Sustainable, safe and economically feasible energy concepts and technologies for European Inland Shipping

See page 35 and 36;

6.8 Conclusions for hybrid and diesel electric ships, yellow highlighted,

Why electric and hybrids are less exonomical than Diesel direct driven ships.

D2.8 Standardize model and cost/benefit assessment for right-size engines

D2.9 Standardize model and cost/benefit assessment for hybrid configurations

Public report

This project has recieved funding from the EU Horizon 2020 research and innovation program

Document version (date)	Comments (changes compared to previous version)	Authorised by
0.1 (11th of December 2017)	First draft version	Dick Abma (TNO)
0.2 (13th of January 2017)	Processed comments from EICB	Dick Abma (TNO)
0.3 (6th of February 2018)	Included stakeholder feedback and additional input	Dick Abma / Ruud Verbeek (TNO)

Authors of the document

Responsible organisation	Principle author
TNO	Dick Abma, Ruud Verbeek
EICB	Bas Kelderman, Boudewijn Hoogvelt
STC	Martin Quispel

Grant Agreement: 633929
(Sub)Work Package: WP2
Deliverable No: D2.8, D2.9
Author: Dick Abma, Ruud Verbeek
Version (date): February 9, 2018

Contents

1 Introduction

1.1 PROMINENT project

The activities within the European research project PROMINENT[1] (Promotion of Innovation in Inland Waterway Transport) are focussed on the development of standardised concepts for reducing emissions in a main share of the European inland waterway fleet. With these activities, it is aimed that in 2020 these concepts will be applicable to at least 70% of the European inland waterway fleet and that the implementation costs of these concepts will be reduced by 30%. The standardisation of these concepts is the focus of WP2 of this project with a close interaction with the pilots performed in WP5 and resulting in the roll-out of these technologies in WP6.

In SWP 1.1 of this project a study was performed to gain insight into the composition of the European inland waterway fleet and the operational use of these vessels. This resulted in an macromodel of the European fleet with 12,263 vessels, a categorisation of these in groups of comparable vessels ('fleet families') and a selection of 60 representative journeys on the different European waterways. For most of the representative IWT journeys the operational profiles (providing a power distribution over time) were elaborated.

In SWP 1.2 of this project best available technologies were identified. To assess the applicability and feasibility of these best available technologies and the further development of concepts for mass implementation, an understanding of the fleet and how this fleet is used is essential. As there are major variations between the different vessel types and the operational use (in e.g. power, fuel consumption), different technologies can be beneficial for different parts of the fleet. Two of these concepts, as concluded in the D1.2 report, are the application of hybrid configurations and the right-sizing of the engines.

In WP2 of this project the development of advanced concepts for mass introduction has been targeted, these concepts are LNG, diesel after-treatment, energy-efficient navigation, right-sizing and hybrid configuration. For the first three concepts pilot projects are and will be performed. WP2 also concerns the definition of the pilot test specifications and an ex-post analysis of the costs and benefits. The activities for right-sizing and hybrid configurations are focussed on the development of a mathematical model for standardised engine configurations. For these configurations, analyses of the costs and benefits are performed.

WP2 also investigates the electrification on board as a potential solution to lower emissions and improve fuel efficiency. Electrification can be done in a range of different ways, and each of these ways has advantages and disadvantages. This deliverable provides a global overview of what the of different hybridization techniques mean for the performance and control strategies of the driveline.

In the preface of PROMINENT it was expected that many ship in the European fleet carry more propulsion power than necessary for their activities. On board monitoring in WP5 showed that this is indeed the case for most of the inspected vessels (results in D5.7). Carrying too powerful equipment decreases the energy performance of the ship, increases emissions, and limits the potential of applying aftertreatment of exhaust gases. Oversizing of ship engines also has a financial impact on the companies that operate these vessels through investment and operating costs.

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[1] http://www.prominent-iwt.eu/

1.2 PROMINENT D2.8 & D2.9 objectives

The main objective of this deliverable is to develop cost-benefit models for inland ships drivelines with right-size engines or with hybrid drivelines.
To develop these models also extensive modelling needs to be done in order to determine suitable driveline options and to determine the influence on fuel consumption and investment costs. This modelling is also a main part of this work.

Regarding the driveline options, the focus of this work is on the following types:

- Conventional diesel direct drive
- Conventional diesel direct drive with smaller diesel engine(s), referred to as 'right size' engine
- Diesel-electric propulsion
- Hybrid electric propulsion

These options are seen as the most popular options. Not included in the drivelines options are the mechanical hybrids.

1.3 Structure of this report

The contents of the chapters of this report is as follows:

- Chapter 2: Overview of driveline options including fleet observations, engine load profiles, definitions and a market overview of existing hybrid and diesel electric inland vessels.
- Chapter 3: Discussion of the energy model to simulate diesel direct, hybrid and diesel electric ships
- Chapter 0: Presentation of the modelling results including detailed energy losses and the impact on fuel consumption
- Chapter 5: Introduction of the relevant variables and cost-benefit equations in the cost-benefit model
- Chapter 6: Presentation of the cost-benefits and Net Present Value (NPV) calculation results of different types of drivelines including right sizing of the engine(s).

1.4 Aknowledgement

For this study important input was deliverd by the 'Right sizing working group' lead by Boudewijn Hoogvelt from the EICB. The members of this working group; Dolderman, EICB, Koedood/Hybrid Ship Propulsion, PON Power Systems and Volvo Penta delivered engine efficiency maps and cost figures for purchasing engines, generator sets and maintenance costs. Their input was essential for this study.

2 Driveline options

2.1 Right-sizing

2.1.1 Fleet observations

In PROMINENT, the engine load profiles of some 20 ships sailing on Rhine, Danube and other waterways were determined based on long term on-board monitoring. In total over 100.000 hrs of on board monitoring data was collected. The conclusion of this monitoring was that for most of the ships, the average power of the propulsion engines was between 30% and 35%. This was the case for both the motor vessels on the Rhine, as well as for the pushers on the Danube. Of almost all of these ships the maximum power used seldom or never exceeded 60% or 70% of the maximum power. The analysed vessels on the Rhine have a total installed power range from 1500 to 2300 kW, which is average to high compared to the fleet(see figure 10 in D1.1). The total power for the Danube vessels ranges between 1900 and 2500 kW, with one smaller vessel with 600 kW engine power.

On top of the monitoring results from PROMINENT, Caterpillar distributer PON made engine load profiles available. The profiles are derived from about 270.000 hrs of monitoring for different types of ships. The engine size of these ships ranged from about 1100 to 1350 kW, which is in the lower 25 percentile for 100m liquid and dry cargo ships(see figure 10 in D1.1). The table below shows the average load per vessel type based on this data. It shows that the average load of container, ARA tankers and dry cargo vessels is between 25% and 35%, basically in line with the PROMINENT monitoring data. The Rhine tankers have and average power between 38% and 51% which is substantially higher. More important is whether high power conditions are often used, for example with upstream river sailing. Refer to the figue below. This shows that for the tankers and the dry cargo vessels, sailing on high power regularly occurs; from 2% to about 37% of the time engine power of 70% or more is used. For the container vessels these high power condtions are seldom used. It can be concluded that for many ships the full power range is regularly used except for the tanker vessels.

	Average load %	Power > 80%
Container	25-26%	Hardly used
ARA tanker	28 – 30%	Used
Rhine tanker	38 – 51%	Used
Dry cargo	35%	Used

Table 1: Summary of the load profiles in Figure 1.

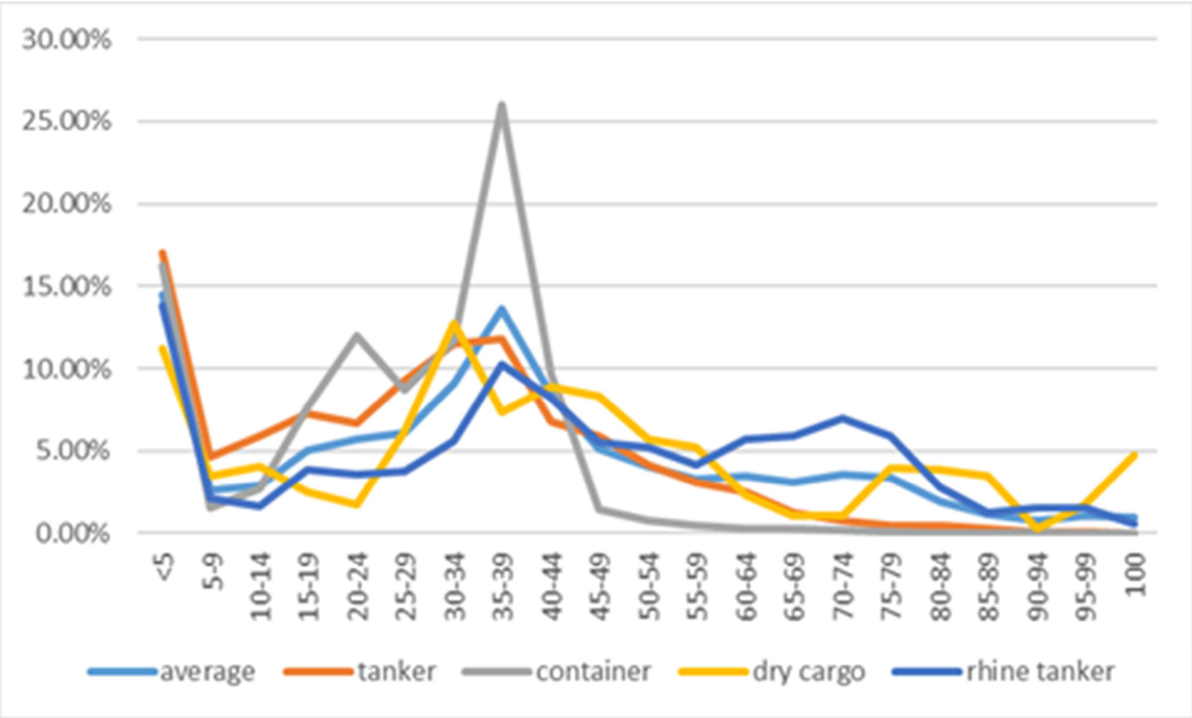

Figure 1: Engine load profiles provided by PON for 13 ships. The ships have relatively light engines compared to the fleet as reported in D1.1. Source PON 2018.

2.1.2 Barriers for implementation of right sizing

In PROMINENT and in other studies(MoVe-IT! D4.1), it was concluded that inland vessels are often equipped with oversized an engine(s): 1500 – 2000 kW propulsion power is installed, while in practice, even for sailing the Rhine upstream about 900 kW may be sufficient. Two main explanations were found for the high installed power: flexibility and regulations.

More installed power results in more flexibility. This flexibility is beneficial for the ship owner, as they often sail under a contract for a couple of years, after which they may need to ship different goods or on a different route. A higher installed power therefore increases the chances of finding a good contract. The value of the larger engine is therefore reflected in the reselling value. The additional reselling value must be compared with the costs or benefits arising from the model in this report.

Other reasons to install a certan engine size are associated with safety and manoeuvrability. For dimensioning, the most important requirements are the minimum speed and stopping distance requirements, as defined by CESNI in the ES-TRIN standard. For the minimum speed, it is required to be able to obtain a speed of 13km/h relative to the water in all waterway conditions.

The stopping distance depends on the dimensions of the ship. In an emergency braking procedure, the stopping distance is mostly influenced by two factors. The first is the capability to reverse the propeller. Downsizing may cause issues here as smaller engines have less inertia, a may therefore lose too much speed while slowing down the propeller.
After consultation of engine suppliers, they indicated that they compensate the lack of inertia by adding mass to the flywheel, or implement a brake on the propeller shaft.

The second factor is to produce enough power the slow down the ship. The smaller engine has less power to slow down the ship. Once the engine speed has been reduced, the engine cannot produce its maximum power, which increases the stopping distance. The is due to the propeller thrust in reversing conditions, which is optimized to move forward, and not for braking. To determine the actual power needed to stop the ship, tank tests or real-life tests results are needed. If these are not available, additional tests may be required.

Therefore, we will use the following definition for a right-sized ship driveline:
A righted sized ship driveline has the minimum power installed to fullfil its operational duties, while complying with the regulations for manoeuvrability.

In the case of a hybrid ship, advantage can be taken from the high torque that the electromotor can produce at low rpm. Therefore, the electromotor can be used to support the diesel engine for emergency stopping. This is on the condition, that the power of the generator sets can be available fast enough.

In summary, although on-board monitoring of an existing ship may be used to determine the desired propulsion power, it is also necessary to account for minimum braking power. To estimate this required braking power, existing tank test or test trial results for braking power can be used.

2.2 Introduction diesel electric and hybrid drivelines

In the search of reducing emissions and creating cleaner, more economic ships, electrification and downsizing plays an important role. Large successes in fuel savings are being referred to J.J.H. Paulides (2015), J.J.H Paulides (2016), publications only report performance of part of the drivetrain, and lack the overview of the whole ship. It is therefore hard to translate the findings to the effect of hybridization of other ships.
The problem is that there are seldom two sister ships with different drivelines and comparable operational deployment. Therefore, it is not easy to determine the effect of hybrid propulsion on the fuel consumption. And even then, detailed measurements must be performed in identical conditions, in order to compare the effectiveness of electric propulsion. Furthermore, there are many kinds of hybrids appearing in the fleet, since electromotors and conventional propulsion can be combined in different configurations.

In general, the installation of extra generators and electromotors result in higher investment compared to a conventional driveline. Hence, hybridization should earn back the extra investment via extra revenue in operations. This should be achieved via operational expenses, such as a reduction of fuel expenses, lower maintenance costs or special capabilities to perform extra actions.

