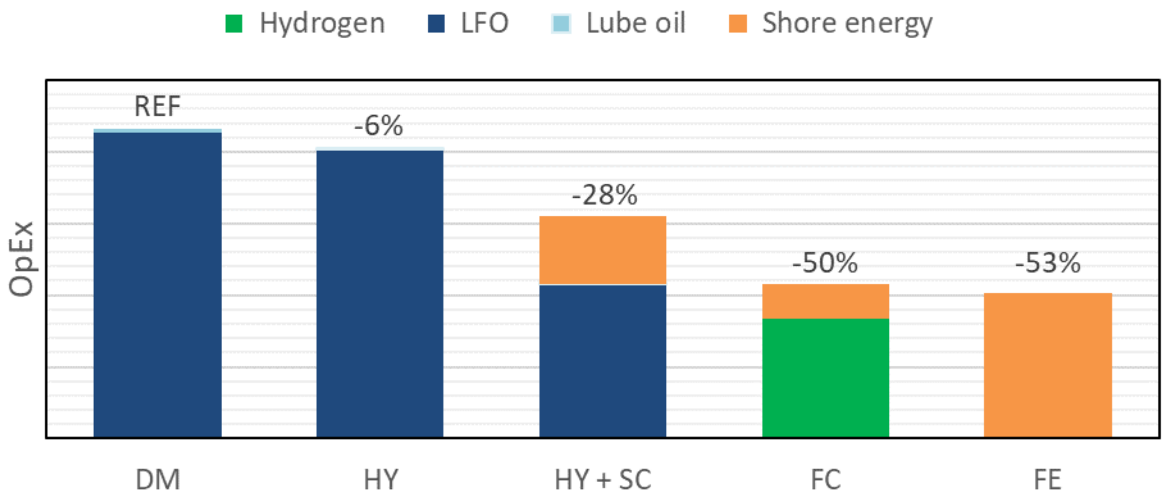

Figure 14: Operating Expenses for the double ended ferry.

Since the shore connection plays a relevant role in the simulated configurations a sensitivity analysis has been performed to assess in which scenarios our solutions are feasible. The Figure 15 highlights that under *100 €/kWh* solutions became competitive, especially the full electric concept. As expected for a short route the full hybrid is the best solution from both economic and environmental point of view.

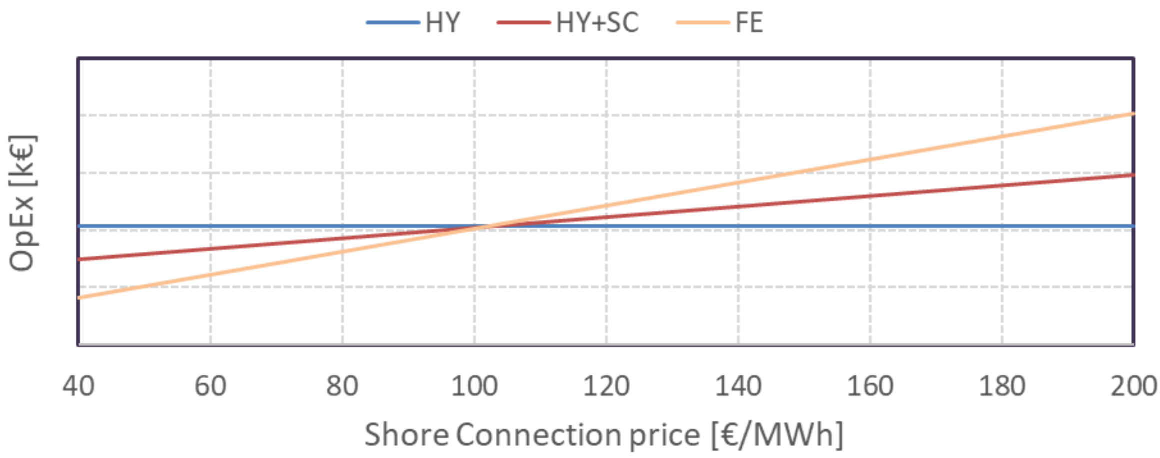

Figure 15: Sensitivity analysis of shore connection price on OpEx for the double ended ferry.

2.4.4 Effect of the shore connection power on the results

The effect of the shore connection on the HY+SC, FC, and FE solutions is appreciable, as shown by the previous results. Indeed, the reductions in emissions and OpEx in respect to the conventional propelled solution (DM) are significant. However, to achieve such results it is required to install in the port a suitably sized charging station, capable of delivering more than 1.5 MW to the ship. This may not be possible, depending on the existing shore and land power infrastructure, as well as the future modification opportunities (refer to Deliverable 4.1 and 4.2 for these topics). Therefore, it is useful to evaluate how the emissions and the OpEx changes following a variation in the available shore connection power. The selected configuration is the HY+SC one, which is tested with four different SC powers (250 kW, 500 kW, 750 kW, and 1 MW) and compared with the DM solution.

The results regarding overall emissions are depicted in Figure 16, where the DM solution (Concept #0) is compared with the HY+SC solution with variable SC power. It is evident how increasing the power of the shore connection reduces emissions, being an increasing quota of energy used by the ship delivered by the land power system. However, using a low power shore connection is still better than running a conventional Diesel-powered vessel, and the achievable emission reduction is still sensible.

