The Advantages of a Low-emission Hybrid E-tug, Driven by a Revolutionary Podded Drive with Flexible and Green Diesel-electric Configuration

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SYNOPSIS

The use of greener harbour tugs is becoming ever more important to both contractors and authorities. As a result of new emission rules, the expansion of Emission Control Areas (ECAs), stricter local regulations, public opinion and the need for sustainability, Offshore Ship Designers (OSD) undertook to design a new energy efficient – and therefore low emission – e-tug.

Our original concept, in 2010, was based around hydrogen power and the use of a fuel-cell. Unfortunately, this technology has yet to be proven mature, and as of 2017 this solution is not yet available for high-power marine use. As a result, OSD worked on a design using a podded drive with a flexible diesel-electric configuration.

INTRODUCTION

During the research phase we looked at the following design parameters of a tug *(Figure 1)*:

- optimised hull designs;
- the operational profile of a harbour tug;
- scope for lower emissions and fossil fuel consumption;
- the propulsion/engine room layout;
- the design layout, with a higher comfort level for the crew regarding noise and vibrations.

We came to the following conclusions. Based on their operational profile, tugs use full power for only 2 per cent of their lifetime. All the components and the hull are designed and optimised for that full use of bollard pull at zero speed. Most of the time – during assisting, for example – tugs are over-powered, and the engines suffer from inefficient fuel consumption. In addition, all engines have to be in continuous operation because power needs to be available at any time during operations.

In order to minimise fuel consumption, power demand has to be optimised to different configurations. We compared three different propulsion systems:

- diesel direct (DD);
- diesel-electric (DE);
- diesel-electric hybrid with battery technology (DE hybrid).

Figure 1: Design image for the OSD e-tug

The conventional DD tug design has a layout that gives no flexibility for positioning primary engine room components. DE layout enables a better loading of the engines and gives more flexibility in the layout. Using battery technology also opens up the possibility of reducing the size of the gen sets and making use of shore power *(Figures 2 and 3)*.

A podded drive has the motor inside the housing of the unit. This ensures less mechanical loss, and the electric motor also gives direct torque to the propeller shaft. A revised engine room layout also means that the accommodation arrangements can be optimised, though of course they still have to comply with the latest version of MLC regulations.

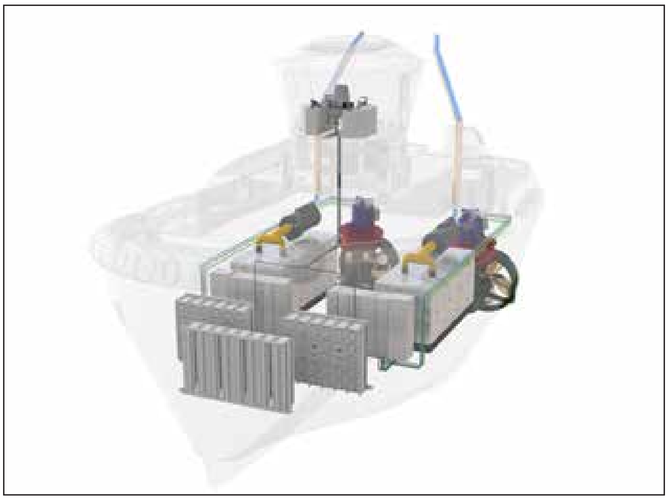

Figure 2: Open layout front

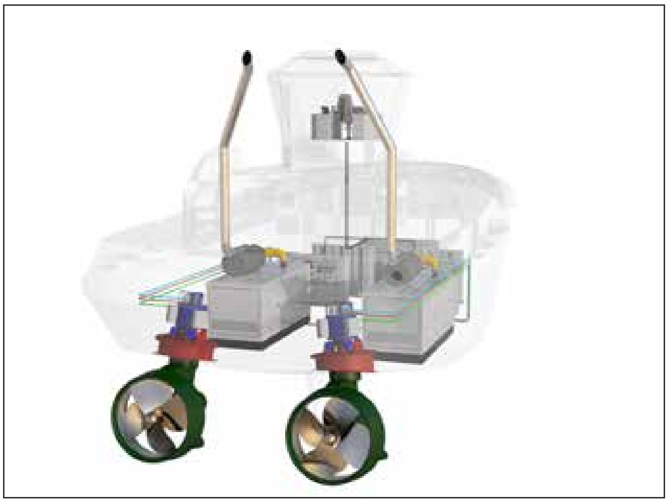

Figure 3: Open layout aft

OPTIMISED HULL DESIGN

Although a tug usually operates for a limited time in transit mode, and distances are short compared to other vessels, there are two reasons to try to reduce the resistance of the vessel. First, the lower the propulsion power at a given speed, the lower the fuel consumption, hence emissions. The second reason is less obvious, but most important for this hybrid design. Power, which is provided by batteries, is limited and relatively expensive. Lower propulsion power in transit will lead to a smaller fuel battery capacity, which will result in a more economical design.

Earlier research and tank tests on this design parameter led to the conclusion that a triple chine hull with integrated bulbous bow and lifted transom gave the best results. These models showed 40 per cent reduced energy consumption at 7 knots transit speed compared to a standard design *(see Figures 4 and 5)*. The hull form was optimised in order to reduce resistance at a speed of 7 knots, but other requirements were also considered, such as keeping construction costs as low as possible, and providing good manoeuvring and pulling performance both ahead and astern.

TUG LAYOUT

Operational profile

The operational profile of the tug is shown in *Figure 6.* There is a lot of variety in power demand during assisting and transit. The load profile *(Figure 7)* shows the percentage use of engine power during assisting. The engines run for 85 per cent of the time on less than a 30 per cent load, which gives high specific fuel consumption and leads to high maintenance costs.