Examples of such capabilities are:

- When placement of the prime mover is important, diesel electric ships have more freedom in the location of the generator sets.
- Navigation that requires sailings speeds so low, that diesel direct propulsion cannot sustain due to the idle speed of the engine.
- Tanker ships have generator sets installed to operate the pumps. These can be utilized for propulsion, so only the electromotor and controllers need to be installed to enable electric propulsion

- Passenger ships are already equipped with generator sets to supply the auxiliary load, so they can easily install larger ones to power an electromotor
- The number of propellers yields different investments, as multi propeller hybrid ships require multiple electromotors while sailing on a single generator sets.
- For retrofit the installation costs strongly depend on the system that is installed before retrofitting takes place.

2.3 Definitions

An overview of the different drivelines options is presented in the table below:

Name	Definition
Diesel direct drive	Conventional diesel propulsion with the engine mechanically coupled to the (fixed pitch) propeller
Hybrid (electric)	Power input mechanically by engine and/or by an electric motor. Electric power provided by generator set(s) Sub variants: - In-line hybrid: electromotor on the propeller shaft - PTI hybrid: electromotor via gearbox
Diesel-electric (Engine-electric)	generator set(s) with electric motor driven propeller(s) Sub-variants: diesel-electric and gas-electric
Mechanical hybrid	Two or more engines are mechanically coupled to the propeller shaft such as father-son.
Parallel electric (hybrid with batteries)	Generator set(s) and/or battery provide power for electric motor driven propeller(s)
Battery electric	Full electric vessel, only powered by batteries

The focus of this report is on right sizing and the first two alternative drive lines in the table above. Battery-electric drivelines, mechanical hybrids or hybrids with batteries are not evaluated in this report. Also, hybrids with variable speed generator sets are not included due to a lack of performance information about these generator sets during the modelling period. A right-sized engine is interpreted as the minimum engine power for the application.

In summary, the following drivelines will be evaluated:

- Conventional diesel direct drive
- Conventional diesel direct drive with smaller diesel engine(s), referred to as 'right size'
- Diesel electric propulsion with fixed speed generator sets
- Hybrid electric propulsion with fixed speed generator sets

With diesel electric propulsion, modelling will be done with one or two diesel generator sets. In practice up to four generator sets are used.

For the hybrid drivelines, two sub-options are distinguished:

- The sum of mechanical and electric motor power is equal to the desired total propulsion power. This can be applied to new build ships.

- The mechanical diesel power is equal to max propulsion power. The electric motor is only used for low speed sailing with relatively low power requirements. This is a typical Retrofit solution where electric motors are added to the propeller shaft.

Parallel hybrid ships have three basic control strategies which can be used to propel the ship:
- Directly from diesel engine to propeller,
- Diesel electrically by generators to the propeller
- The boost or support mode where the electromotor supports the diesel engine by adding torque to the propeller shaft.

Further details are discussed at the beginning of section 5.

2.4 Market overview drivelines

An overview of inland ships with hybrid or engine-electric drivelines is given in Table 3. In total there are about 30 of those vessels, more or less 50/50 split in hybrid and diesel-electric (with one gas-electric ship). Hybrid means that a diesel engine is directly coupled to the propeller shat(s), with a parallel electric drive. The electric driveline is retrofitted to a conventional driveline for 3 vessels (out of 14 hybrid vessels in total).

With engine-electric and hybrid drivelines, the number of generator sets that are running can be adapted to the power needs. The table 2 an overview is given for the number of vessels that are equipped with one, two or three or more generator sets. These generator sets are also used for the auxiliary power needs (household, bow propeller, cargo).

# gensets	1	2	3 or more
# of vessels	1	6	5

Table 2. Number of vessels with engine-electric driveline with 1, 2 or 3 or more generator sets

An overview of the installed power for diesel direct propulsion, electric propulsion and generator sets is given in the figures 2 and 3 below, for respectively vessels with hybrid drivelines and for vessels with engine-electric drivelines.

Name Ship	lengh (m)	New/ Retrofit	Type of hybrid	Diesel direct	Electric motor	Generator set	Bateries
Prisa (Eurotrans)	110	R	?	?	2x 400 kW	2x 196 kW	-
MTS Copenhagen	110	N	diesel-electric	nee	4x 375 kW	4x 485 kW	-
MTS Amulet	135	N	diesel-electric	nee	2x 850 kW	4x 450 kW	-
KVB Indus	110	N	diesel-electric	nee	1x 400 kW + 1x 600 kW	2x 635 kW	-
Invotis IX	44	N	diesel-electric	nee	2x 253 kW	2x 360 kW	136 kWh
MS Gouwenaar 2 (ex Bonjovi)	90	N	diesel-electric	nee	1x 600 kW	1x 603 kW + 2x 192 kW	-
MCS poolster	110	N	diesel-electric	nee	2x 600 kW	2x 603 kW + 1x 192 kW	-
Prins 6 Kraanschip	65	N	diesel-electric	nee	1x 441 kW + 1x 283 kW	1x 603 kW + 1x 221 kW	-
Matthinge	86	N	diesel-electric	nee	2x 500 kW	1x 940 kW	-
MTS Jolina	135	N	diesel-electric	nee	1x 600 kW	2x 700 kW	-
MPV 30	30?	N	diesel-electric	nee		2x 255 kW	882 kWh
Bilgenentöler 10	40	N	diesel-electric	nee		2x ?	-
Green Stream	110	N	gas-electric	nee	2x 500 kW + 1x 279 kW	4x 300 kW	-
MTS Duandra	110	N	hybrid	2x 550 kW	2x 350 kW	2x 500 kW	-
MS Goblin	135	N	hybrid	2x 650 kW	2x 285 kW	1x 650 kW	-
MTS Martinique	85	N	hybrid	1x 480 kW	1x 285 kW	2x 240 kWe	-
MTS Mystery	110	N	hybrid	2x 551 kW	2x ?	2x 405 kW	-
MVS Nadorias	110	R	hybrid	1x 1250 kW	1x 385 kW	2x 210 kW	-
Borelli (Bontekoe)	110	R	hybrid	1x 1250 kW	?	2x 180 kW	149 kWh + s
MTS Hedy Jaegers	85	N	hybrid	1x 470 kW	1x 285 kW	1x ?	-
MTS Guadeloupe	135	N	hybrid	2x 700 kW	2x 600 kW	2x 600 kW + 1x ? + 1x ?	-
Telstar	30?	N	hybrid	2x 850 kW	2x 800 kW	2x 805 kW	-
Semper Fi	110	N	hybrid	ja?	2x 330 kW	2x 512 kW	-
MTS Noordzee	130	N	hybrid	2x 747 kW	2x 699 kW	1x 580 kW	-
Zembla (Temptation	135	N	hybrid	2x 890 kW	2x 400 kW	1x 980 kW	ja
MTS Felicia	85	R	hybrid?	1x 970 KW?	1x 285 kW	1x ?	-
MS Linjad	110	N	hybrid?	c32	1x 500 kW	2x ?	-
IJ-Veer 60	33	R	parall. electric	Nee	2x 250kW	4x 115 kW	136 kWh
IJ-Veer 61	33	R	parall. electric	Nee	2x 250kW?	4x 133kW	136 kWh
Roro Terra 2	135	N		2x 514 kW	2x 285 kW	1x 550 kW + 1x 250 kW	-

Table 3: Overview of IWT cargo ships capable of electric propulsion.

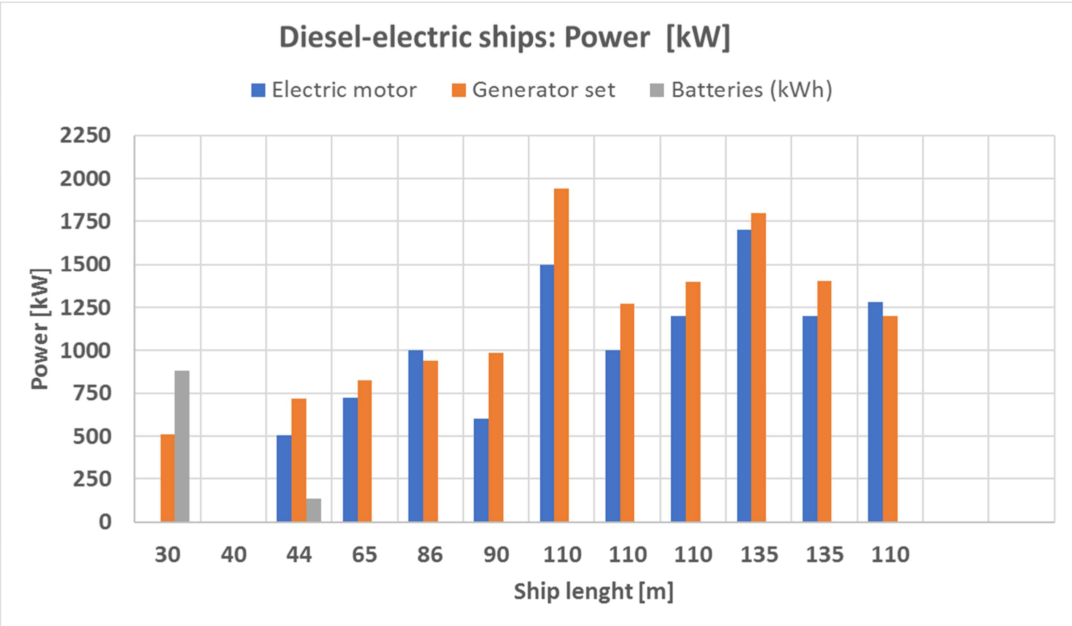

Figure 2: Bar plot installed powers of the diesel-electric ships in Table 3.

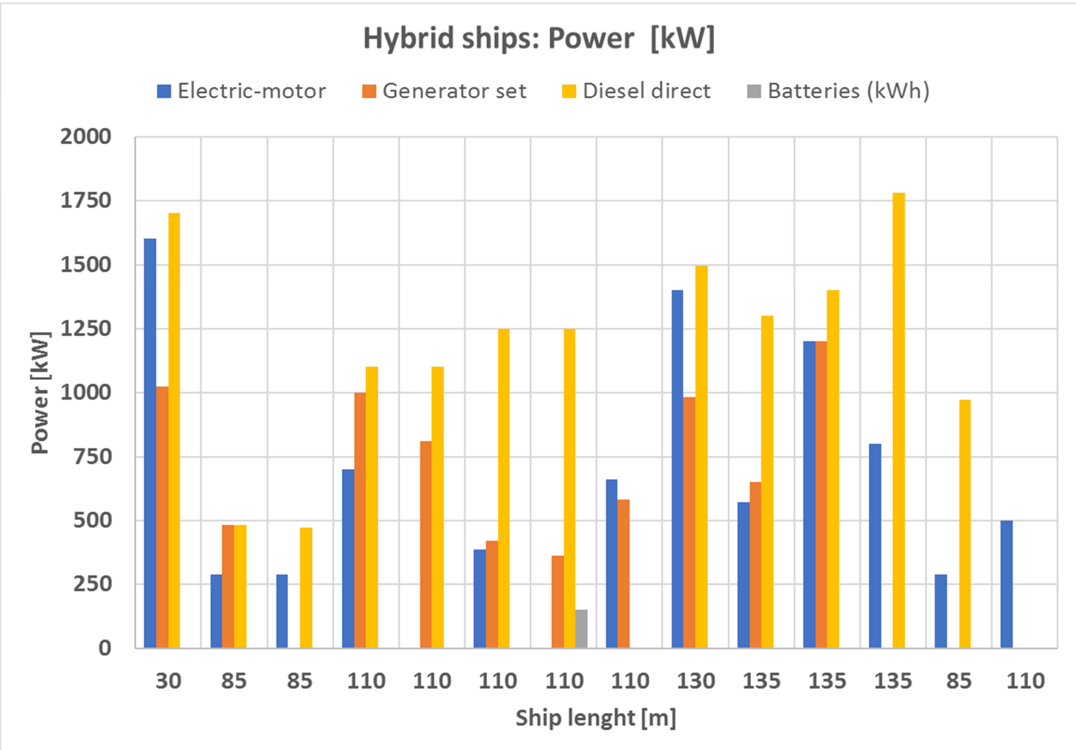

Figure 3: Bar plot installed powers of the hybrid ships in Table 4.

3 Modelling methodology

The expected fuel consumption is key to a reliable NPV calculation. However, the actual fuel consumption will only be certain after the ship has been built. The most reliable way to obtain information about fuel performance is to follow a similar ship for a long period. This period is ideally a year to represent the different seasons with corresponding fairway conditions and cargo transported. Also, the sailing area should be representative.

Once this information is gathered, the driveline or energy model can be calibrated and can calculate how changes to the ship driveline affects the fuel performance. This section discusses how the model validated in PROMINENT D2.7 can be used to model the effects of engine downsizing or 'right sizing' or by replacing the diesel direct driveline by a hybrid or diesel electric driveline.

3.1 Diesel direct & parallel hybrid ships

The generic energy model that is used, is shown in Figure 6. This model includes the most important parts of the driveline. By removing and scaling components of this generic model, direct-, hybrid en diesel electric ships can be obtained.

With the conventional direct driveline, the propeller is driven by the main engine via a reduction gearbox. The generator set(s) produce(s) energy to supply the auxiliary power demand such as for household energy consumption (more background on drivelines in Stapersma, H. K. (2002)). This driveline can be extracted from Figure 4 by omitting the blue dashed line, the e-motor and the controller. The main energy loss occurs at the diesel engine and the propeller. Small losses occur at the transmission gearbox and the bearings of the propeller shaft. The latter is included in the gearbox losses for this analysis.