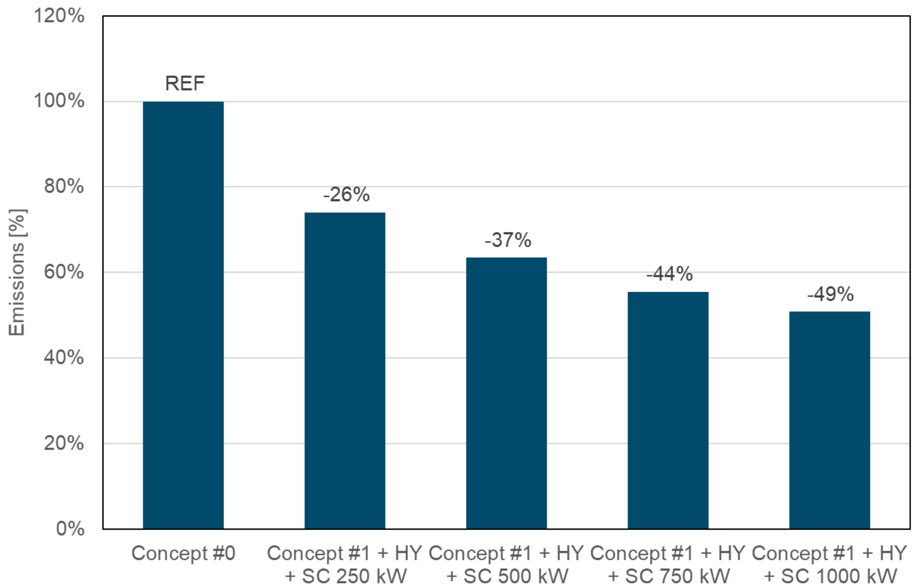

Figure 16 Carbon dioxide emission for the double ended ferry, effect of using different sized shore connection apparatuses.

Similar results can be achieved by considering the effect of the shore connection power level on the ferry OpEx, as shown in Figure 17. Also in this case, using a hybrid propulsion system with a shore connection enables significant gains in respect to the conventional Diesel-propelled solution, which improve with the recharge infrastructure power.

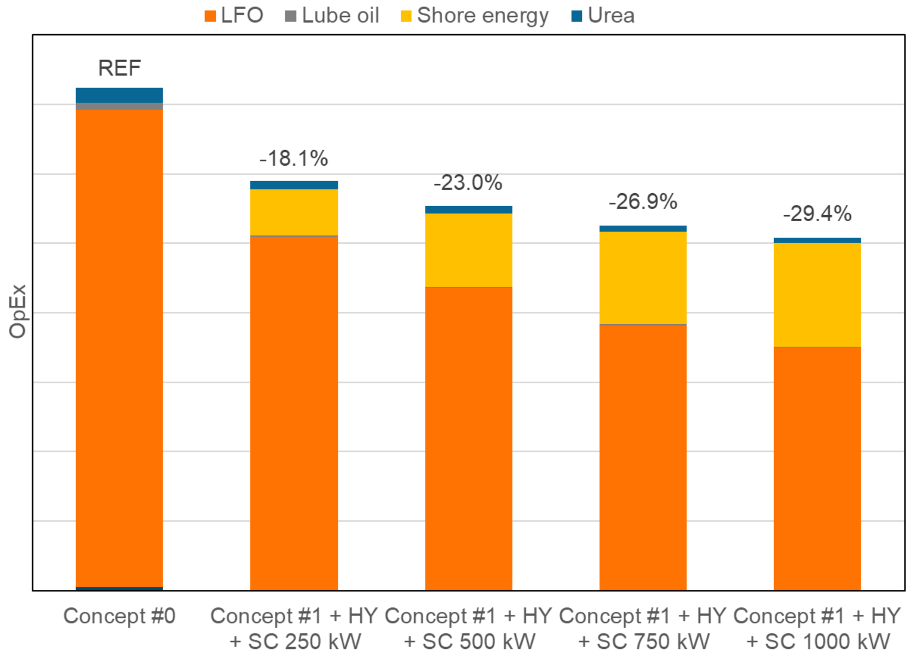

Figure 17 Operating Expenses for the double ended ferry, effect of using different sized shore connection apparatuses.

These results make it evident how the correct sizing of the land-side infrastructure can affect the overall environmental-friendliness of the conceived solution, promoting an integrated design of both the ship and the port. However, the results also show that a solution like the HY+SC one here proposed is capable of delivering substantial improvement in respect to the conventional Diesel-mechanical ones, also in a sub-optimal condition (with very low SC power available).

3 Long range vessel

3.1 RoPax Operating Profile

The longer route selected operate connects Croatia and Italy crossing the Adriatic Sea, between Ancona (Italy) and Split (Croatia), with a distance of approximately 100 NM as shown in Figure 18.

A preliminary evaluation identified the two reference vessels for this route: MV Bol and MV Brestova, whose details are in Table 4.