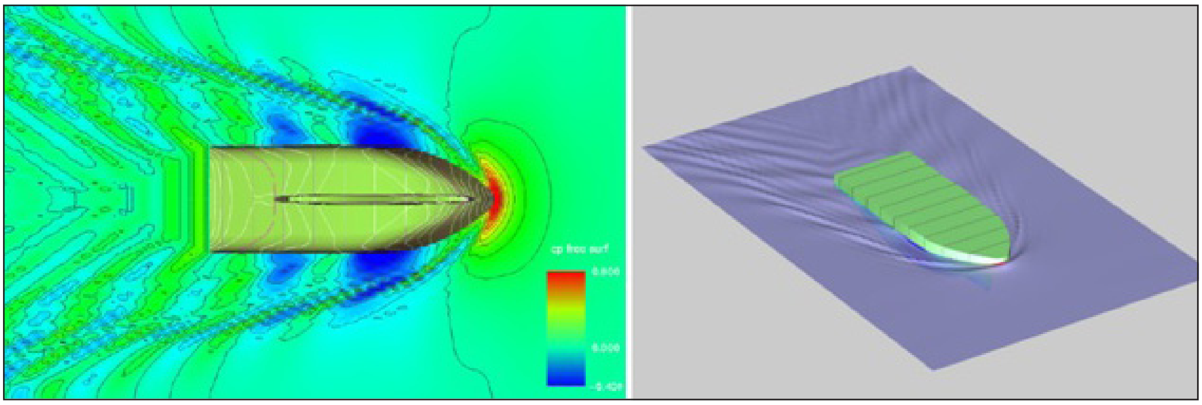

Figure 4: Wave pattern at 7 knots with standard design

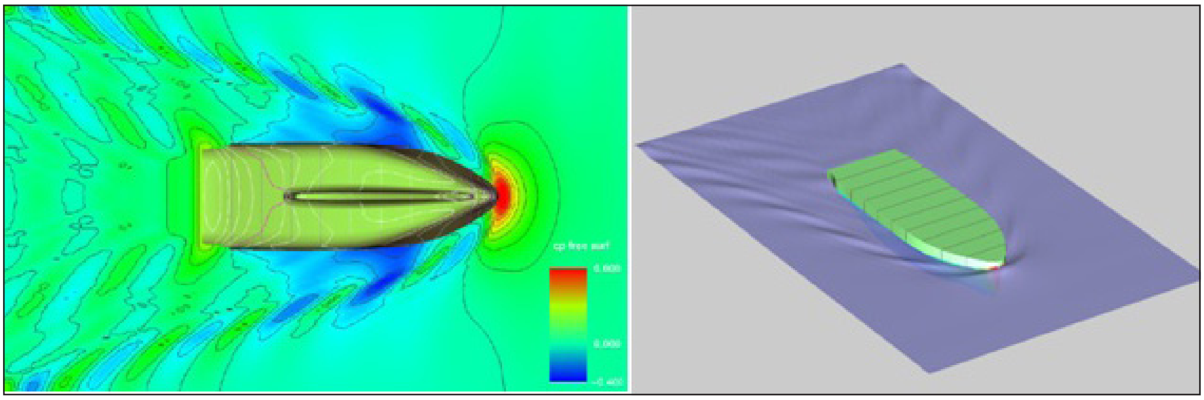

Figure 5: Wave pattern at 7 knots with triple chine hull with integrated bulbous bow and lifted transom

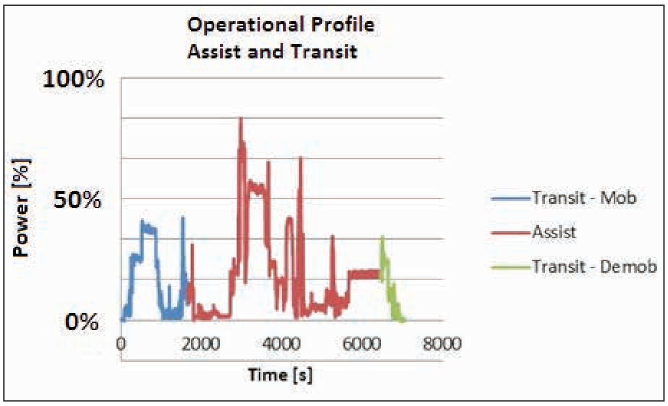

Figure 6: Operational profile

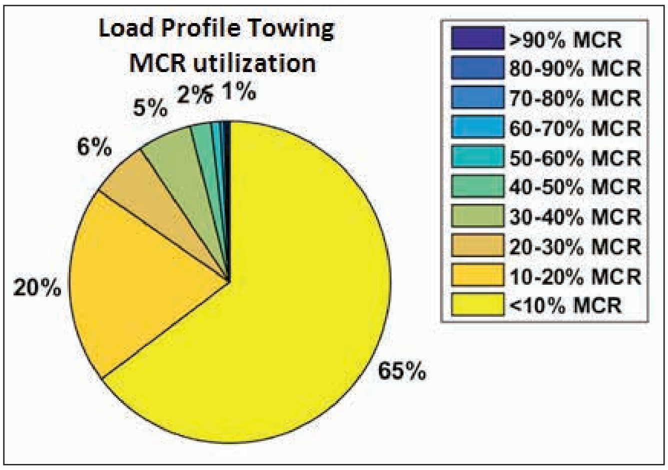

Figure 7: Load profile

A DE propulsion configuration gives a better loading of the engines. During the design of this configuration, contact was made with RH Marine to look into the use of electrical and fuel saving systems (of which more details below).