The second driveline is the electrical hybrid, for which an electromotor is installed on the propeller shaft or via the gearbox. Electrical power comes from the generator sets. The extent to which the electrical hybrid can sail electrically depends on the installed electrical capacity. The diesel electric ship omits (the gearbox and) the main combustion engine.
The third driveline is the diesel electric, in which all propulsion occurs via the electric motor. No direct propulsion by the diesel engine takes place.

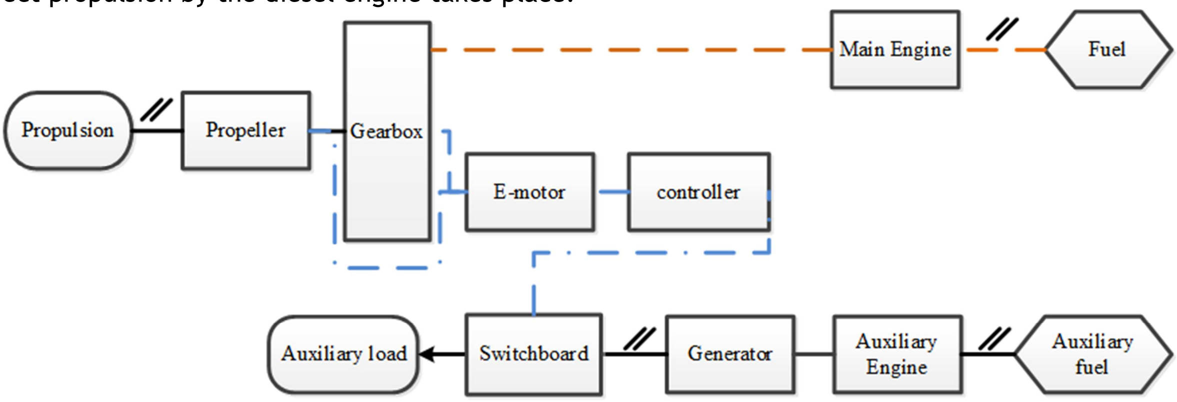

Figure 4: Generic ship energy model for conventional(orange/dashed), full electric (dash dot) and hybrid drives(both). The extend of electrification depends on the relative dimensioning of the electric part.

3.2 Modelling considerations

From the generic driveline in Figure 4, several choices observations must be made before numerical implementation can be done. First, IWT ships are often propelled by more than one propeller, the implications for the required hardware are different for conventional than for diesel electric ships. For the direct drive, multiple propellers imply the need for multiple gearboxes and engines. Electric ships need multiple electric motors. The main difference is that electrically driven ships can obtain electrical power for multiple generators sets, which can be switched on as the power demand increases. This also increases the redundancy of the ship.

Numerical modelling of hybrid and conventional ships may be done with different levels of detail and complexity. In order to estimate fuel consumption, the modelling is done with the aim of calculating the fuel consumption. Therefore, the efficiency of each component is calculated, based on the power it needs to deliver, or the power conversion it needs to make.

An overview of the model used for this report includes (extensively described in PROMINENT deliverable D2.7):

- Resistance model: tank test
- Propeller: standard propeller series
- Electromotor: efficiency map for PM motors based on torque and rotating speed
- Converters: efficiency model bases on voltage and current
- Alternator: efficiency model bases on voltage, frequency and current
- Gearbox: efficiency model based on torque and speed
- Diesel engines: fuel consumption characteristics

This requires the modelling for part engine loading conditions, as ships barely sail at full power and speed. Furthermore, the energy performance of each component does not only depend on the power that is being delivered, but also under which conditions this power is delivered. Energy efficiency of the components decreases when running at part load and speed. In order to take this into account, power flows in the energy are split in so called flow and effort components, a distinction well known from bond-graph modelling.

The distinction made for the different powers are:
Electrical: voltage and current (including power factor for AC, if available)

- Rotational: torque and rotational speed
- Translation: force and translational speed
- Thermodynamic (fuel): burning heat energy and mass flow rate

By making this distinction, and defining component models that handle the effort and flow, efficiencies can be estimated more reliably. Despite the efforts made to implement the interaction between components as good as possible, several effects in the electrical circuit could not be implemented yet. These are:

- The effects of harmonic distortion of the supplied electrical power on the performance of the electromotor
- Losses occurring due to filtering of the distorted signal
- Losses due to electrical resistance in the cables
- Losses in the alternator and electromotor due to a reduced power factor in the electric power
- Cooling of the electric components. Power required for cooling is in the range of a percent of the transmitted power, but strongly depends on how the cooling is installed.

The omission of these power losses is leads to an underestimation of power losses in the electrical systems.

4 Modelling results

This section focusses on the modelling of the fuel consumption with different driveline options. The energy model is suited to calculate this change.

The modelling is based on a typical 105m cargo ship with the following specifications:

- 1.118kW of propulsion power at 1800rpm (not the 'right-sized' variant)
- 1 auxiliary genset of 484kW, running on 20kW auxiliary power

For both direct drive and diesel electric drive, it is shown in detail where energy losses occur, and how this translates to a comparison of ship energy performance.

The two main topics are:

- Engine and generator set performance
- Power losses due to conversions in electrical systems

The different options and possible control strategies are shown schematically in Table 4.
The power percentage refers to the percentage of the total power installed.
Some explanations regarding Table 4 are:

- The diesel direct fully relies on diesel propulsion (100% diesel), which is reflected in the black colouring for the whole power range.
- Diesel electric relies for 100% on diesel electric propulsion. In practice one to four generator sets are used to produce the electric energy. One or two electric motors take care of the propulsion.
- A hybrid with 100% diesel and 40% electric propulsion (fractional percentages are just for illustration) can sail up to 40% power on the electric system, then switches to diesel direct. This is shown by the blue and black areas (Mode I).
- This system may also sail the whole power range using the diesel engine, it then acts as a diesel direct ship. This configuration can also be used to sustain speeds that cannot be achieved by diesel direct sailing due to low rpm (see also Figure 16). This configuration can especially be considered for retrofit hybrid in which the original engine is maintained.
- Hybrid 50:50: A hybrid ship with a diesel: electric ratio of 50%:50% needs to sail on both systems to achieve maximum speed. In this case, the electromotor and controller need to be fitted such, that a broad range of rpms can be reached at maximum power. This will cause a penalty on the electromotor efficiency due to off design sailing (see PROMINENT D2.7) and increased investment for the controller to support this.
- The last option of diesel: electric ration of 70%:30% sails electric at low speeds, diesel direct at medium speeds and electric boost at high speeds.

	Diesel%	Electric%	Power[%] / Speed[%]	10 / 46	20 / 58	30 / 67	40 / 74	50 / 79	60 / 84	70 / 89	80 / 93	90 / 97	100 / 100
1) Diesel direct	100	n/a											
2) Diesel electric	n/a	100	1 gen set 2 gen set										
3) Hybrid	100	40	Mode I Mode II										
4) Hybrid boost	50	50											
5) Electric boost	70	30											

Electric
Diesel
Support

Table 4: Control strategies for diesel, diesel electric and hybrid ships. Relation speed-power is cubic. Colours indicate for each type of configuration which control strategy may be used.

4.1 Diesel direct driveline

The results for the fuel consumption are a result of the power losses in the driveline. For the diesel direct the following components cause power losses:

- Diesel engine
- Diesel engine in generator set
- The alternator in the generator set
- The gearbox

The genset is composed of the auxiliary engine and alternator. The effective SFC curves are shown in Figure 5. The SFC of the constant speed generator set is defined by the effective electrical power output and the fuel consumption. Because the generator set is relatively large (482kW) for the electric load of 20kW (it should also power the bow thruster), the performance is very poor, which is reflected in the high SFCe. The performance of the diesel engine gets better with higher speed and load.

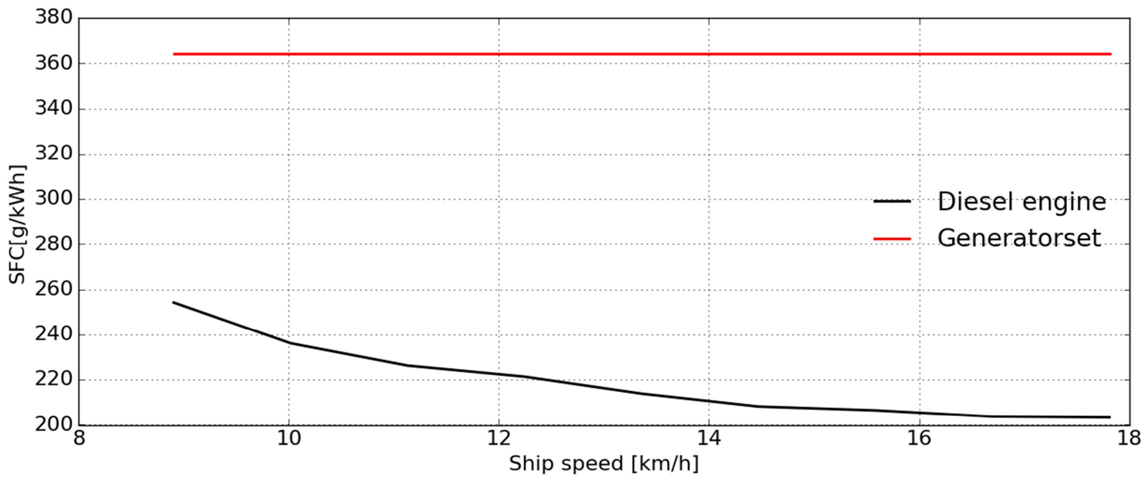

Figure 5: SFC curves for diesel direct propulsion. In red the SFCe curve for the 482kW generator set at 20kW constant power (auxiliary engine + alternator).

An overview of the percentage share in the energy tank-to-propeller losses is found in Table 5.
At low speeds, there is low propulsion power, and most losses occur in the auxiliary engine and the alternator. As the speed increases and more power is transmitted through the diesel engine and gearbox, their share of the total losses increases. At max speed, the diesel engine and gearbox dominate the loss of power.

Speed [km/h]	Diesel Engine [%]	Auxiliary Engine [%]	Alternator [%]	Gearbox [%]	Total [%]
1.1	0.2	97.2	2.5	0	100
2.2	2.4	95	2.5	0.2	100
3.3	8.8	88.6	2.3	0.4	100
4.5	19.9	77.4	2	0.6	100
5.6	34.2	63.3	1.6	0.9	100
6.7	48.6	49	1.3	1.1	100
7.8	61.1	36.7	1	1.2	100
8.9	70.9	27.1	0.7	1.3	100
10	76.1	21.9	0.6	1.4	100
11.1	80.8	17.3	0.4	1.5	100
12.2	84.7	13.5	0.3	1.5	100
13.4	87.4	10.8	0.3	1.6	100
14.5	89.5	8.6	0.2	1.6	100
15.6	91.5	6.8	0.2	1.6	100
16.7	92.9	5.4	0.1	1.6	100
17.8	94.1	4.2	0.1	1.6	100

Table 5: Percentage share of total energy loss per component of tot total energy loss between fuel tank and propeller, for diesel direct propulsion. Auxiliary demand equals 20kW. Rounding errors cause totals unequal to 100%.

4.2 Diesel direct versus diesel electric and hybrid

In this paragraph, the different right-sized options are compared. It is the scenario where 1118kW installed power has shown optimal, and a choice must be made how this power is to be produced. Comparison of different drivelines in terms of energy performance is most clearly done by comparison with a reference vessel, for which the diesel direct ship is chosen. The operational profile is intentionally not part of section 4, as selection of the optimal amount of power has taken place and the results should apply to various operating profiles.

The main parameter to compare results is the total fuel consumption rate . The main input characteristic for this is the resistance curve obtained from tank-tests. Therefore, results are reported as function of the speed through water. Typical speeds in practise are between 10 and 16 km/h relative to the water.

The fuel consumption against speed for four driveline types is shown in Figure 6. The fuel consumption is the fuel consumption from the main diesel engine and generator set (for diesel direct) and the combined generators(s) for diesel electric. Auxiliary load is included. The fuel consumption difference between the electric and diesel direct driveline is presented in Figure 8.

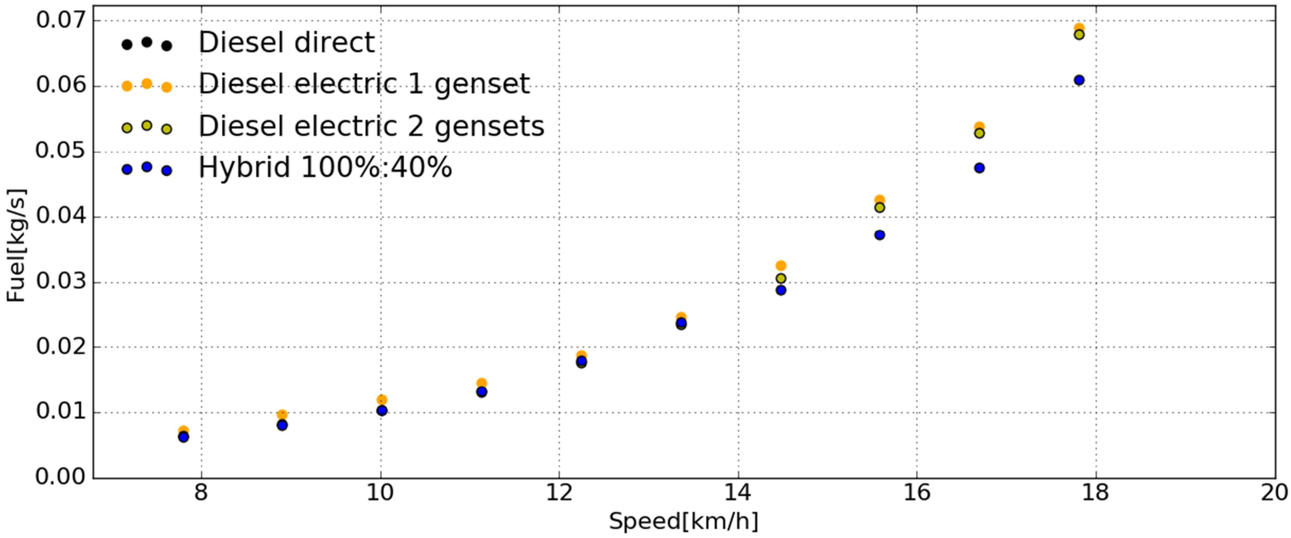

Figure 6: Calculated fuel flows for diesel direct (main engine + constant speed generator sets), diesel electric and hybrid 105m vessel. Speeds below 8 km/h cannot be sustained by the diesel direct propulsion due to the idle speed of the diesel engine.