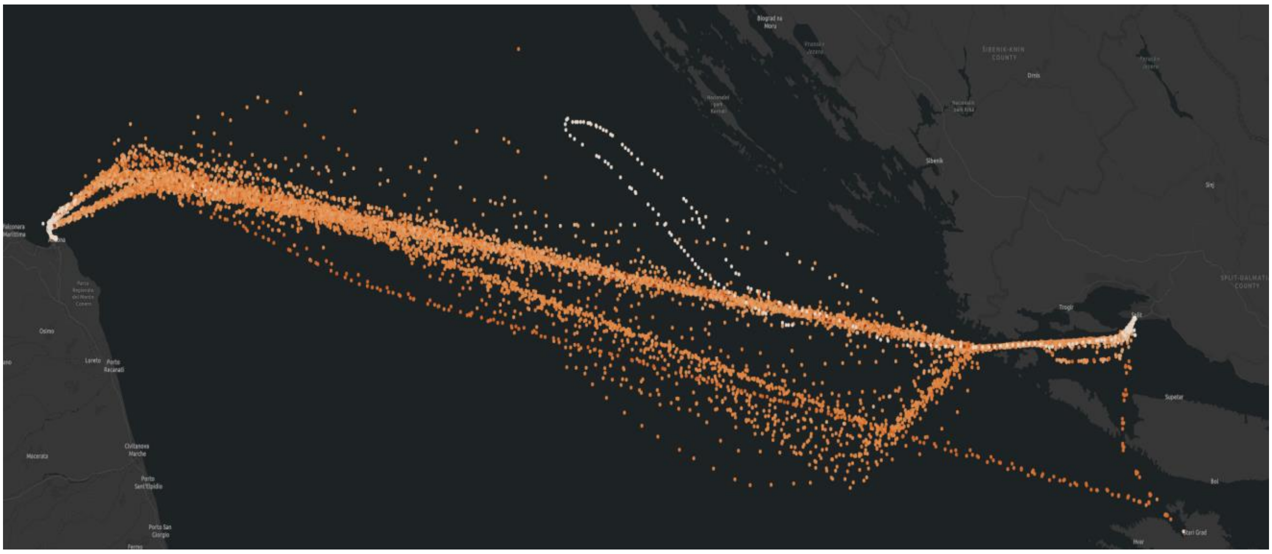

Figure 18: Route RoPax between Ancona and Split

Table 4: RoPax's main particulars, M/V Aurelia and M/V Marko Polo

Main Particulars	M/V Aurelia:	M/V Marko Polo:
LOA	147,97 m	128,13 m
Breadth	25,4 m	19,6 m
Draught	5,8 m	6,2 m
GT	21.518	10.154
DWT	3.250 t	1.132 t
Build	1980	1973
Capacity vehicles/passengers	610 / 2.280	270 / 1.000
Engines	2 x GMT A420 16V Diesel Total: 14.120 kW	4 x STORK WERKSPOOR 8TM410 - 4T Total: 15.000 kW
Speed max/avg	19,5 / 15,5 kts	19 / 16 kts

As it was done for the definition for the propulsion system of double ended ferry, an analysis on the navigation data has been done. This has been achieved by collecting the position and the speed of the selected vessels with an average sampling rate of 15 minutes, in a period from 1 Jan 2016 to 1 June 2019. The final dataset amount to nearly 125 thousand samples, allowing to define the real ship speed profile with a good accuracy.

For this route the algorithm started with the outgoing from Split harbour, then the vessel is accelerating reaching 16 knots (cruise speed) continuing, for some voyages, with slow steaming that means a reduction of speed, around 13 knots. After that the ship starts manoeuvring to enter in the Ancona's dock where the vessel will be moored for several hours waiting to come back to Split with a similar sequence of operating modes but with slightly different durations (that were statistically extracted from data, like reported by Table 5 and shown in Figure 19).

Table 5: General statistics of recorded voyages for the RoPax.

Departure	Destination	Repetitions	Average distance [nm]
ANCONA - Italy (IT)	SPLIT- Croatia (HR)	208	97.02428
SPLIT - Croatia (HR)	ANCONA - Italy (IT)	222	87.33723

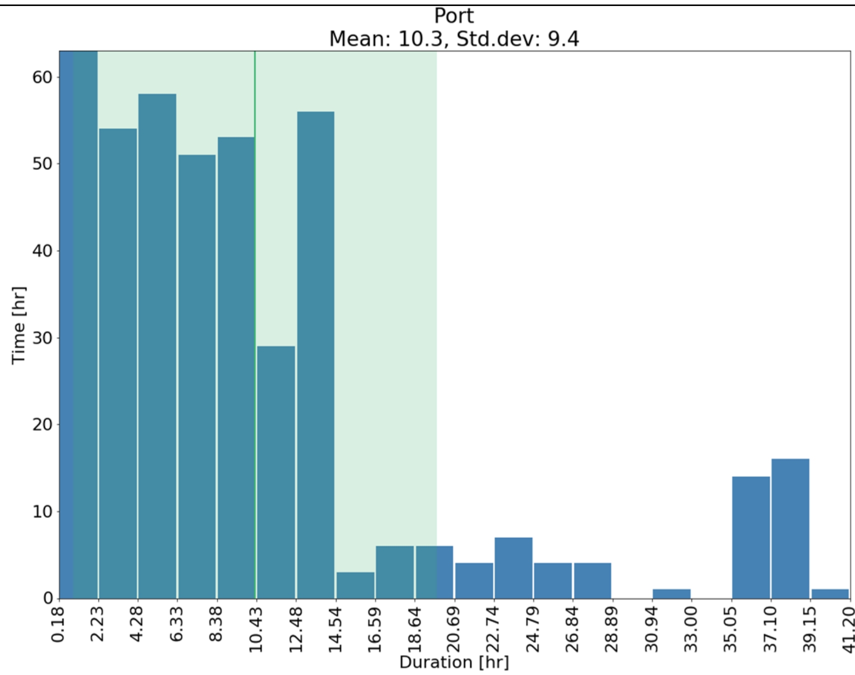

Figure 19: statistical analysis of duration of port stays for RoPax vessel.