Engine room

As mentioned above, a conventional tug has an engine room layout disadvantage. Opting for DE or DE hybrid configuration gives more freedom. A DE configuration gives the option of positioning primary components in positions that lower the vessel's vertical centre of gravity (VCG).

A DE hybrid configuration can do the same, and if batteries are added for propulsion assistance then the engines can be reduced in number or in size. The number of engines and the battery capacity can be optimised according to the power demands of the tug's operational profile. The re-sized engines and battery packs can be positioned in the vessel for easier maintenance access, as well as lowering the tug's VCG further, which results in better performance.

Comfort

An engine room is always noisy. Because of the extra space created by a revised layout, the engines can be equipped with an acoustic enclosure, which reduces the noise level significantly. By using double elastic mountings, vibrations from structure-borne noise are reduced to a minimum.

Propulsion

In a DE configuration, the use of electrical propulsion is an ideal option. Verhaar Omega[1] introduced the V-Pod at *Tugnology* 2013 in London *(Figure 8)*. This is an electrically driven pod with the motor placed inside the underwater casing just behind the propeller. The design results in direct torque to the propeller shaft. The electric motor can rotate at various speeds, with high efficiency even at low rev/min. Placing the motor underwater results in further reductions of vibrations and noise in the steering room.

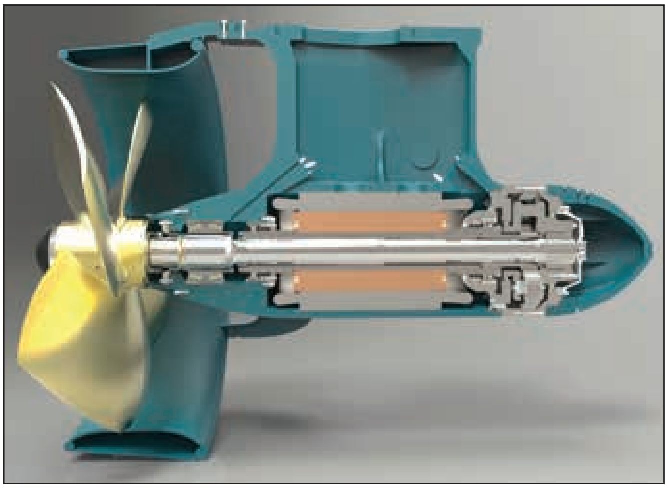

Figure 8: The VPOD670

HYBRID ENERGY MANAGEMENT DESIGN

In order to fully benefit from any hybrid power and propulsion system, it is essential to make sure that the system is designed for use, and that in operation the system is used as designed. Regarding the latter requirement, the captain has a significant role, and therefore the system should be designed from an operational perspective in which the tug and crew play an equally important part *(Figure 9)*.

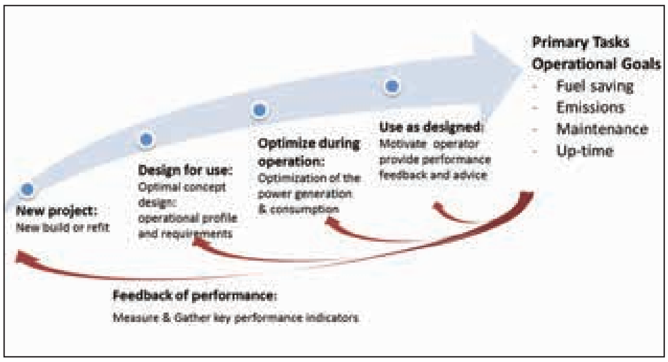

Figure 9: Hybrid power and propulsion design philosophy

In the design of the power and propulsion system, the typical operational profile of a harbour tug was used as starting point *(Figures 10 and 11, overleaf)*. This provided detailed information on power and energy requirements, and the operational modes in which the tug operated. The data was collected by an onboard measurement campaign. During this assessment the starboard and portside shaft power, electrical power, position and speed were logged every second for almost a month.

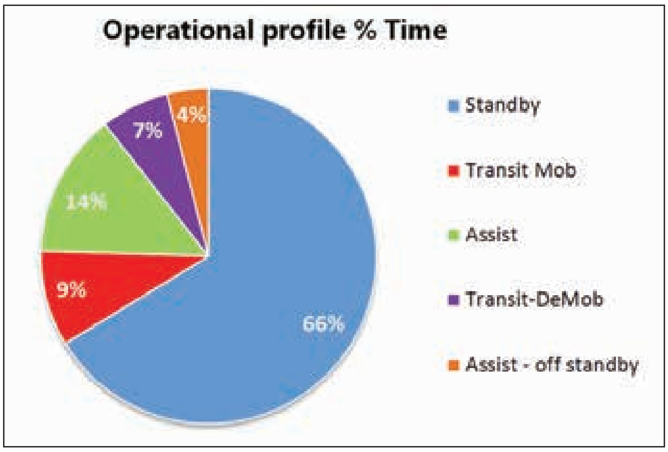

Figure 10: Time in operational modes

Based on this operational profile, the three power and propulsion configurations (DD, DE and DE hybrid) were modelled in the hybrid grid design environment. This simulation environment enabled us to compare different configurations based on fuel consumption, running hours and MCR utilisation. The operational control strategy and energy management automation were also incorporated, which improved the accuracy of the results significantly. The hybrid grid design tool makes use of energy models that provide insights into equipment efficiency under different load and operational conditions. The models are validated both by measurement and by various research institutions.