The following observations are made:

- The fuel consumption is approximately cubic (third power) with speed
- According to these simulations (with constant speed generator sets), electric propulsion consumes significantly more across most of the sailing speed range (0% to almost 25% increase).
- The difference between the configuration is hard to see from the fuel consumption rate
- Being able to sail at slow speeds (below 7 km/h) is an important advantage of the electric propulsion for both the diesel-electric as the electric-hybrid drivelines.

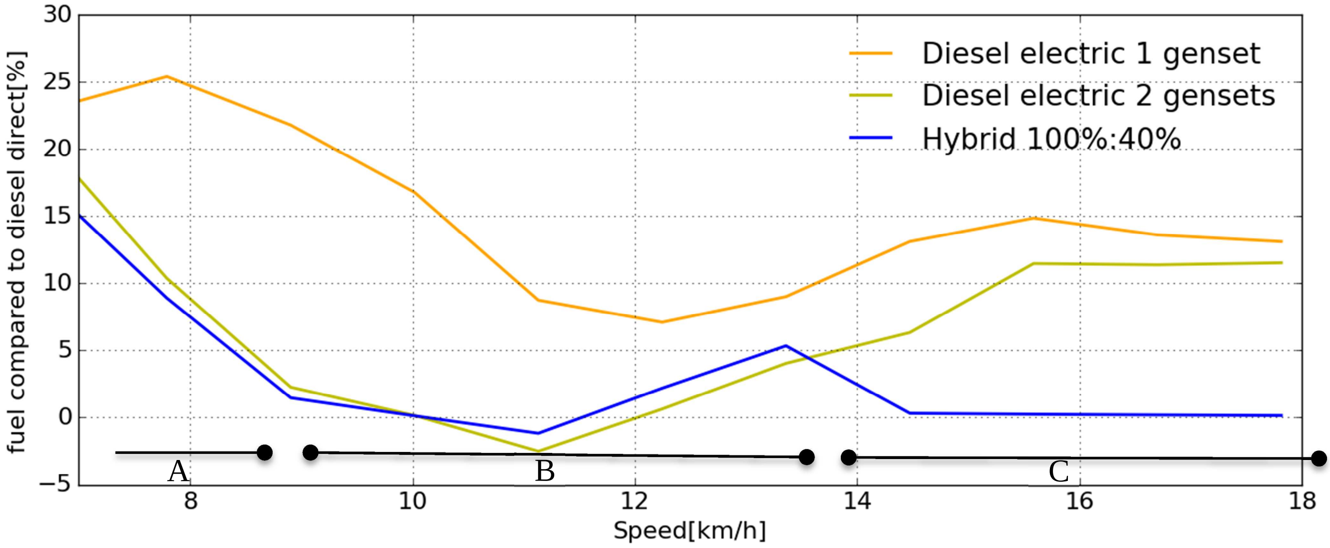

Figure 7: Relative fuel consumption rate of different electric drivelines. Although hybrid and diesel electric ships consume (much) more fuel than the diesel direct ship, there is 1 speed at which minor savings may be achieved. Fuelt consumption peaks may be reduced by using variable speed generators, though the minimum points cannot be lowered since the gensets would be on max power and speed in domain B. Domains A, B and C: see text.

- Although speeds below 9 km/h(domain A) are unreachable for the diesel direct ship in practice, comparison is made as electric propulsion features very slow sailing.
- Diesel direct yields lowest fuel consumption at sailing speed above about 8 km/h
- In domain A, generators fuel consumption can be reduced by applying variable speed generators
- In domain B, hybrid and 2 genset diesel electric is relatively good due to the good loading of the small gensets, and the good performance of the PM motor.
- In domain B, generators fuel consumption of the hybrid and 2 genset diesel electric cannot be optimized by installing variable speed generator sets, as maximum power is required
- In domain C, the hybrid does have equal fuel consumption as the diesel direct ship because it sails on the diesel direct engine solely.
- In general, the electric propulsion then needs 0% to 14% more fuel than the diesel direct ship, and have 2% savings at 1 point.
- The diesel electric ship benefits strongly from two generator sets over one generator set. Two generator sets give 5% to 15% savings compared to one large genset in the speed range from 8 to 12 km/h. The driveline with two gensets then runs on one (small) genset.
- A hybrid ship can reach lower speeds than the diesel direct ship, as engine speed is not a limiting factor. When the propulsion power becomes higher than the installed electrical power, the hybrid switches to direct drive, and the fuel consumption becomes equal to diesel direct (above 14.5 km/h in figure 8).

4.3 Power conversion losses in diesel electric propulsion and hybrid

The diesel electric configuration is chosen to make an example of performance of the subcomponents in partial load. In diesel electric propulsion, all power for the propeller is supplied by one or multiple generator set(s). This means that no direct propulsion via diesel engine and gearbox takes place. The electromotor is coupled directly to the propeller to avoid additional gearbox losses.

4.3.1 Generator set fuel consumption

Table 7 shows the SFC curves for a ship with a single, large generator set of 1118kW, and the same ship with 2 generator sets of 559kW. The SFC curve of the 2 generator sets is considerably better than the single generator sets between 6 and 15 km/h. Below 15 km/h, only one generator set is running at relatively high load. It has a better efficiency then the larger generator set at relatively low load. The second generator is switched on when the first generator set reaches its maximum power. This is above 15 km/h. The efficiencies are then about equal. Figure 5 also shows, that at very low power, at sailing speed below 6 km/h, the efficiency of the large generator set is actually better than for the small generator set. This is seen more often with large engines: a good engine efficiency is maintained down to very low power levels. For the fuel consumption in practice this is not very important, since the fuel consumption is anyhow low at those speeds.

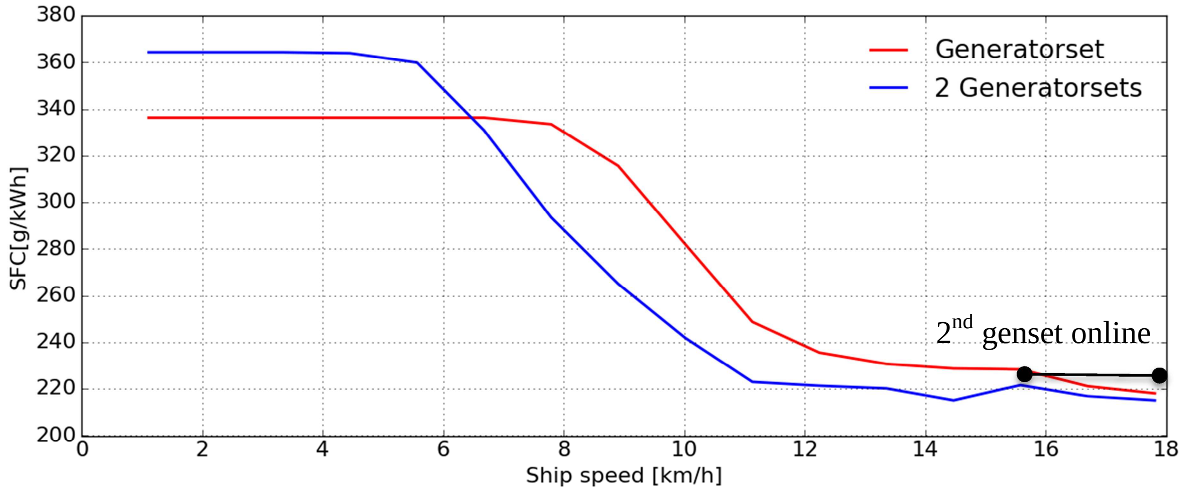

Figure 8: Effective SFC based on produced electrical work for the large genset(1118kW) for the diesel electric configuration, and the configuration with 2 half-sized gensets(559kW). SFCs of the combustion engines in accordance with engine supplier.

In order to be able to obtain an equal propeller speed as in the diesel direct case, an electromotor with 10 pole pairs are installed in the model, which is corresponds to 300rpm nominal speed. This is comparable with the 1800rpm diesel engine combine with gearbox with a reduction ratio of 5.5. The nominal power is chosen at 1118kW, as is for the generator set and converters.

4.3.2 Tank to propeller power losses

A better understanding of the reason why the electric variant consumes more fuel, the power losses must be assigned to the various components in the ship. The share of the total power losses for the diesel electric case is shown in Table 6 and Figure 10. Total power loss is defined as de power lost in the components between the fuel tank and the propeller. Figure 8 excludes the combustion engine to keep the components distinguishable, and thus shows electrical losses. The table includes the combustion engines as well.

The following observations are made:

- At low speeds, there is almost no power needed for the propulsion, and losses are caused while producing power for the auxiliary load. As propulsion power increases, the PM motor and inverter cause more power losses.
- At full power, the electrical losses sum up to 140 kW.
- Losses in the converters are significant, at about 50% of the PM motor losses.

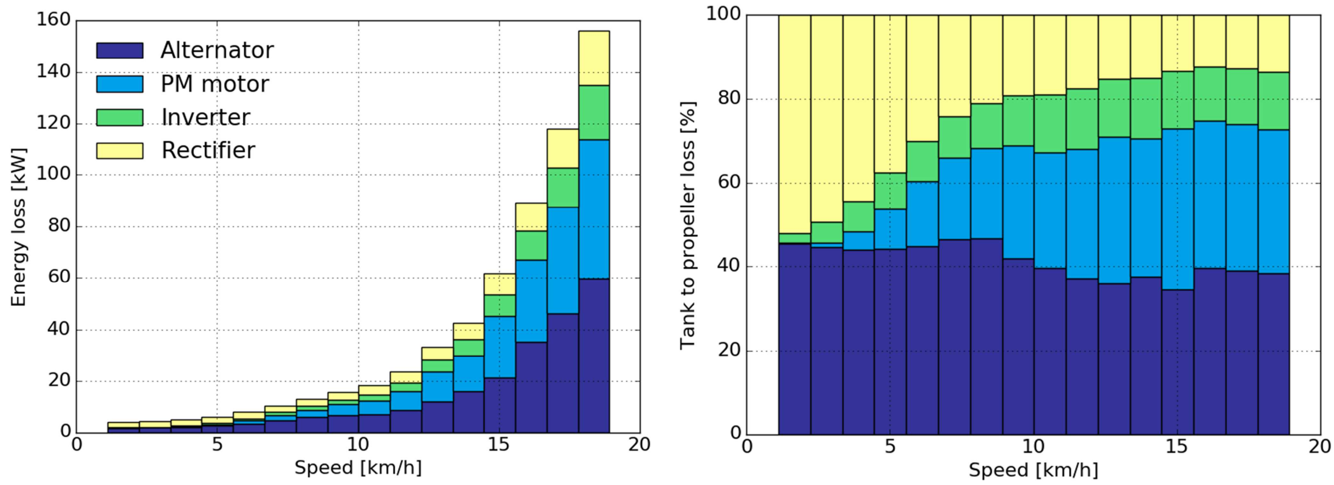

Figure 9: Left: Absolute energy losses per component electrical components in diesel electric propulsion. Right: relative losses per electrical component. Installed power is 1118 kW.