3.2 Power Assumption

Figure 20 shows the break power for speed from 13 to 18 knots for this vessel: this curve has been used in the design tool to get the power profile from the speed profile. For the calculations reported in the following pages we employed a 15% margin on the speed power estimation (dotted line). This curve is the output of the deliverable *Act 3.2 Hull modelling and design*.

The hotel load has been estimated of 1200 kWe with an additional 1000 kWe given by the bow and stern thrusters during manoeuvring.

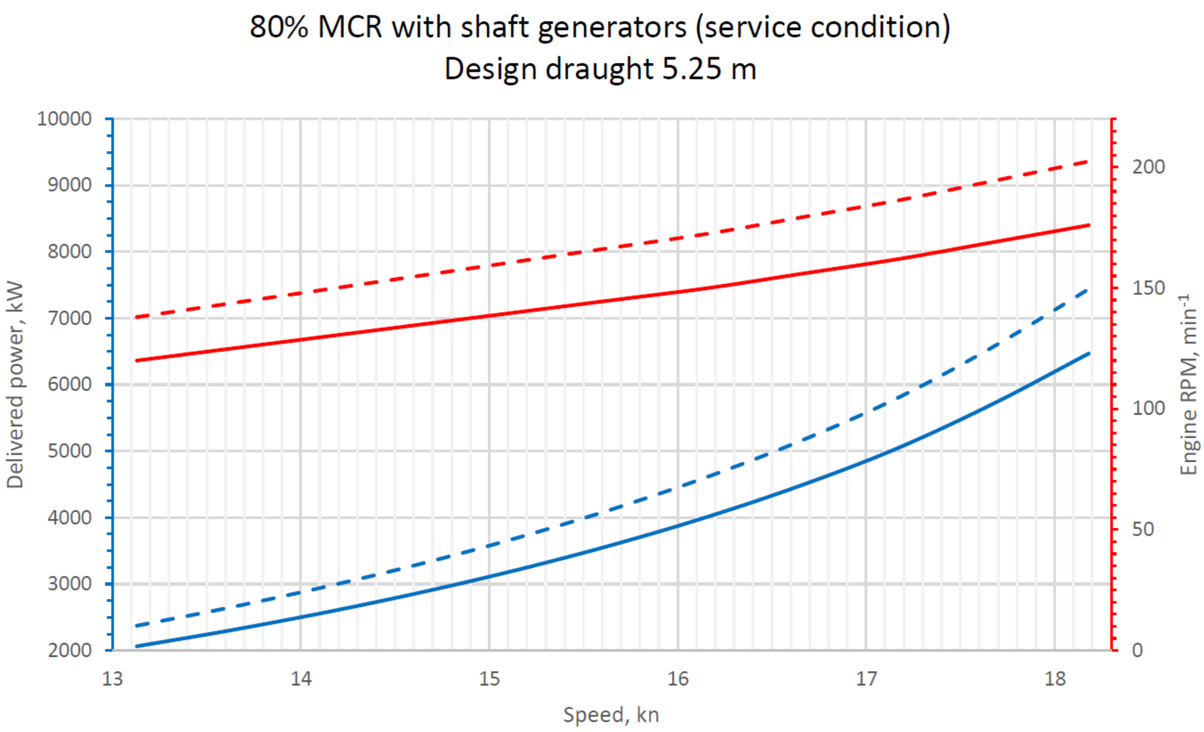

Figure 20. Speed-power curve for the RoPax.

3.3 Machinery Configurations

For this vessel four concepts, summarized in Table 6, have been compared with the following assumptions (made accordingly to preliminary evaluations):

- Only **Diesel Mechanical** configuration, since the electrical losses for a DE configuration are higher than the benefits given for this type of vessel.
- Only Single Input Single Output (SISO, i.e. one engine per propeller) gearbox given the required power at cruise speed.
- LNG has been selected as next generation fuel for improving the efficiency and lowering emissions with a good compromise for bunkering.

Table 6: configurations for RoPax.

	DM	DF	HY	HY + SC
Main power supplier	2 x W8L32 4480kW @750 rpm	2 x W8L34 DF 4000kW @750 rpm	2 x W8L34 DF 4000kW @750 rpm	2 x W8L34 DF 4000kW @750 rpm
Gensets	3x W6L20 1320 kW @50 Hz	3x W6L20 DF 1110 kW @50 Hz	2x W6L20 DF 1110 kW @50 Hz	–
PTO/PTI	–	–	2x PTO/PTI VS 1000 kW	2x PTO/PTI VS 1000 kW
ESS	–	–	ESS 1 x 5000 kWh	ESS 1 x 5000 kWh
Shore connection	–	–	–	1x 2000 kW

3.3.1 DM (reference configuration)

The configuration of Figure 21 is a simple Diesel Mechanic concept with two CPP with one engine for each propeller, three generators for the hotel load. All the engines are supposed to be LFO powered.