The operational profile was based on a reference vessel with a higher bollard pull. As the installed propulsion power of the e-tug is 75 per cent of the reference vessel, the operational profile was scaled down for analysis accordingly. In order to compare 'apples with apples', it was also important to define the required level of redundancy per operational mode. Among other considerations, this implied that during towing in the diesel-electric configuration all generators were running. During mobilisation, the battery state of charge (SOC) was kept above 80 per cent in the hybrid configuration, such that 80 per cent power was available at the start of the towing job.

Diesel direct (DD) configuration

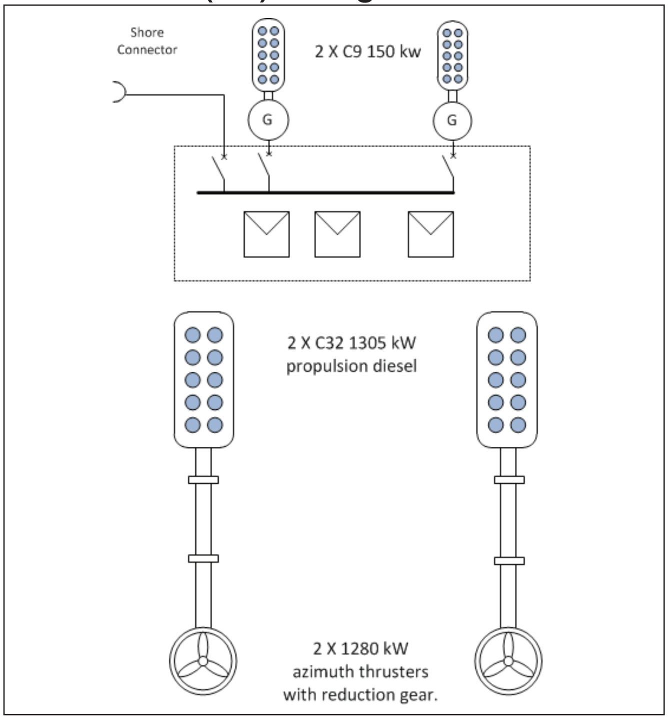

Figure 12: Diesel direct configuration

- azimuth CPP with reduction gear
- shaft bearings
- 2 main engines, 1,400kW
- 2 auxiliary diesel gen sets, 150kW
- assumed combinator curve
- 40 per cent minimum rev/min
- rev/min linear increase with shaft kWs

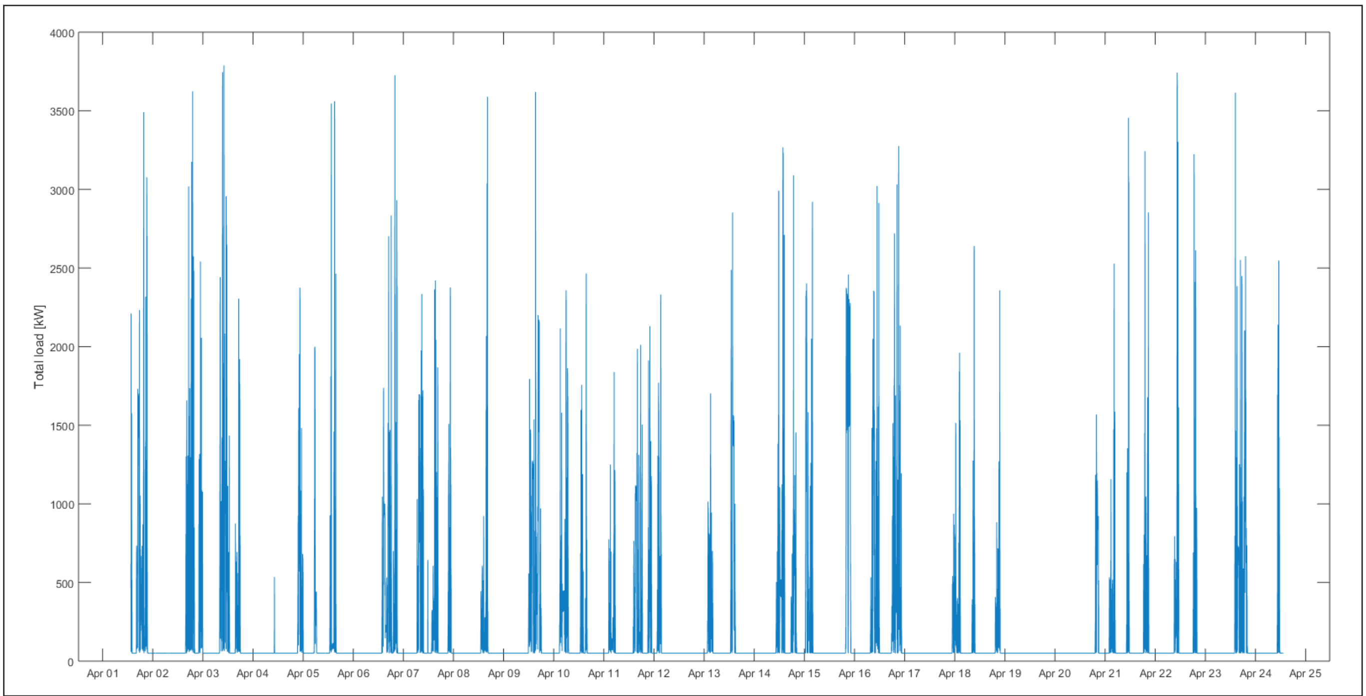

Figure 11: Power demand profile measured on the shaft and electrical at the bus bar