Speed[km/h]	Alternator[%]	PM[%]	Inverter [%]	Rectifier[%]	Aux Engine[%]	Total
1.1	3.1	0	0.1	1.9	94.9	100
2.2	3.1	0.1	0.2	1.8	94.8	100
3.3	3.1	0.3	0.3	1.7	94.7	100
4.5	3.1	0.7	0.3	1.4	94.5	100
5.6	3.1	1.1	0.3	1.1	94.3	100
6.7	3.1	1.3	0.3	0.8	94.4	100
7.8	2.8	1.3	0.3	0.6	94.8	100
8.9	2.4	1.5	0.3	0.5	95.2	100
10	2.2	1.5	0.4	0.5	95.4	100
11.1	2.3	1.9	0.4	0.5	94.8	100
12.2	2.5	2.5	0.5	0.5	94.1	100
13.4	2.6	2.3	0.5	0.5	94.1	100
14.5	2.6	2.9	0.5	0.5	93.4	100
15.6	3.3	3	0.5	0.5	92.7	100
16.7	3.4	3.1	0.6	0.6	92.3	100
17.8	3.5	3.2	0.6	0.6	92	100

Table 6: Percentage share of total energy loss per component of tot total energy loss between fuel tank and propeller, for diesel electric propulsion. Auxiliary demand equals 20kW. Values are rounded at one decimal. Rounding errors cause totals unequal to 100%

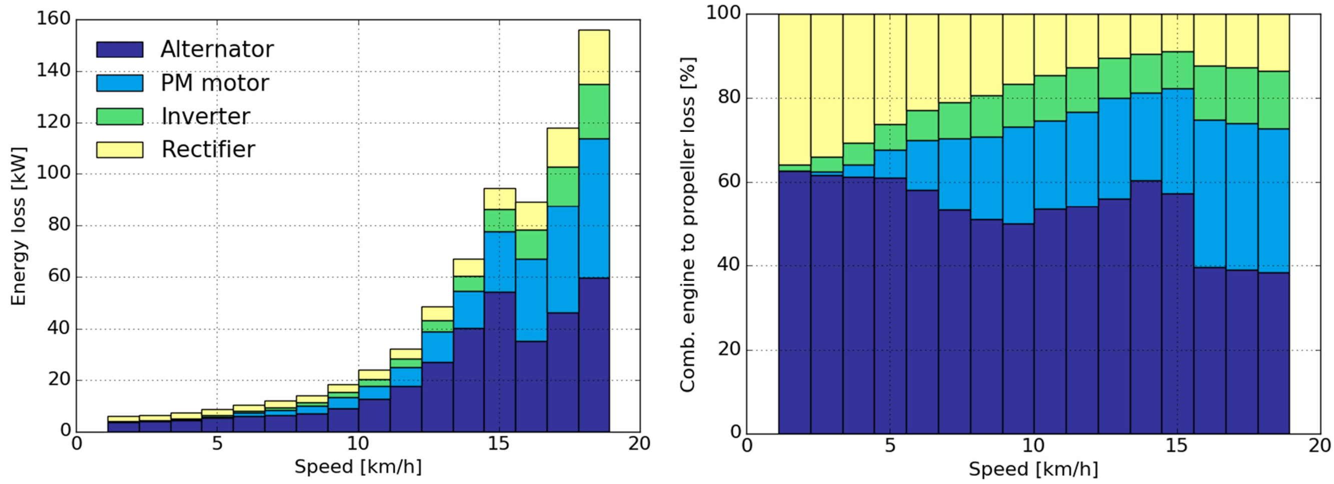

Figure 10: Absolute (left) and relative (right) electrical power losses for diesel electric ship with 2 generator sets.

The hybrid ship (Figure 11) shows how the losses between combustion engines and propeller change when electric propulsion is taken over by direct propulsion (above 14.5 km/h). Most power losses are then caused by the gearbox. Only minor losses occur in the alternator, as the generator set then only powers the auxiliary load.

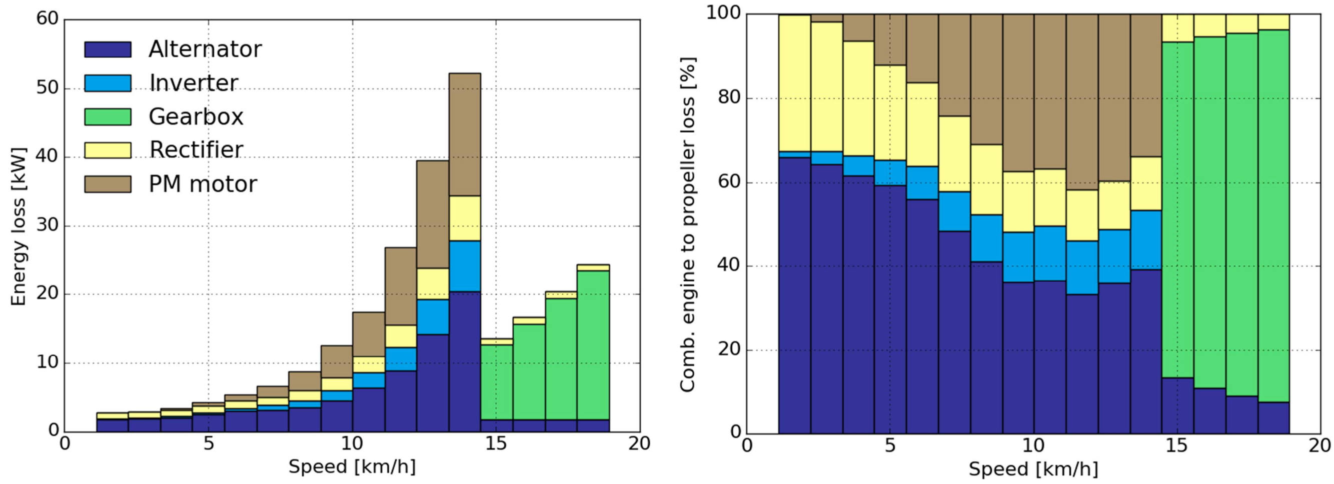

Figure 11: Absolute (left) and relative (right) electrical and gearbox power losses for hybrid ship. Conversion losses reduce when propulsion is taken over by the diesel motor at 15 km/h.

4.4 Analysis of results

Simulations show that electrically driven configurations are expected to consume more fuel than directly driven ships. The extra fuel consumption is mainly caused by the additional power conversions between the auxiliary engine and the propeller, mainly due to the alternator in the generator set, and the electric motor at the propeller. Performance of the electric components combined is optimal at high power/speed, and decreases at part load. At part load, voltage and frequency at the PM motor decrease, which leads to a relative increase of electric losses.

4.4.1 Effects not modelled

4.4.1.1 Variable speed engines

Variable speed generators instead of constant speed generators are often used in order to improve the fuel performance of the generator sets. Although fuel benefits are obtained in practice, a constant speed generator set cannot be changed to variable speed, and actual benefits are not calculated easily.

Three main topics that complicate the calculations:

- Whether or not the inverter to the electromotor can be connected at the DC-bus
- How the alternator performs at part speeds
- What the fuel consumption of the auxiliary engine becomes at part speeds

Prominent received a large collection of SFC maps for engines from Caterpillar, Mitsubishi, Volvo Penta and Scania.

Relatively large losses are associated with the constant speed auxiliary engines. The engine SFC namely ranges from around 200 g/kWh at full power up to above 300 g/kWh at the lower end power output. The high SFC of the constant speed auxiliary engines is explained by the higher internal friction losses of an engine running at high rotational speed. For the diesel direct propulsion, the SFC ranges from around 200 g/kWh at full low up to about 230 g/kWh at part load, so much more favourable than constant speed gensets. Analysis of engine maps and information of a variable speed generator set, has shown that the engine of a variable speed genset would likely have a similar efficiency as an engine in direct propulsion.

An important advantage of the electric propulsion is the fact that the household power consumption is taken from the genset(s) used for propulsion. This leads to a higher load for the genset, which is favourable for the fuel consumption. This aspect is considered in the simulations.

Apart from electric and mechanical losses, the engine efficiencies play an important role in the overall efficiency. The variation in engine efficiencies as reported by different engine suppliers is in the same range as the additional fuel, diesel electric ships need according to the simulation. Therefore, comparison has to be done based on the same brand and type of engine.

The difference in reported SFC maps is related to the precise test conditions, but possibly also to legal safety margins. In order to avoid claims, the manufacturer may publish relative high values. On the other hand, the manufacturer could use official accuracy bands in an optimistic way and publish relative optimistic values.

Apart from fuel consumption considerations, advantages are linked to electric propulsion. When small engines are used, the aftertreatment systems (e.g. for Stage V) can also be compact and possibly be derived from low cost automotive systems. Also, if in normal sailing only one (or more) relatively small generator set is running, than the average load will be high. This leads to an optimal operation of DPF (diesel particulate filter) and SCR catalyst. Also, the engine size can be chosen relatively small. If later in the lifetime of a ship more propulsion power is needed, due to different cargo or sailing route, a generator set can be added. Diesel electric propulsion can also be seen as a step towards battery electric propulsion. Batteries can be added for a certain zero emission sailing, or gensets can even be completely exchanged for batteries in order to go to permanent electric propulsion.

4.4.1.2 Electric components

As mentioned in section 3.2, several factors that cause power losses in the electrical conversions were not modelled, their effects on the results are discussed here.
Interaction of inverter and electromotors: The effects of the harmonic distortion of the supplied electrical power on the performance of the electromotor.
This interaction is different for inverters producing sine wave or square wave voltages, as well as 6 pulses, 12 pulses or PWM inverters. Additional losses in the electromotor are more than 1 percent.

Losses in the alternator and electromotor due to a reduced power factor in the electric power.

Cooling of the electric components. Power required for cooling is in the range of a percent of the transmitted power, but strongly depends on how the cooling is installed. This can be done mechanically by a fan, or using water cooling. The power required for the cooling is supplied by the component itself, or using an external power source.

4.5 Conclusions

For a 110m vessel, electric drivelines (diesel electric and hybrid) have been modelled and compared with the diesel direct driveline. The simulations have only been done with constant speed generator sets.

This leads to the following conclusions:

- Electric propulsion consumes significantly more across most of the sailing speed range (0% to some 15% increase).
- Between 8 and 14 km/h, the fuel consumption increase of the electric propulsion can be limited to max 5%.
- The main reasons for the fuel consumption increase of electric propulsion according to these simulations are the electric power losses in generator, electric motor and invertor/rectifier: 12% or more of the power output.
- Diesel electric propulsion with two (half-sized) constant speed generator sets performs much better that with one (full sized) constant speed generator set. The fuel consumption of the first one is 5% to 15% lower in the sailing speed range from 8 to 12 km/h.

Analysis of engine fuel consumption maps showed the following:

- A large difference of SFC between variable speed auxiliary engines and constant speed auxiliary engines. With constant speed, the specific fuel consumption (SFC) is much higher at medium and low power output: around 9% higher at 50% power up to around 30% higher at 25% power output
- With variable speed auxiliary engine, the difference between one big and two small gensets will become smaller: up to about 4% fuel saving with two gensets instead of one.
- Large differences in fuel consumption along the propeller curve between different types of small engines (<500 kW). According to the specifications, a number of engines are around 220 g/kWh (above 40% load), while some other engines are around or below 200 g/kWh. Possibly safety margins or exploitation of tolerances play a role along with emissions class. Fuel consumption figures between 190 and 200 g/kWh are seen for IMO III or Euro VI emission class engines. This gives a promising outlook for Stage V engines. These low NOx engines can be optimised for fuel consumption, while the SCR deNOx system will reduce the relatively high engine out NOx below the requirements.

- The SFC of large engines (>1000 kW) ranges often between 200 and 2010 g/kWh (40% load and higher).

Apart from simulations and specifications the following advantages can be linked to electric propulsion:
- Preparation of the ship for future conversion to battery-electric propulsion
- Diesel genset power can be chosen rather small (right sizing). It can be increased later during the ship life time if required by the application or sailing route.
- By installing small diesel gensets, possibly lower costs Stage V engines can be purchased (lifting on the mass production of truck aftertreatment systems).
- Aftertreatment systems of higher loaded small engines might operate better (better DPF regeneration and SCR NOx conversion) than relatively low loaded large engines. Although also for large engines, the engine manufacturer can take measures to improve DPF and SCR operation at low load.

5 Cost-benefit method

The cost benefit analysis is used to determine whether the benefits of an investment outweigh the costs. In this study the costs related to dimensioning ship drivelines and implement hybrid propulsion lines are balanced against possible benefits relative to conventional propulsion.

The required initial investment is referred to as capital expenditure (CAPEX). This is the initial investment that needs to be done, before operations can start. The operational costs are referred to as operational expenditure (OPEX), and the margin that is made due to the investment. Lower OPEX needs to compensate CAPEX for an investment to be profitable.

5.1 Net Present Value

The main measure for the revenue on an investment is the Net Present Value (NPV). The NPV represents the sum of all cash flows resulting from an investment or project, discounted to the present. In other words, it represents the current value of the specific project or investment. Calculating this value helps investors to decide whether they should invest and which project to choose. An investment is profitable if the NPV yields a positive value. Break-even is obtained when the NPV equals 0. The NPV equation can be used to calculate:

- The fuel savings of a certain technology in order to be profitable
- The discounted payback period of the investment
- The present value of new technology, based on fuel price and fuel savings

The NPV is calculated as follows:

$$NPV = -\Delta C_0 + \frac{\Delta C_1}{(1+r)} + \frac{\Delta C_2}{(1+r)^2} + \cdots = -\Delta C_0 + \sum_{i=1}^{k} \frac{\Delta C_i}{(1+r)^i}$$
$$= -CAPEX\ (1) - discounted\ OPEX\ (2)$$

With

- ΔC_0 the difference in the initial investment relative to a reference vessel.
- ΔC_i the change in cashflow resulting from the investment, for example due to a
- change in maintenance or fuel costs.
- i represents the year counted from the investment time
- r the discount rate
- k the number of years for which the NPV is calculated. Usually this is the engine lifetime or the period in which the investor wishes to earn back the investment

5.1.1 Additional investment costs (1)

Taken into account under the additional investment costs is the change in costs relative to a conventional one, occurring from implementing changes. These costs depend on many factors and tend to be very ship specific. Therefore, the choice is made to estimate the investment compared to an (existing) reference ship, so that costs can be isolated and attributed to the changes in the driveline proposed here. In this study a change of the main propulsion engine(s), generator sets, and electromotors are considered. The propeller is out of scope and assumed to be left unchanged.

Therefore, the following parameters will determine the investments with respect to the reference ship:

- ΔP_{diesel} the change in installed direct diesel power in kW
- $\Delta P_{electric}$ the total installed electric power (genset + electromotor excl. aux power) in kW
- i_{diesel} the investment costs per kW for the diesel components (Table 7)
- $i_{electric}$ the investment costs per kW for the electric engine and gearbox (Table 7)
- $yard$ extra costs of e.g. deinstallation of the engine in case of retrofit

Hence, the difference in investment costs(CAPEX) is calculated as follows:

$$\Delta C_0 = \Delta P_{diesel}\, i_{diesel} + \Delta P_{electric}\, i_{electric} + yard$$

Where the first part represents the difference in costs corresponding to the diesel parts of the engine configuration and the second part the extra costs for the electric part of the engine.