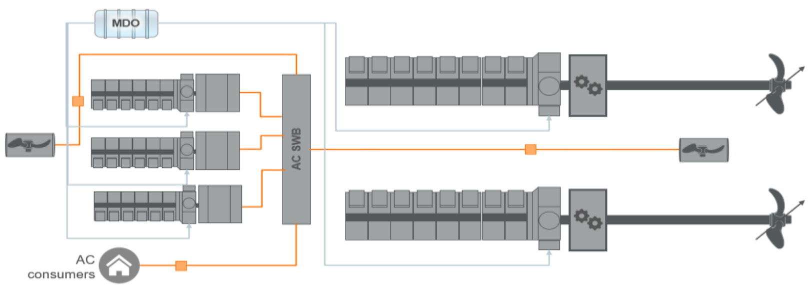

Figure 21: conceptual diagram for RoPax's for DM configuration (reference).

During sailing both propulsive engines are running at moderate load and only one genset is needed for the electrical supply. During port stay only one genset is running, while during manoeuvre the systems is supposed to run with all three gensets at half load and, obviously, all main engines running at a quite low load.

3.3.2 DF

This concept in Figure 22 is almost identical to the DM one, but the engines are all Dual Fuel (DF), therefore an additional LNG tank needs to be installed.

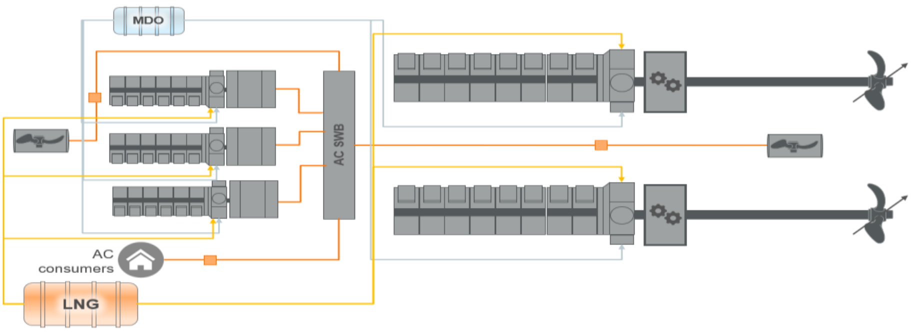

Figure 22: conceptual diagram for RoPax's for DF configuration.

The usage of the engines is again similar to the DM configuration with the only difference that the total power is slightly lower and therefore the load of each engine is slightly higher.

3.3.3 HY

Figure 23 shows the hybrid version of the DF configuration, therefore the 2 gearboxes are equipped with variable speed electrical motors (PTO/PTI), while one genset is replace by an ESS.

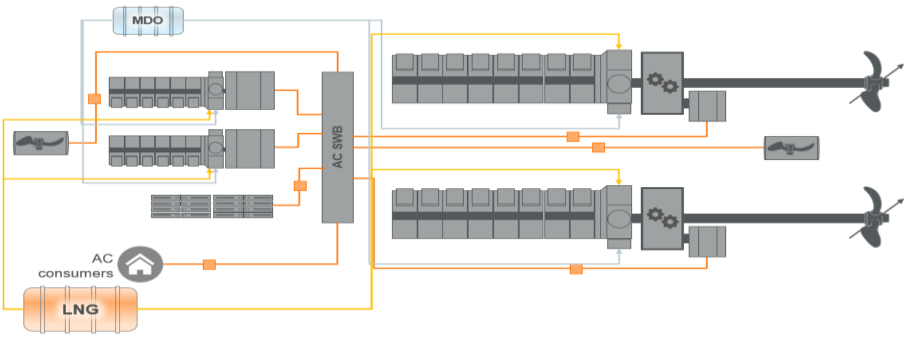

Figure 23: conceptual diagram for RoPax's for HY configuration.

When sailing the two engines work with higher load compared to the DF setup, because through the PTO they are also providing power to the hotel load and to the battery (that in this way will recharge), allowing to avoid running the diesel generators.

During stays in port, batteries are used in start & stop mode: batteries are discharging for only a part of all port stay allowing to shut off all the genset, while for the remaining time one genset is charging the batteries. During manoeuvring the system is designed to run in green mode: both main engines and gensets are not running and the ESS will provide the needed energy for both hotel and propulsive load (through PTI).

3.3.4 HY+SC

The configuration in Figure 24 is almost identical to the HY setup, except that this solution is equipped with a shore connection and does not require any generators. With this configuration is possible to get rid of engines also during port stay because the shore connection will supply the power needed for both hotel load and charging of the batteries.

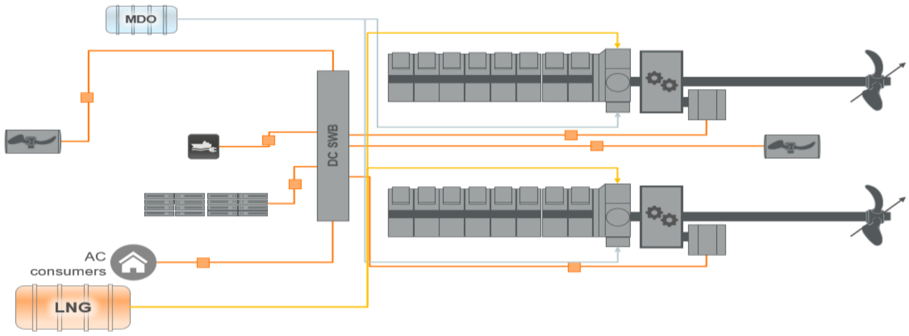

Figure 24: conceptual diagram for RoPax's for HY+SC configuration.