Diesel-electric (DE) configuration

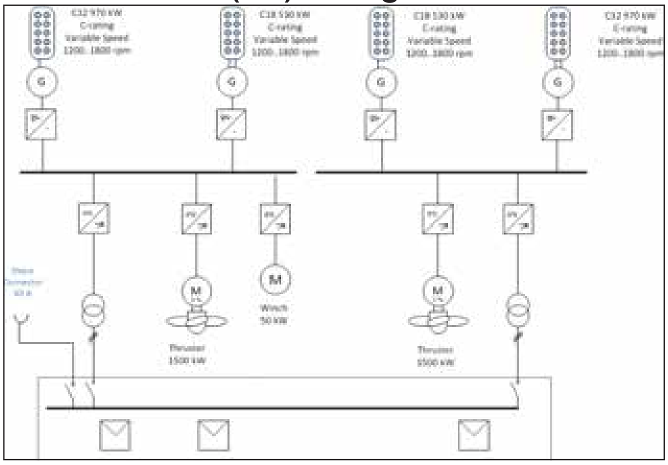

Figure 13: Diesel-electric configuration

- 2 main diesel gen sets, 1,000kW
- 2 main diesel gen sets, 600kW
- DC switchboard
- V-Pod e-motor and drive
- load dependent start/stop
- 85 per cent, 10sec start delay
- 100 per cent direct start
- 70 per cent, 120sec stop delay

DE hybrid configuration

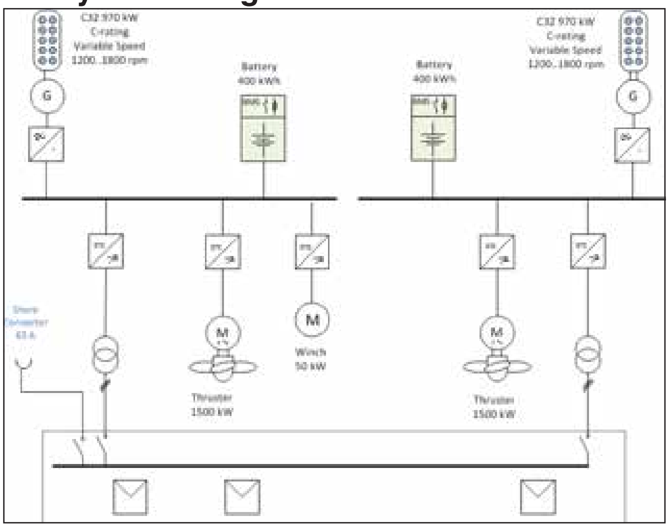

Figure 14: Diesel-electric hybrid configuration

- 2 main gen sets, 1,000kW
- 2 battery banks: 400kWh / 600kW
- DC switchboard
- V-Pod e-motor and drive
- No 'plug-in' hybrid
- Energy Management System (EMS) operational optimisation goal
- Fuel reduction
- State of Capacity (SOC) 'assisting' constraint (this constraint in the EMS ensures there is enough capacity in the battery for assisting and towing)

COMPARISON

The three configurations are compared based on:

- fuel consumption (kg MGO)
- energy consumption (kWh)
- specific fuel consumption (gr/kWh)
- running hours of the diesel engines (hours online)
- MCR utilisation (% MCR)

Table 1 provides the results of the comparison[2] between configurations. In this comparison, DD is set as the benchmark. The comparison shows that the DE configuration can save 39 per cent fuel; 6 per cent of this is realised by a more efficient engine loading, expressed in specific fuel consumption (gr/kWh). The remaining fuel savings for the DE configuration are realised by a more efficient propulsion system. In this case the CPP propulsion (in combinator curve) uses significantly more energy in low load conditions than the V-Pods.

The hybrid configuration also increases the efficiency (specific fuel consumption) by another 5 per cent, while the main benefit of the hybrid system is a reduction of 75 per cent diesel engine running hour cost. Should we include better engine loading in the overall maintenance costs, these are then even further reduced in the hybrid case. From this comparison the operational expenditures are calculated. Together with the different investment cost the total cost of ownership is calculated. This shows that the hybrid system is not only technological and environmental beneficial but also economically viable *(see Table 2 and Figure 15, overlead)*.

Key performance indicator (KPI)	Diesel Direct (DD)	Diesel-electric (DE)	Diesel-electric hybrid (DE Hybrid)
Fuel consumption	100%	-39%	-42%
Energy consumption	100%	-35%	-35%
Specific fuel consumption	100%	-6%	-11%
Running hour consumption	100%	-4%	-75%
MCR utilisation	26%	17%	54%

Table 1: Results comparison

HYBRID CONFIGURATION

Power generation/storage	
Marine diesel engine for propulsion	2 x 970bkW variable speed
Generator	1,350kVA, 690V, 40-60Hz, 1,200-1,800 rev/min, DECS-250 AVR
Battery system	Lithium nickel manganese cobalt oxide 2 x 400kWh installed capacity Design lifetime: 10 years Weight: ±17,000kg Rack floor area 17m^2 Batteries are directly coupled to a common DC-bus on each switchboard. This increases efficiency, effective capacity and reduces volume by eliminating the need for a DC-DC converter
DC distribution	
2 * DC switchboard	Two separated DC switchboards with power supply from each generator to both switchboards and all power converters for all major consumers. The voltage is variable between 1,000-700V and is actively regulated in order to charge or discharge the directly connected batteries
Main consumers	
V-Pods	V-Pod Series III, 900-1,500kW, 900-1,350 rev/min, 690V, gear ratio 4.17, 2.3m diameter fixed pitch with Optima nozzle type
Anchor and towing winch	Pull 250(80)kN at 0-9(0-28)m/min. Brake-holding force 1,250kN. Electric power supply 45kW, 1,000 rev/min at 50Hz
Fi-fi pump	Optional: 1,200m^3/hr, 700kW
Compressor	30 bar operational, 44 bar at 1,450 rev/min, 5.5kW
2 x grid transformers	80kVA, 400V/230V, 50Hz. This transformer will be used to create a reliable and safe AC distribution system
AC distribution	
Auxiliary switchboard	AC for all ‘sensitive’ consumers needing 400/230V, 50Hz, 200A
Shore connection fields	Connects AC switchboard with shore supply, automatic synchronisation.