5.2 Prices of diesel engines and electrical components

The investment in a driveline depends on a combination of hardware prices and installation costs. As the calculations in this report are intended to be generic, the costs of mechanic and electric drivelines are translated to prices per installed engine power unit in kW (see Table 7).

In case of retrofit, additional costs will occur for additional yard time due to efforts of removing and transforming the engine room. Retrofit may also yield revenues from scrap value of the removed components. This is, however, very case-specific to a certain ship, and should be either subtracted or added to the investment depending on the ship in question.

5.3 Reinvestment costs

Diesel engines require revision after a certain amount of running hours, in which the engine is revised. The price of this action is significant, and accounted as a reinvestment to keep using the engine. This is included in the NPV calculation. The price is extracted from the NPV at the time when the revision takes place.

5.4 Cash flows (2)

To keep the calculations as generic and simple as possible, the maintenance costs of the combustion engine are spread evenly over the payback period. They are related to both the nominal power of the engine, and the number of running ours (via the fuel consumption). Often, maintenance costs are related to the number of running ours, but as the operating conditions of the ship do not change, this is not a variable in the calculations. However, it is expected that maintenance does increase under increased use of the engine in terms of power, en therefore by the fuel consumption. Also, the maintenance will be cheaper for a smaller engine producing the same power as a larger engine.

Therefore, the change in cash flows due to the alternative engine configuration is equal for each year and is calculated as:

$$\Delta \mathrm{C_n} = \left(€_{fuel} + €_{\mathrm{maint.,fuel}}\right)\Delta\mathrm{Fuel} + €_{\mathrm{maint.,power}}\left(\Delta \mathrm{P_{diesel}} + \Delta \mathrm{P_{electric}}\right) + revision$$

With

- $€_{fuel}$ the fuel price $€/m^3$
- $€_{\mathrm{maint.,power}}$ maintenance costs in $€/kW/year$
- $€_{\mathrm{maint.,fuel}}$ maintenance costs in $€/m3/year$
- $\Delta Fuel$ change of fuel consumption in $m^3/year$

Aside from fuel expenses, maintenance costs are considered. These costs are estimated after consultation of several engine suppliers (values in Table 7). Maintenance costs include both day-to-day maintenance, engine revisions are discretely billed at the time of revision.

We assume both fuel prices and maintenance costs to be constant over the considered time of k years. As a result, the cash flow formula can be rewritten to:

$$\sum_{i=1}^{k} \frac{\Delta \mathrm{C}_i}{(1+r)^i} = \left(\left(€_{fuel} + €_{\mathrm{maint.,fuel}}\right)\Delta\mathrm{Fuel} + €_{\mathrm{maint.,power}}\left(\Delta \mathrm{P_{diesel}} + \Delta \mathrm{P_{electric}}\right)\right) \sum_{i=1}^{k} \frac{1}{(1+r)^i}$$

Hence, after selection of the driveline configuration and making above choices, the summation of the cash flows solely depends on the period over which the NPV is calculated.

5.5 Minimum fuel savings

While the NPV calculation is mostly used to estimate the value of and investment over a given period, the equation can also be reversed to calculate the maximum amount one should invest in a certain technology.

Furthermore, the equation can be used to estimate the necessary fuel savings a technology should yield in order to be profitable for investors. By setting the NPV equal to zero the necessary fuel savings can be calculated as follows:

$$\Delta Fuel = \frac{\Delta \mathrm{C_n}}{\left(\left(€_{fuel} + €_{\mathrm{maint.,fuel}}\right)\Delta\mathrm{Fuel} + €_{\mathrm{maint.,power}}\left(\Delta \mathrm{P_{diesel}} + \Delta \mathrm{P_{electric}}\right)\right) \sum_{i=1}^{k} \frac{1}{(1+r)^i}}$$

6 Cost benefit results

6.1 Introduction

The large variety in the design of propulsion lines makes it impossible to present a single cost benefit analysis for all types of hybrid ships. The outcomes are very ship specific. Therefore, the estimations of both CAPEX and OPEX are given in ranges and scenarios. Again, the results of the comparison between diesel direct and diesel electric of the case ship is taken).

6.2 CAPEX parameters

This price range for hardware is extracted from prices received from various suppliers of diesel engines and electrical propulsion systems (refer to section 1.4). In order to keep the investment costs as generic as possible, an extensive overview of engine configurations and corresponding consequences can be considered for different types of ships.

Component	*price*	*min*	*max*
	€/kW	€/kW	€/kW
Diesel engine CCRII incl. gearbox	220	170	270
Generator set	350	250	400
Electromotor + controller	500	350	650

Table 7: Used prices for investment components for the NPV calculation, as estimated by hardware suppliers. The price for the electromotor stronly dependend on the speed for which the motor is build.

6.3 OPEX parameters

After consultation of various engine suppliers, maintenance costs were estimated as shown in Table 8. The diesel price (September 2017) is 571$€/m^3$, which will serve as our base reference fuel price. On top of that we take one scenario in which the fuel price increases by 30%, and one scenario in which it decreases by 30%. This is done since strong fluctuation in oil prices makes it very complicated to predict future fuel prices.

Day-to-day fuel based maintenance costs is estimated at $€0.12€/\mathrm{m}^3$ and $4.60€/\mathrm{kW}/\mathrm{Year}$ (kW of the installed engine power). For engine revision, a fixed period of 30,000 running hours between revisions is taken, which is reached every 6 years. The revision price is set to 63€/kW. This price will be substracted from the NPV every 6 years in this calculation.

Component	*price*	*min*	*max*
Fuel price [€/m^3]	570	400	742
Maintenance(power based) [€/kW/year]	4.7		
Maintenance(fuel based) [€/m3]	12		
Engine revision [€/kW]	63		

Table 8: Values for the OPEX parameters

6.4 Diesel direct ship

For this cost-benefit analysis a 110m general cargo ship is taken as a reference for potential savings by right sizing or hybridization. The ship is taken from D1.1, with one propeller and an installed power of 1250kW and fuel use of 472 cubic meters of fuel per year.

Right sizing can be applied to new build ships or in a retrofit/revision situation. The following costs are not included in the calculation:

- For new ships additional costs may occur from monitoring of a sister ship, or comparable ship.
- For retrofit, on top of the monitoring, extra investments may be needed to remove the old engine and rebuild the engine room. This calculation gives the investment that would be cost-effective.

In Table 8, two cases for downsizing the engine and gearbox. The engine power is reduced by respectively 20% and 40% (labelled as RS 80% and RS 60%). Both the engine and gearbox perform with increased efficiency due to higher loading. It is estimated that this will lead to a saving of 1% to 4% in fuel use, depending on how much the system can be downsized.

	Diesel	*ΔFuel pessimistic*	*ΔFuel optimistic*
Baseline	1250	0%	0%
Right size 80%	1000	-1%	-3%
Right size 60%	750	-2%	-4%

Table 9: Reference case for cost-benefit analysis. Negative fuel save means the configuration consumed less fuel. Actual savings are ship dependent.

As mentioned in paragraph 2.1.2, there may however be reasons to oversize the driveline despite the savings presented here. Examples are changes in cargo mass or route during the lifetime or the reselling value of the ship. In that case, the NPV values shown here, are the minimum additional reselling value of a ship that should arise for oversizing to be feasible. This is however very ship dependent, and not considered here.

6.5 NPV projections

The development of the NPV over time is shown in Figure 12 and for a period of 20 years. Per ship, the ‘optimistic’ and ‘pessimistic’ scenario are shown, these terms refer to the experience of the investor, e.g. most positive and least positive scenario. Fuel and component prices are taken from the “price” Table 7.

Figure 14 shows that with engine downsizing, the NPV ranges form about 50 to 100 kEUR at the start to about 150 to 350 kEUR after 20 years. The values at the start are the savings in investment costs (due to downsizing). During the 20 year operation savings of fuel consumption and maintenance (including engine revisions) are added to this. The NPV are the total savings after the 20 year period. The fuel savings contribute significantly to the value of the right sizing action.
The net present value of a downsized engine is positive from day one, because both CAPEX and OPEX reduce with downsizing.

	Mech [kW]	Investment savings [k€]	Fuel [m3/year]	NPV [k€]
Baseline	1250	0	0	0
Right size 80%	1000	55	-4.72	136
Right size 80%	1000	55	-14.16	208
Right size 60%	750	110	-9.44	273
Right size 60%	750	110	-18.88	345

Table 10: NPV for engine downsizing from 1250kW to 1000kW and 750kW. NPV for 20 years (50.000 hrs). Installing 1000kW instead of 1250kW and realizing 1% fuel saving, results in a positive NPV of 136kEUR over a period of 20 years. This can be interpreted that if this ship were built today, it would be worth 136kEUR to install a smaller engine instead of the conventional one. Discount rate at 4%.

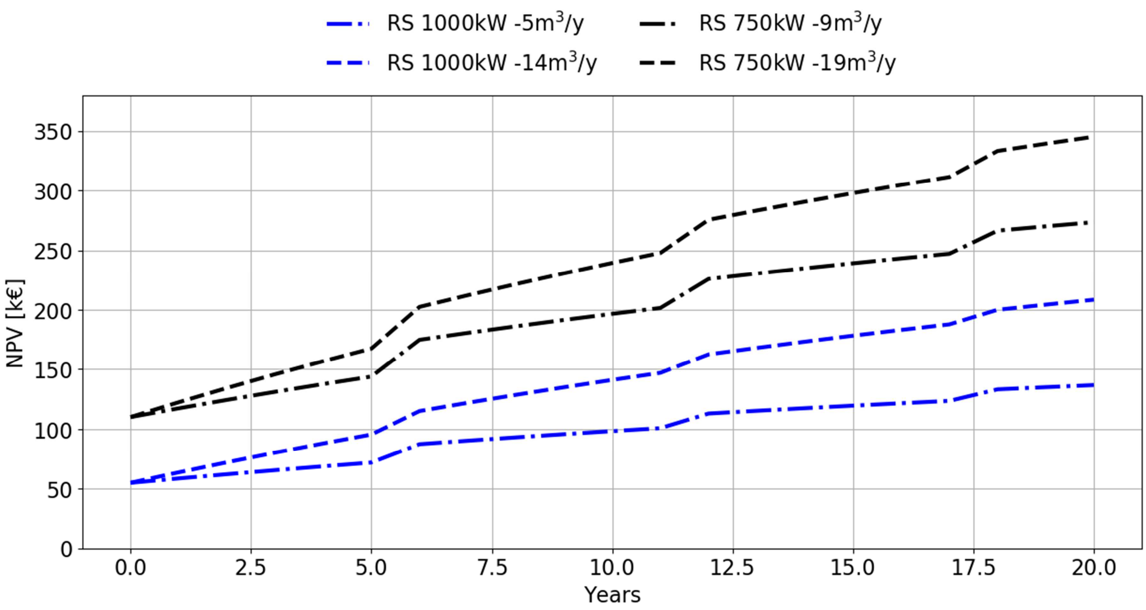

Figure 12: Net Present Value during the life time for installing smaller engines compared to a 1250 kW engine. Fuel consumption saving range from 4.7 m3/y (pessimistic) to 14 m3/y (optimistic). Positive NPV indicates that the decision is beneficial, due to reduced investment costs combined with reduces operational costs. Discount rate is 4%.

6.6 Conclusions for right sizing

The calculations show, that engine downsizing or ‘right sizing’ from 1250 kW to 1000 kW or 750 kW saves respectively 55,000 EUR and 110,000 EUR in investement costs. During the 20 year life time, the NPV are respectively 136,000 EUR and 273,000 EUR (overall savings).

6.7 Diesel electric and hybrid ships

The investment costs and operational costs (CAPEX and OPEX) of four righ size hybrid and diesel electric drivelines are calculated in comparsion to the 1250 kW diesel direct driveline. An overview of the cases are presented in Table 9. The hybrid and diesel electric drivelines have 1000 kW total propulsion power. For each hybrid or diesel electric driveline an optimistic and a pessimistic fuel consumption difference with diesel direct is taken. These values are based on the simulations reported in section 4.

Hybrid ships are expected to have a performance that is in between the diesel direct and diesel electric ship, though the exact performance strongly depends on the dimensioning, control strategies and operational profile. From the simulation of the diesel electric driveline, it can be seen (Figure 6) that the additional power conversions lead to higher power losses, compared to diesel direct drive.

	Diesel	*Electric*	*ΔFuel pessimistic*	*ΔFuel optimistic*
Baseline	1250	n/a	0%	0%
RS hybrid 60% - 20%	750	250	+1%	-1%
RS hybrid 40% - 40%	500	500	+5%	-1%
RS diesel electric 0% - 80%	0	1000	+15%	+5%
RS diesel electric 0% -2x40%	0	2x500	+10%	0%

Table 11: Reference case for cost-benefit analysis. Negative fuel save means fuel was saved. Actual savings are ship dependent. Fuel savings for right sized hybrid ships are due to savings in the direct propulsion.

The NPV values for the 6 scenarios are shown in Figure 13, with numerical values in Table 10. The diesel electric ship with a single generator. is omitted in the figure.