3.4 Simulation Results

In this section the results from the simulations of the configurations showed in the previous section are reported. Since for the configuration simulated the fuel is the same (except for the first one which runs only on LFO) the carbon dioxide emissions and fuel consumption have the same trend only with different scale.

3.4.1 Emissions

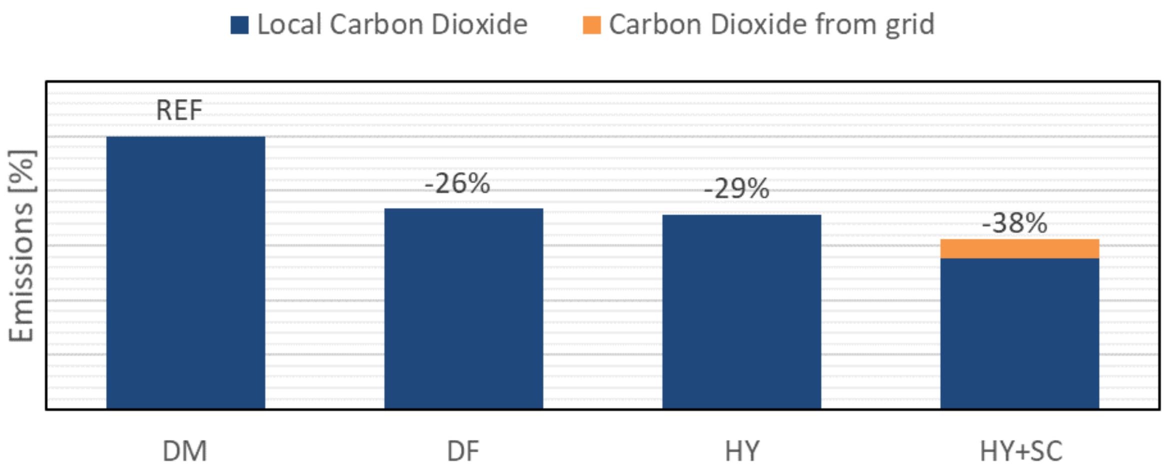

Figure 25: Carbon dioxide emission for the RoPax (210 gCO2/kWh).

Figure 25 underlines that the DF concept greatly reduces CO_2 emissions only with LNG as fuel since it contains less carbon for the same mass, has higher LHV (less amount of fuel for the same amount of energy) and the engines are more efficient thanks to the different technology. If we are only considering fuel consumption the difference will be lower since the content of carbon of each fuel would be not considered.

It's interesting to notice that hybrid solutions enable only a marginal saving in terms of carbon dioxide emissions compared to the change of fuel due to the operation: the major influence is given by the shore connection and the possibility to avoid any emission in port enabling also to charge batteries for the green mode operations.

The local carbon dioxide is again related to vessel's emissions, while the carbon dioxide from the grid is connected to the production of energy for the shore connection. Moreover for the RoPax the electricity carbon intensity for cold ironing is assumed to be *210 gCO2/kWh*.

3.4.2 Running hours

Figure 26 shows the annual sum of running hours of all the engines for the simulated configurations. Reference and DF configuration have approximately the same amount of running hours since, as already explained, the usage of the engines is almost the same.

Batteries and shaft generators make possible to greatly reduce (-26%) the running hours of auxiliary engines keeping them running only during the port stops. Finally the introduction of shore connection completely saves all the running hours of genset, that are not useful anymore, allowing a further decrease of running hours (-44%) and therefore maintenance cost.

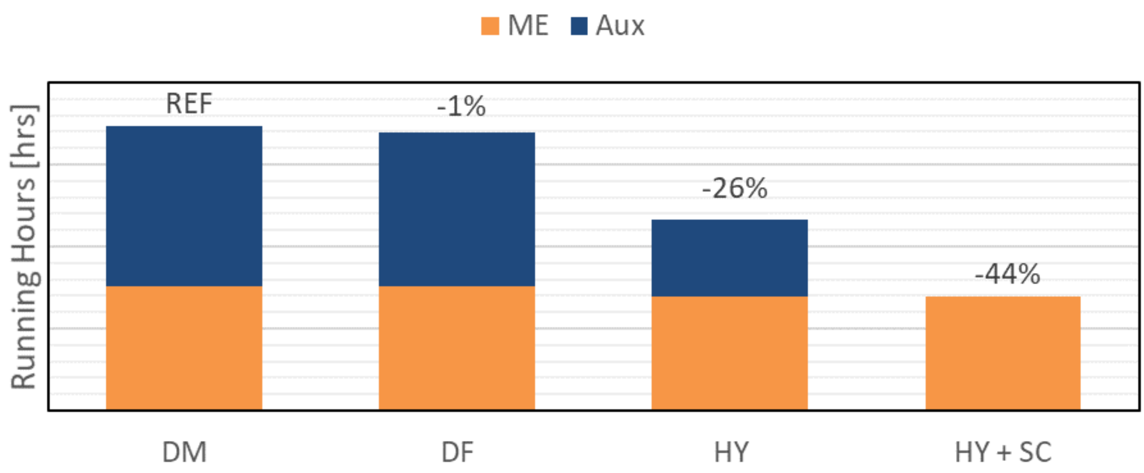

Figure 26: Running hours summary for the RoPax.