Table 2: Diesel-electric hybrid configuration

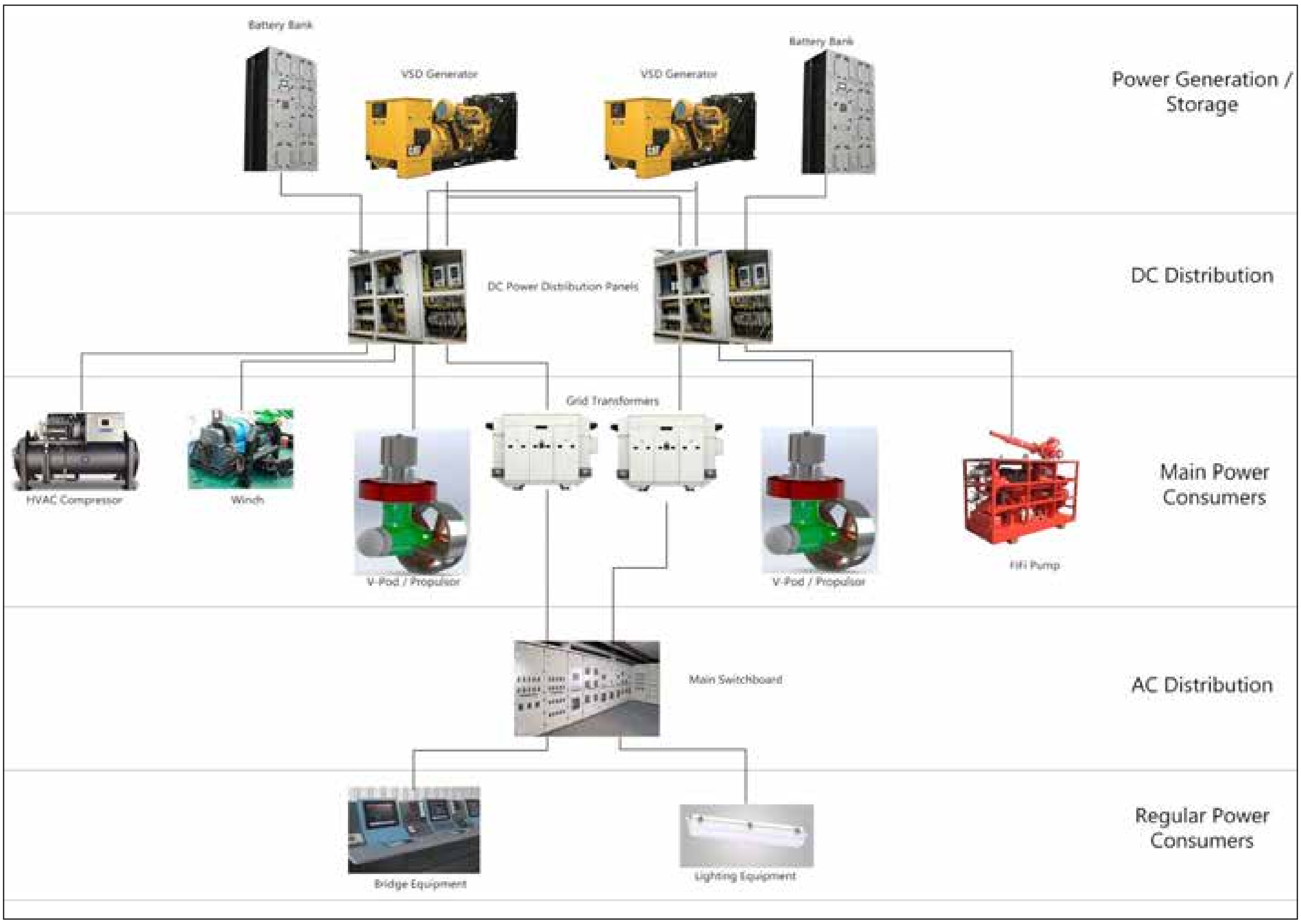

Figure 15: Representation of the diesel-electric hybrid system

OPERATIONAL MANAGEMENT

The automation system controls management of the power system, the batteries, the propulsion system and the alarm monitoring and control system, offering optimal deployment of energy resources, smooth transition between operational modes, redundancy and full control by the captain *(Figure 16).*

Captain control

The captain is mainly in control of the consumption side of the energy system, while the automation system will automatically select which mode the system operates in. In this tug design, four operational modes are defined:

- assisting (towing);
- assist standby (waiting for a new job);
- free sailing (to and from an assisting job);
- moored (waiting, or overnight moored at the quay).

The selection of operating mode is based on the adaptive learning potential of the automation system, which uses parameters such as GPS, historical data and navigational data. Fine-tuning of this system still needs to be performed during extended sea trials, in which the automation system will learn how the vessel is typically used.

Assisting

In this mode, all power sources remain online and the battery capacity can be fully deployed to supply peak loads during towing. The diesel generator will be set at fixed nominal rev/min in order to increase load step time response *(Figures 16 and 17)*.