The investment costs for the hybrid and diesel electric drivelines are 102 kEUR to 575 kEUR higher. Refer to Table 10. This is explained by the relatively low prices for diesel direct hardware compared to the more expensive electric hardware.The higher investment costs are shown as negative NPV numbers at the start of the 20 year period in Figure 15. During the 20 years, this value will reduce or grow depending on whether there is a fuel saving (optimistic) or a fuel consumption increase (pessimistic) due to the hybrid or diesel electric driveline. From the figure, it can be concluded that the total costs over 20 years are a lot higher for the electric drivelines. This is expressed as negative NPV numbers. For the hybrid driveline the NPV ranges from –393 kEUR to -20kEUR compared to the diesel direct driveline. For the diesel electric drive line the NPV ranges from -887 to -529 kEUR.

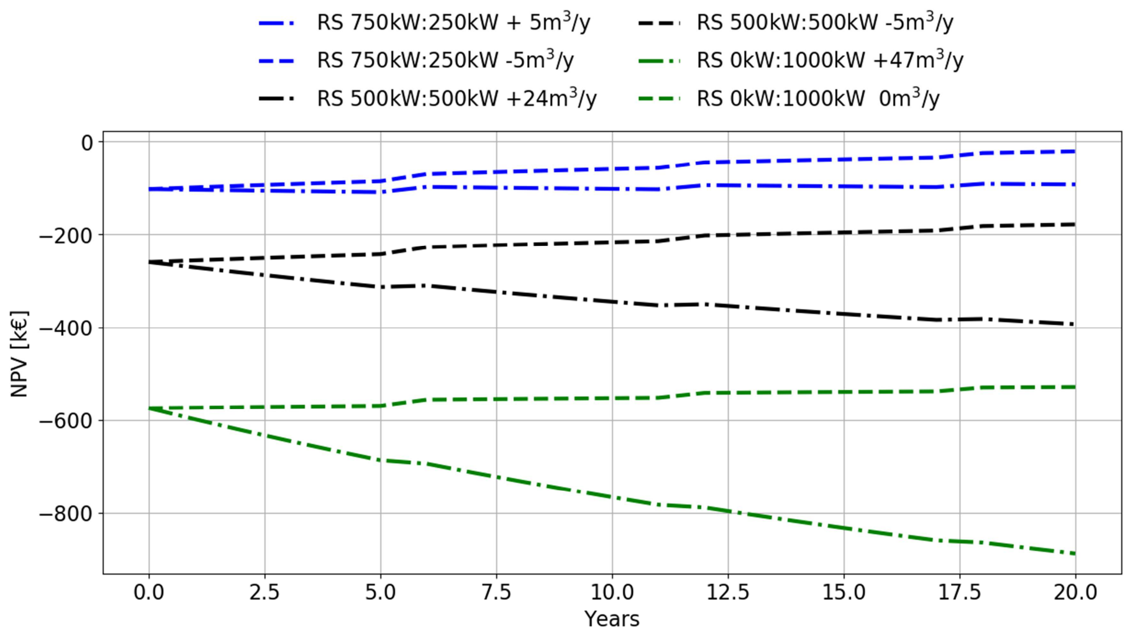

Figure 13: Net Present Value projections for hybrid and diesel electric cases from Table 12, relative to an oversized diesel direct ship. Negative NPV are caused by increased investment costs. Decreasing NPV is caused by increased operational cost.

	Mech [kW]	Electric [kW]	Extra Investment [k€]	Fuel change [m3/year]	NPV [k€]
Baseline	1250	0	0	0	0
hybride	750	250	-102	4.72	-92
hybride	750	250	-102	-4.72	-20
hybride	500	500	-260	23.6	-393
hybride	500	500	-260	-4.72	-178
Diesel electric	0	1000	-575	47.2	-887
Diesel electric	0	1000	-575	0	-529

Table 12: NPV for a period of 20 years compared to a 1250kW baseline. Used parameters: fuel 571€/m^3, mechanics 220€/kW, electromotor + controllers 500€/kw genset 350€/k.

6.8 Conclusions for hybrid and diesel electric ships

Hybrid and diesel electric drivelines are considerably more expensive than diesel direct driveline. This is due to the relatively high component costs of electric components. The higer investment costs range from 102 to 260 kEUR for the hybrid drive lines to 575 kEUR for the diesel electric driveline. The Netto Present Value (NPV) over 20 years ranges from -20 kEUR to -393 kEUR for the hybrid drivelines and ranges from -529 to -887 kEUR for the diesel electric drivelines, both in comparsion to the diesel direct driveline. Negative values indicate higher costs during the life time. The NPV includes investement-, fuel consumption and maintenance costs (CAPEX and OPEX).

Due to the high investment costs and extra fuel costs, return on investment is not expected based on fuel savings. For a return on investment, other benefits than fuel reduction has to be found to financially justify the extra investment needed for the electric systems (see paragraph 2.2).

7 Conclusions

In PROMINENT WP2, the development of advanced driveline concepts of ship greening for mass introduction has been targeted. PROMINENT focusses on right-sizing and hybrid configurations. In particular, generic models are developed to assess the cost/benefit for right-size engines, as well as, diesel electric and hybrid propulsion systems.

Right-sizing

For some categories of ships, installed propulsion power has shown to be larger than strictly needed. For these ships smaller engines can be fitted which is meant by right-size engines. The installation of smaller engines leads to benefit-benefit analysis as the choice for smaller engines (and other components) reduce investment costs. In operation, fuel costs will reduce due to the better performance of the right-size engine. Furthermore, maintenance costs will reduce. Stakeholders indicate that right-sizing may be unfavourable with respect to obtaining contracts that require sailing on different routes or with different cargo.
Engine suppliers indicate that reduction of engine size is possible in practice, and proposed the case of replacing a 1250kW engine to 1000kW or even to 750kW. This leads to investment savings of at least 55kEUR to 110kEUR, respectively. And a 20year net present value of at least 136kEUR to 273kEUR.

Hybrid and diesel electric

For a 110m vessel, the energy model developed in PROMINENT was used to compare the fuel performance of electric drivelines (diesel electric and hybrid) with a diesel direct driveline.

- Electric propulsion consumes significantly more across most of the sailing speed range (0% to some 15% increase).
- Between 8 and 14 km/h, the fuel consumption increase of the electric propulsion can be limited to max 5%.
- The main reasons for the fuel consumption increase of electric propulsion according to these simulations are the electric power losses in generator, electric motor and invertor/rectifier: 12% or more of the power output.
- Diesel electric propulsion with two (half-sized) constant speed generator sets performs much better that with one (full sized) constant speed generator set. The fuel consumption of the first one is 5% to 15% lower in the sailing speed range from 8 to 12 km/h.

Some effects could not be simulated, and are believed to be of second order importance for the quantitative conclusions of the comparison between hybrid and diesel direct.

- The simulations have been done with constant speed generator sets. Variable speed generators are expected to improve part-load performance of hybrid and diesel electric ships.
- Interaction between the type of inverter and the electromotor
- Cooling of the electric components

Where possible, generic, scalable efficiency models of electric motors, alternators, inverters and mechanical gearboxes are used. The advantage of this approach is that different modelled ships can be one-on-one compared. A disadvantage is that the results are not exact if during the ship design components are chosen that deviate from these models.

Apart from simulations and specifications some advantages can be linked to electric propulsion such as that it will be easier to convert such as ship to battery electric propulsion in the future. Also the high average engine load of generator sets will leads to optimal conditions for SCR and DPF aftertreatment (Stage V technology).

Life time costs

The total lifetime costs including investment, fuel consumption and maintenance costs have been calculated for different types of drivelines based on the modelling results (for a 1250 kW reference driveline). Initial investment increases due to the higher per kilowatt price of the electric components. Choosing for a hybrid with 750kW mechanical and 250kW electric propulsion requires additional investment of 102 kEUR. This number becomes 260 kEUR with 500kW for both mechanical and electric power. A full diesel electric driveline of 1000kW requires 575kEUR additional investement costs.

The total costs over a period of 20 years expressed as Net Present Value[2] (NPV) yields from -92kEUR to -20 kEUR for 250KW electric hybrid, and from -178kEUR to -393kEUR for the 500kW electric hybrid ship. For the diesel electric the, NPV ranges from -887 to -529 kEUR. Range for each configuration depends on the uncertainty in the actual fuel consumption realized. It can be concluded that according to the simulations, the costs of hybrid (electric) or diesel electric propulsion leads to higher costs during the lifetime of the ship.

Online energy model

The TNO energy model can be used to estimate changes in fuel consumption due to driveline changes. This model is also available online. It is capable of simulating fuel consumption and emission for both diesel direct and hybrid ships. The standard operational profiles and ships in the webtool are based on the results of the on-board monitoring within PROMINENT. They can also be adapted.

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[2] With Netto Present Value, NPV, the ‘benefits’ during the life time are expressed as value at the start of the life time. Negative values such as here, indicate higher life time costs.

8 Recommendations for future work

The conclusions in this report strongly depend on extensive numerical modelling. Although computer models are not physical reality, the work indicates the significant financial and environmental savings can be obtained by the downsizing of ship engines. On the other hand, choosing for electric systems may incur some financial and environmental losses. These conclusions should therefore be validated and challenged with real world data, even though this data is not easy to obtain.

8.1 Right sizing

The potential about right sizing of ships can only be utilized if the margins that need to be kept in order to comply with minimum power and stopping regulations are better quantified. Monitoring of ships such as in WP5 show the operationally required minimum power, though it is likely that this is not enough to comply with the regulations. Because most ships are differently build, this power margin on top of the used power is not the same for each ship. To utilize the potential of right sizing, more data should become available for how existing ships perform in stopping and minimum power tests. This data has to be put in context by providing full details about ship dimensions, propeller characteristics and the dimensions of the installed driveline components.

8.2 Hybrid ships

A measurement campaign with the goal of increasing the accuracy in the modelling and ship design process is recommended. This campaign will also contribute to the discussion on environmental and economic investments.

Manufacturers of hybrid ships that claim savings of their technology can already challenge the results in this report, by publishing the details of the real-world performance of their ships.

A comprehensive and reliable measuring campaign and/or publication should at least contain:

- Full description of all components installed in the ship
- Full description of all components installed outside of the ship, together with ship dimensions
- Currents, voltages, power factors for all electrical systems
- Torques and rotating speeds for all mechanical systems
- Engine performance characteristics
- Generator performance characteristics, in particular for variable speed generator sets (two-, three- or constant variable speed)
- Exact conditions under which the measurements have taken place
    - Location
    - Cargo
    - Current
    - Water depth

A measurements campaign on a twin propeller hybrid ship would be ideal, as one propeller can operate in diesel direct mode while the other uses the electric driveline. In this way, sailing conditons (e.g. water depth) are eliminated, just as cargo load and ship resistance paramters. To eliminate possible differences between the propellers, the directly and electrically driven sides should also be switched.

The motivation for these specific requirements is that the discussion about potential energy benefits of hybrid ships is complex by nature. This is due to the large amount parameters that can be varied when designing the ship, and the many interactions occurring between the components. When a project is done to (in)validate the results from the model, it is of greatest importance to achieve very clear and understandable results. It has to be clear what was measured, and under which conditions the measurements were performed.
End results should be expressed in terms of fuel consumption and emissions. Ideally such as in Figure 6 and Figure 8, so that the discussion does not get confused by the details of the sub components. When multiple ships are compared, the measurements should take place under equal conditions. However, it is important to obtain real wordt performance of the components, to allow for interpretation of the results. And to provide data which engineers can use to design more efficient ships.

The last goal relates to the costs of designing new ships. Because each sub component of the driveline plays a role in the efficiency of the driveline, a lot of background information needs to be gathered when optimizing a ship. This is a labour intensive and complicated task, as it is hard to obtain (reliable) information, if available at all. Future work should therefore focus on making real wordt performance characteristics of hybrid ships available.

9 References

PROMINENT D5.7. (2017) Technical evaluation of procedures for Certification, Monitoring & Enforcement Technical evaluation of the monitoring results on Rhine, Danube and other vessels. TNO et. al. PROMINENT WP5 report, grand agreement 633929.

PROMINENT D2.7 Validated Mathematical Ship Energy Model. TNO et. al. PROMINENT WP2 report, grand agreement 633929.

MoVe-IT! – D4.1 Operational Profiles, http://www.moveit-fp7.eu/assets/d4.1.pdf

PON (2018) Engine load profiles provided by Caterpillar distributer PON. The profiles are based on 270.000 hrs of engine monitoring for different types of ships.

Stapersma, H. K. (2002), Design of Propulsion and Electric Power Generation Systems.

J.J.H. Paulides, N. Djukic and L. Encica (2015), Hybrid Shipping for Inland Navigation: Loss Analysis of an Aluminum Direct-Drive High Performance 11,OOONm Permanent Magnet Machine, 20I5 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)

Paulides, J.J.H.; Djukic, N.; de Roon, J.A.; Encica, L(2016), Hybrid propulsion testing using direct-drive electrical, International Journal of Transportation Engineering and Technology, machines for super yacht and inland shipping

CESNI, 2017, European Standard laying down Technical Requirements for Inland Navigation vessels

10 Indexes

10.1 Figures

10.2 Tables

11 List of abbreviations

Auxiliary engine
The combustion engine in the generator set.

Alternator
The generator placed on the output shaft of the auxiliary engine, which converts mechanical energy into alternating current power. This term is used to avoid confusion with the power take in (electromotor).

Diesel direct propulsion
Conventional propulsion system where the propeller is rotated solely by an internal combustion engine via direct mechanical transmission of power

Diesel electric propulsion
Propulsion system where the propeller is rotated solely by an electromotor. The electricity is produced by one or more generator sets (auxiliary engine plus alternator).

Driveline
All hardware in a ship that contribute to the propulsion

Electromotor
The electromotor drives the propeller via the reduction gearbox or directly.

Kmh
Kilometre per hour.