3.4.3 OpEx

These considerations lead to the economical results showed in Figure 27, which has been calculated using the assumptions on the price of the consumables from Table 7.

Table 7: consumables price assumptions for RoPax.

Consumable	Price
LNG	*400 €/mt*
LFO	*550 €/mt*
Shore energy	*80 €/MWh*
Lube oil	*2300 €/mt.*

As expected from the consideration made in the previous sections, DF solutions enables considerable savings of fuel consumptions, that are also increased from the lower price of LNG in respect to LFO.

HY solution does not differ much on consumables consumption but add an additional economic interest thanks to the lower maintenance: due to the cost of the energy from the grid and the big amount of energy required, the solution with shore connection might not be very economically effective according to the scenario, for this reason a sensitivity analysis has been performed to understand the conditions needed for an economic feasibility of this last solution.

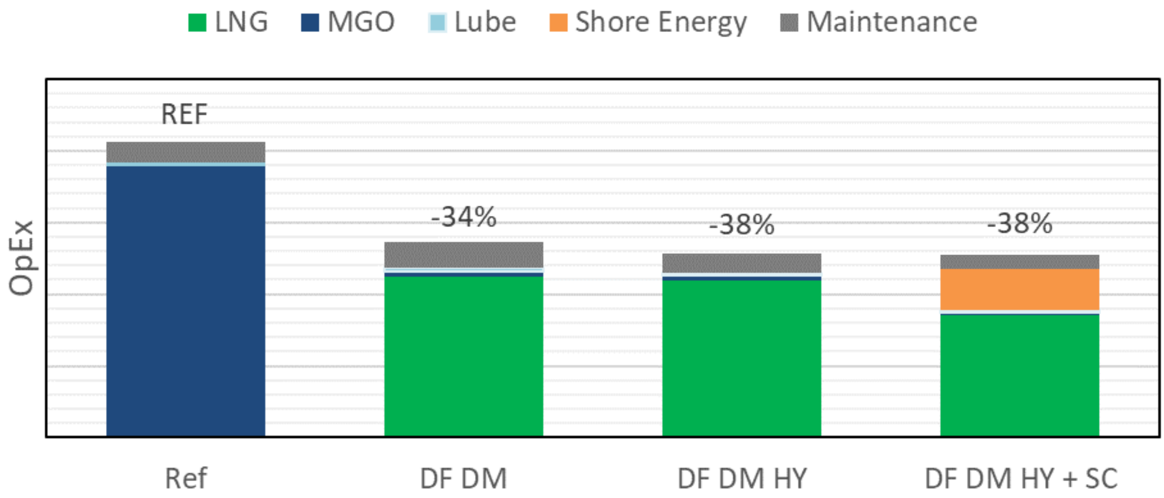

Figure 27: Operating Expenses for the RoPax.

Figure 28 shows that shore connection is economic viable only when the cost of shore energy is under 80 €/MWh: compared to the study of the ferry, the configuration with shore connection is attractive only with a much lower price for energy, which might be not in line with prices in the region.

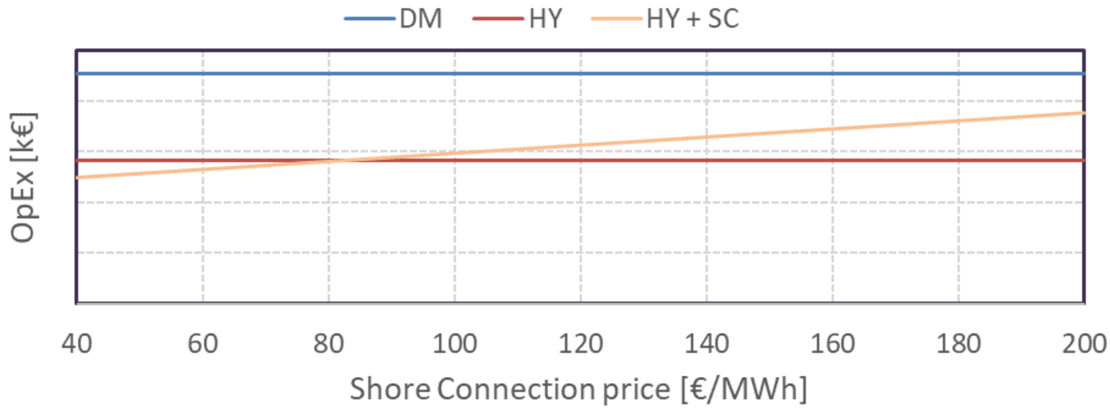

Figure 28: Sensitivity analysis of shore connection price on OpEx for the RoPax.

4 CONCLUSIONS

After the comparison of different concepts from economical, technical and environmental point of view one configuration for each vessel have been selected for the complete design.

4.1 Ferry

The hybrid solution with W16V14 and shore connection concept (HY+SC) showed good economical (-30% OpEx) and environmental performance (-35% CO_2), with low footprint and weight. Although the optimal design of the shore-side infrastructure will allow the best results to be achieved, this solution is still capable of providing significant emissions and OpEx reduction also in presence of an undersized recharging apparatus. A future solution for this typology of vessel seems to be the expansion of battery capacity towards full electric solution (-75% CO_2 and -55% OpEx).