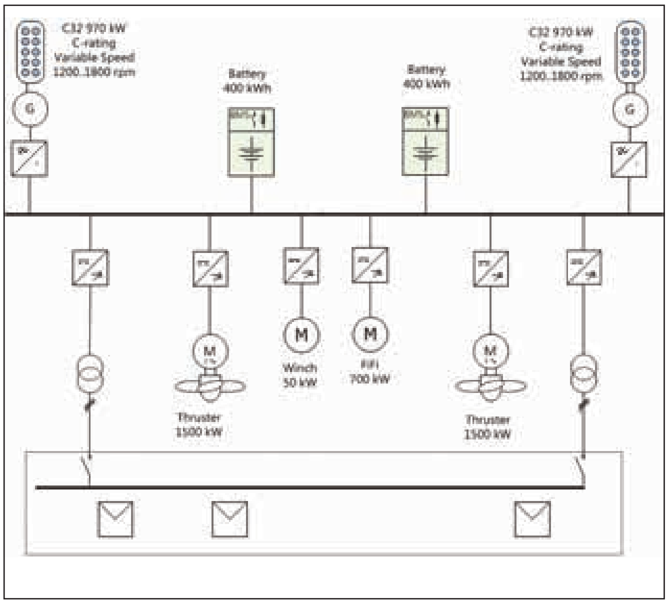

Figure 17 : Assisting mode energy sources and consumers online

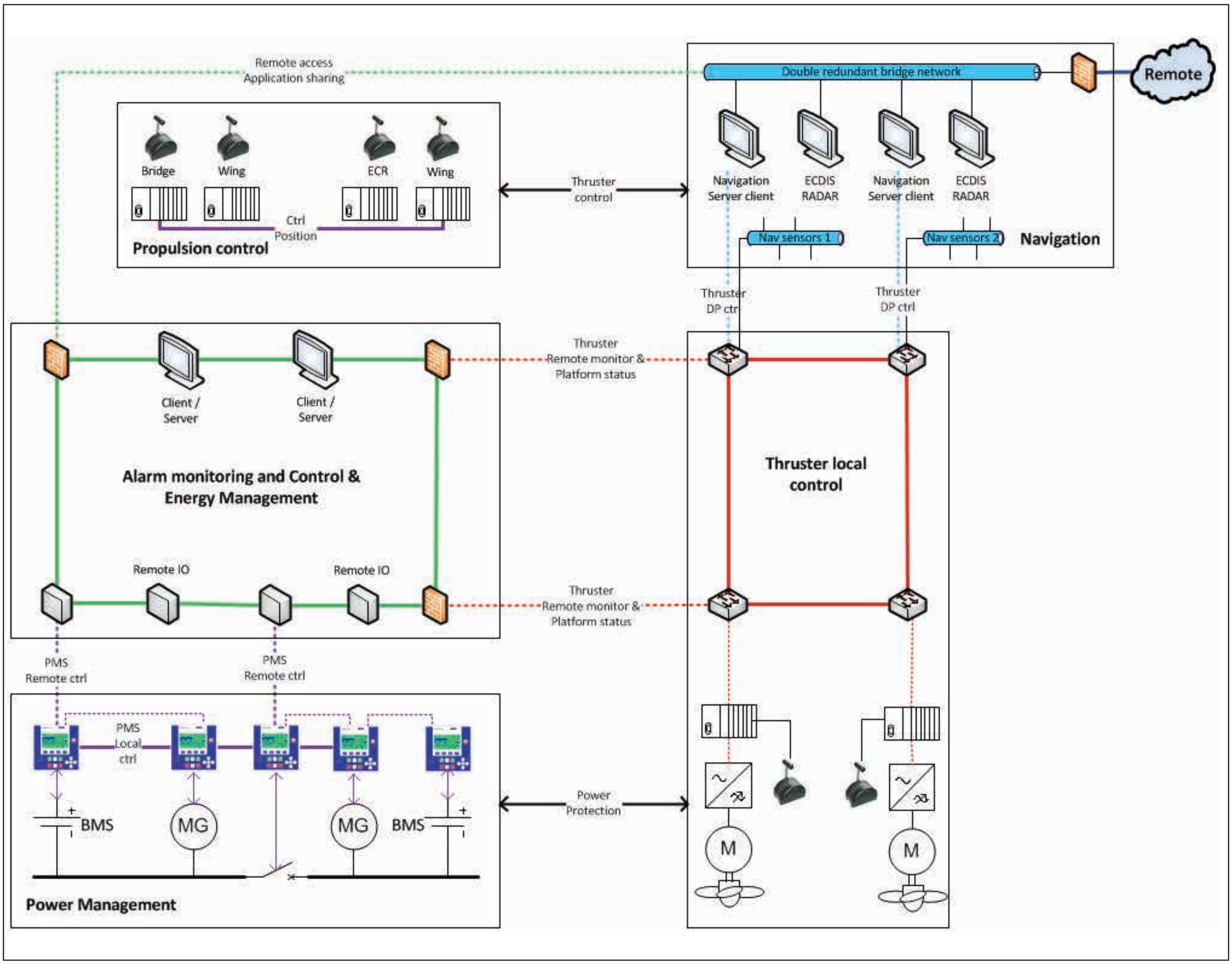

Figure 16: Automation configuration design

Assist standby and free sailing

In this mode the tug is sailing, or in an idle state and waiting for next assistance job. One variable-speed diesel generator supplies the required energy, and a part of the battery capacity can be used for peak shaving. If more power is required then the system will automatically start the second diesel generator *(Figure 18)*.