Ship Energy Performance
Quantitative judgement of how total fuel consumption responds to certain changes in the ship design.

Inverter
The inverter converts direct current electricity to alternating current.

Monitoring
Monitoring is the collection and storage of on-board ship performance and/or operating data.

Parallel hybrid
Propulsion system composed of both diesel direct and diesel electric propulsion

Rectifier
The rectifier converts alternating current electricity to direct current

Retrofit
Making (large) changes to the ship, after the ship has been commissioned. This can be on the propulsion system, structure or otherwise.

Abbreviations

CESNI Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure (European Committee for drawing up Standards in the field of Inland Navigation)

ES-TRIN European Standard laying down Technical Requirements for Inland Navigation vessels

CAPEX Capital Expenditure
OPEX Operational Expenditure
SFC Specific Fuel Consumption
NPV Net Present Value

12 Overview NPV projection

Complete overview NPV projection for a 20-year timespan (4% discount rate) or the hybrid and diesel electric variants the projections are:

Mech[kW]	El[kW]	Investment[k€]	ΔFuel[m3/year]	NPV[k€]
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
1250	0	0	0	0
750	250	-102	4.72	-92
750	250	-102	4.72	-81
750	250	-102	4.72	-103
750	250	-102	-4.72	-20
750	250	-102	-4.72	-31
750	250	-102	-4.72	-9
750	250	-65	4.72	-55
750	250	-65	4.72	-44
750	250	-65	4.72	-65
750	250	-65	-4.72	16
750	250	-65	-4.72	5
750	250	-65	-4.72	27
750	250	-127	4.72	-117
750	250	-127	4.72	-106
750	250	-127	4.72	-128
750	250	-127	-4.72	-45
750	250	-127	-4.72	-56
750	250	-127	-4.72	-34
500	500	-260	23.6	-393
500	500	-260	23.6	-338
500	500	-260	23.6	-448
500	500	-260	-4.72	-178
500	500	-260	-4.72	-189
500	500	-260	-4.72	-167
500	500	-172	23.6	-305
500	500	-172	23.6	-250
500	500	-172	23.6	-360
500	500	-172	-4.72	-90
500	500	-172	-4.72	-101
500	500	-172	-4.72	-79

500	500	-322	23.6	-455
500	500	-322	23.6	-400
500	500	-322	23.6	-510
500	500	-322	-4.72	-240
500	500	-322	-4.72	-251
500	500	-322	-4.72	-229
0	1000	-575	47.2	-887
0	1000	-575	47.2	-777
0	1000	-575	47.2	-997
0	1000	-575	0	-529
0	1000	-575	0	-529
0	1000	-575	0	-529
0	1000	-387	47.2	-700
0	1000	-387	47.2	-590
0	1000	-387	47.2	-810
0	1000	-387	0	-341
0	1000	-387	0	-341
0	1000	-387	0	-341
0	1000	-712	47.2	-1025
0	1000	-712	47.2	-915
0	1000	-712	47.2	-1135
0	1000	-712	0	-666
0	1000	-712	0	-666
0	1000	-712	0	-666

For the right sizing of the direct drive example ship:

Mech[kW]	Investment[k€]	ΔFuel[m3/year]	NPV[k€]
1250	0	0	0
1250	0	0	0
1250	0	0	0
1250	0	0	0
1250	0	0	0
1250	0	0	0
1250	0	0	0
1250	0	0	0
1250	0	0	0
1000	55	-4.72	136
1000	55	-4.72	125
1000	55	-4.72	147
1000	55	-14.16	208
1000	55	-14.16	175
1000	55	-14.16	241
1000	42	-4.72	124

1000	42	-4.72	113
1000	42	-4.72	135
1000	42	-14.16	195
1000	42	-14.16	162
1000	42	-14.16	228
1000	67	-4.72	149
1000	67	-4.72	138
1000	67	-4.72	160
1000	67	-14.16	220
1000	67	-14.16	187
1000	67	-14.16	253
750	110	-9.44	273
750	110	-9.44	251
750	110	-9.44	295
750	110	-18.88	345
750	110	-18.88	301
750	110	-18.88	389
750	85	-9.44	248
750	85	-9.44	226
750	85	-9.44	270
750	85	-18.88	320
750	85	-18.88	276
750	85	-18.88	364
750	135	-9.44	298
750	135	-9.44	276
750	135	-9.44	320
750	135	-18.88	370
750	135	-18.88	326
750	135	-18.88	414

13 Model component efficiencies

The model results in chapter 0 are presented in terms of total power losses, and share of all power losses between the fuel tank and the propeller. Here the efficiencies per component are given.

Alternator	AuxiliaryEngine	DieselEngine	Gearbox	Speed
92	26.8	35.4	75.9	1.1
92	26.8	35.4	88.3	2.2
92	26.8	35.4	92.3	3.3
92	26.8	35.4	94.1	4.5
92	26.8	35.4	95.2	5.6
92	26.8	35.4	95.9	6.7
92	26.8	35.4	96.4	7.8
92	26.8	35.4	96.8	8.9
92	26.8	38.1	97	10
92	26.8	39.8	97.2	11.1
92	26.8	40.7	97.4	12.2
92	26.8	42.1	97.5	13.4
92	26.8	43.2	97.6	14.5
92	26.8	43.6	97.7	15.6
92	26.8	44.2	97.8	16.7
92	26.8	44.3	97.9	17.8

Table 13: Component efficiencies for the simulation of the diesel direct 105m vessel, with 1118kW installed power.

Alternator	AuxiliaryEngine	Inverter	PTOI	Rectifier	Speed
92	29.1	39.3	93	6.6	1.1
92	29.1	77.9	93	30.9	2.2
92	29.1	89.6	93	60.9	3.3
92	29.1	93.9	93	79.4	4.5
92	29.1	95.9	93	88.5	5.6
92	29.1	96.9	93.7	93	6.7
92.8	29.1	97.5	94.8	95.3	7.8
94.3	30.2	97.8	95	96.6	8.9
95.5	33.4	98	96	97.4	10
96	37.7	98.2	96	97.8	11.1
96	39.8	98.3	95.5	98.1	12.2
96	40.6	98.3	96	98.2	13.4
96	41	98.3	95	98.3	14.5
95	41.5	98.2	95	98.3	15.6
95	42.8	98.2	95	98.2	16.7
95	43.4	98.1	95	98.1	17.8

Table 14: Component efficiencies for the simulation of the diesel electric 105m vessel, with 1118kW installed power.

Alternator	AuxiliaryEngine	Inverter	PTOI	Rectifier	Speed
92	26.8	39.3	93	6.6	1.1
92	26.8	77.9	93	30.9	2.2
92	26.8	89.6	93	60.9	3.3
92.1	26.8	93.9	93	79.4	4.5
93.1	26.9	95.9	93	88.5	5.6
94.6	28.8	96.9	93.7	93	6.7
95.6	32.1	97.5	94.8	95.3	7.8
96	35.4	97.8	95	96.6	8.9
96	38.8	98	96	97.4	10
96	42	98.2	96	97.8	11.1
95.5	42.6	98.3	95.5	98.1	12.2
95	43	98.3	96	98.2	13.4
95	44.1	98.3	95	98.3	14.5
95	42.7	98.2	95	98.3	15.6
95	43.7	98.2	95	98.2	16.7
95	44.1	98.1	95	98.1	17.8

Table 15: Component efficiencies for the simulation of the diesel electric 105m vessel, with 2x 559Kw generator sets.

Alternator	AuxiliaryEngine	DieselEngine	Gearbox	Inverter	PTOI	Rectifier	Speed
92	26.8	0	0	61.5	93	10.1	1.1
92	26.8	0	0	89.3	93	49	2.2
92	26.8	0	0	95	93	78.2	3.3
92	26.8	0	0	96.9	93.7	89.8	4.5
92.9	26.8	0	0	97.7	95	94.4	5.6
94.4	28.5	0	0	98	95	96.4	6.7
95.5	31.8	0	0	98.2	95	97.4	7.8
96	35.3	0	0	98.3	94.5	98	8.9
96	38.8	0	0	98.3	95	98.2	10
96	42.1	0	0	98.2	94	98.3	11.1
95.4	42.6	0	0	98.1	94	98.3	12.2
95	43.1	0	0	98	95	98.2	13.4
92	26.8	43.2	97.6	0	92	0	14.5
92	26.8	43.6	97.7	0	92	0	15.6
92	26.8	44.2	97.8	0	92	0	16.7
92	26.8	44.3	97.9	0	91	0	17.8

Table 16: Component efficiencies for the simulation of the hybrid 105m vessel, with 248kW electrical power.

14 Right sizing tooling

The energy is presented here as one of the means to estimate fuel performance of hybrid ships. To make it accessible to non-experts, it is made available as a webtool, together with the operational profiles obtained in WP5. The aim of the tool is to support the calculation fuel consumption after right sizing or hybridization of a ship. The results are meant to be indicative, and support the decision process. Therefore, investment choices should never be made solely on the webtool.

The main ingredients for the comparison are:

- The technical specifications of the monitored ships (see D2.7 and D5.1)
- Operational profiles measured with the on-board units (see D5.7)
- User input for modifications of the operational profile for different operating conditions
- An optimization algorithm to find optimal components for alternative drivelines
- The ship energy model to estimate driveline performance

14.1 Workflow

After selecting a ship and operational profile, the operational profile becomes visible as in

Figure 14(left). The user defines an own operational profile based on speed, for upstream, downstream and canal sailing. For each of the profiles, the sum of the percentages must be 100%.

The model now has multiple objectives:

- Determine the minimum required installed power required by the combination of the ship and operational power.
- Find matching components for parallel hybrid variations to this driveline. The different variations have different ratios in direct and electric installed power.
- Calculate the relative performance of the alternative drivelines in terms of fuel cost and CO_2 and NO_x emissions (Figure 16 (right)).
- Communicate the choices of the alternative drivelines effectively to the user (Figure 16 (right)).

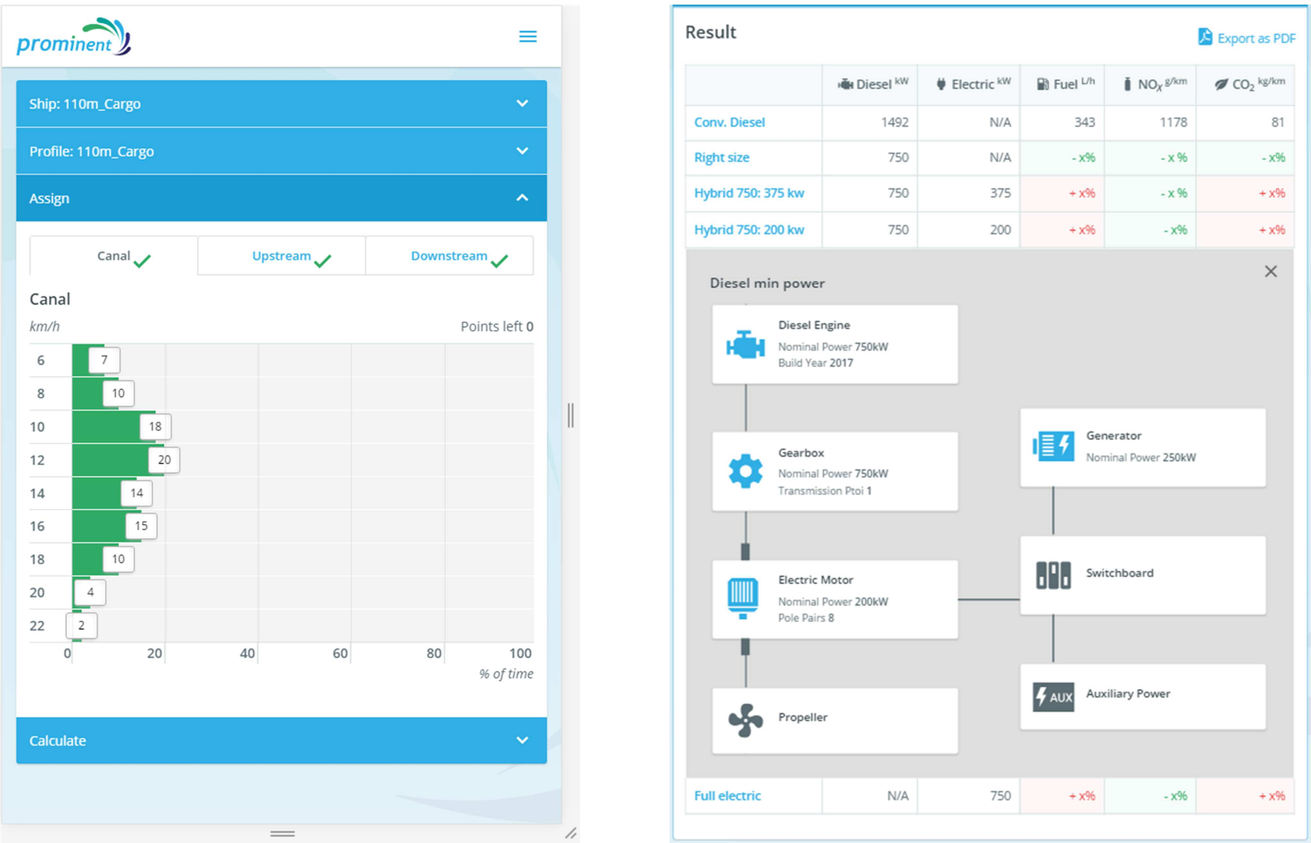

Figure 14 left: Editable operational profile in right-sizing webtool. Right: Performance comparison for right sizing and hybid options, based on fuel and NOx performance. The used component dimensions are also shown, depending on what is relevant for the specific ship.