- *Running hours*: all studied configurations are able to reduce running hours by 80%, reaching 90% through shore connection.
- *Emissions*: the studied solutions enable to reduce CO_2 emissions by 5% up to 40%. Actual reduction is strongly influenced by local carbon intensity of electricity generation.
- *OpEx*: the proposed solutions enable to reduce OpEx by 6% up to 30%. The actual results are quite influenced by shore energy price: to get an actual reduction of OpEx also for solution with SC price should be lower 100€/MWh.

4.2 RoPax

The hybrid solution with W8L34DF and shaft generators (HY) showed good economical (-37% OpEx) and environmental performance (-30% CO_2). Solutions with also the shore connection (HY+SC) is quite challenged by the price of shore connection (to promote more environmentally friendly solution government incentives might be needed).

- *Running hours*: hybrid configurations are capable to cut running hours from 25% to 50%.
- *Emissions*: the studied solutions enable to reduce CO_2 emissions by 25% up to 40%. Actual reduction is strongly influenced by local carbon intensity of electricity generation only for the Shore Connection solution.
- *OpEx*: proposed solutions enable to reduce OpEx by 33% up to 38%. The actual results are again very influenced by shore energy price: to get an actual reduction of OpEx also for solution with SC price should be lower than 80€/MWh.

Appendix A: Technical Specification

The documents "*D3.1 - Technical Specification Ferry"* and "*D3.1 - Technical Specification RoPax"* describe the machinery technical specification of the selected configurations for the 2 vessels.

Appendix B: Functional Description

This section provides an overview of the system functionalities, each vessel has its own set of functionalities therefore they will be reviewed separately.

Appendix B.1: Ferry

The double ended ferry has 4 main functionalities:

1. **Green mode**: the ESS is supplying all the needed energy for the vessel's power demand, the amount of time in which this mode is available is limited since batteries are discharging and therefore it is regulated by the EMS. In this mode no genset is running and therefore the vessel has no local emissions.
2. **Green mode + SC**: the shore connection is available and is supplying all the needed energy for the vessel's power demand and the charging of the batteries. In this mode no genset is running and therefore the vessel has no local emissions.
3. **Hybrid mode**: in this mode one/two genset are running supplying all the needed energy for the vessel's power demand and charging/discharging/peak shaving the batteries according to vessel's operation.
4. **Mechanical:** in this mode the ESS is not operative and the EMS/PMS is using the genset to supply the vessel's power demand. This is considered an emergency mode in case of any fault on the hybrid system.

These functionalities are not available in all conditions but are limited to certain vessel's operating condition. Moreover, according to the typical power and duration of a certain operation is it possible to operate the system differently (e.g. charging or discharging the ESS according to actual power demand). For this reason, Table 8 provides the matrix of functionalities and operating modes and the details in the specific combination.

Table 8: Functionalities availability and details with vessel operation for the double ended ferry.

Operating mode	Green mode	Green mode + SC	Hybrid mode	Mechanical
Port	Available - Discharging ESS	Available - Charging ESS	Available - Charging ESS	Available - Emergency
Manoeuvre	Available - Discharging ESS	Not available	Available - Peak shaving	Available - Emergency
Sailing	Not available	Not available	Available - Discharging ESS	Available - Emergency

Appendix B.2: RoPax

The RoPax has 5 main functionalities:

1. **Green mode**: the ESS is supplying all the needed energy for the vessel's power demand, the amount of time in which this mode is available is limited since batteries are discharging and therefore it is regulated by the EMS. In this mode no genset is running and therefore the vessel has no local emissions.
2. **Green mode + SC**: the shore connection is available and is supplying all the needed energy for the vessel's power demand and the charging of the batteries. In this mode no genset is running and therefore the vessel has no local emissions.
3. **Hybrid mode**: in this mode one/two genset are running supplying all the needed energy for the vessel's power demand and charging/discharging/peak shaving the batteries according to vessel's operation.
4. **Optimal loading**: in this mode the engines are always running above a certain load in order to optimize their specific fuel consumption and they will charge the batteries. When the batteries are loaded over a preset SoC, the EMS will shut down one engine in order to reduce fuel consumption and running hours letting the ESS covering the remaining power. Since this cycles are fully dependent on SoC, the EMS will monitor when to operate the switch of the condition.
5. **Mechanical:** in this mode the ESS is not operative and the EMS/PMS is using the genset to supply the vessel's power demand. This is considered an emergency mode in case of any fault on the hybrid system.

These functionalities are not available in all conditions but are limited to certain vessel's operating condition. Moreover, according to the typical power and duration of a certain operation is it possible to operate the system differently (e.g. running only 1 or both main engines). For this reason, Table 9 provides the matrix of functionalities and operating modes and the details in the specific combination.

Table 9: Functionalities availability and details with vessel operation for the RoPax.

Operating mode	Green mode	Green mode + SC	Hybrid mode	Optimal loading	Mechanical
Port	Available - Discharging ESS	Available - Charging ESS	Available - Charging ESS	Available	Available - Emergency
Manoeuvre	Available - Discharging ESS	Not available	Available - Discharging ESS	Not available	Available - Emergency
Sailing at low speed	Not available	Not available	Available - Peak shaving / Charging ESS	Available	Available - Emergency
Sailing at cruise speed	Not available	Not available	Available - Peak shaving	Not available	Available - Emergency