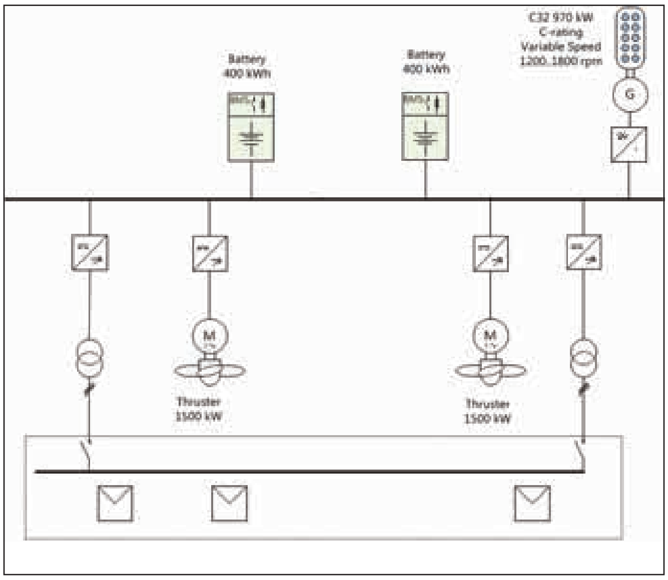

Figure 18 : Assist standby and free sailing mode energy sources and consumers online

Moored

When the tug is moored in harbour, a shore connection will power the ship. In the absence of a suitable shore connection the diesel generator and battery will go into harbour cycle mode, in which the battery and diesel generator will supply the power alternately *(Figures 19 and 20)*.

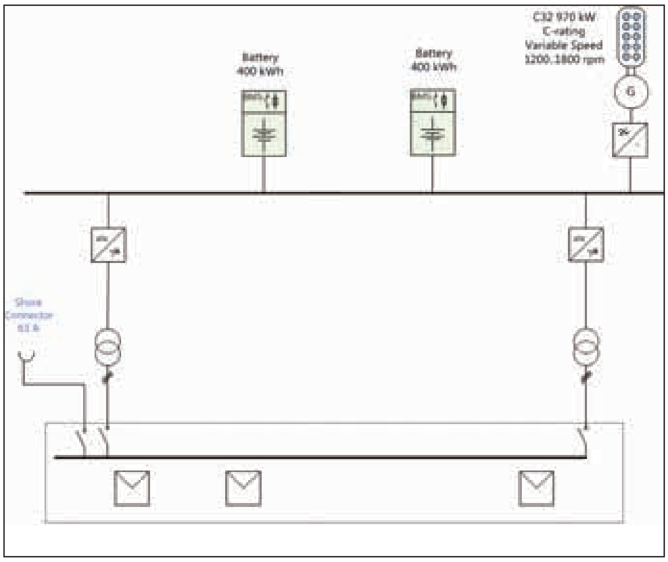

Figure 19: Moored mode energy sources and consumers online

ENERGY MANAGEMENT

The energy management system (EMS) is mainly used to control power generation and buffering. It calculates the optimal diesel rev/min and deploys the battery in accordance with the four specific operational conditions: assisting, assisting standby, free sailing and moored. The power set-point for the diesel engines is calculated based on specific fuel consumption data and the operational mode.

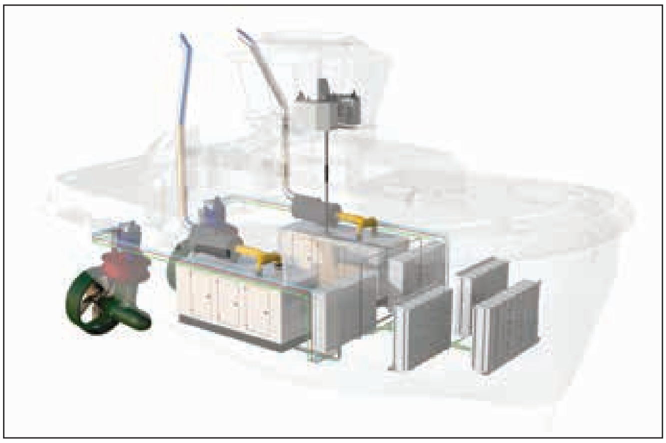

Figure 20: Open layout side

CONTROL SYSTEM ARCHITECTURE

The control system has three levels of control, as indicated in *Figure 21*.

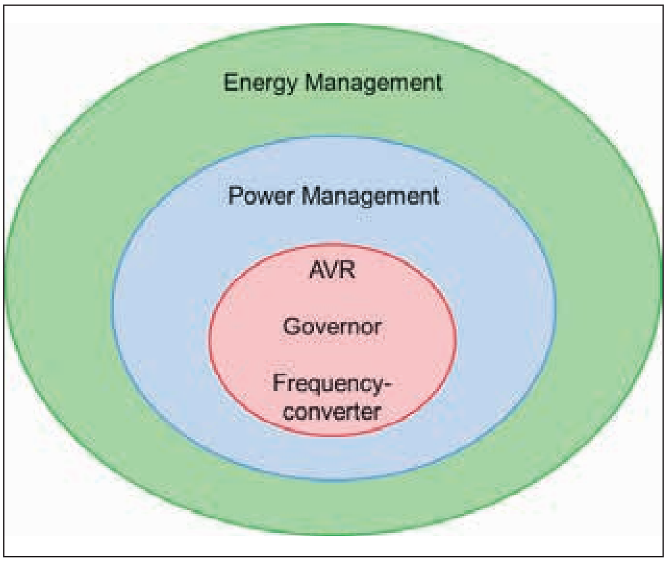

Figure 21: Energy management – the tertiary control loop

- The automatic voltage controller and the governor (diesel engine speed controller) control each source locally, such that the frequency and voltage are within set tolerances
- The power management system controls the running generators and starts back-up diesel generators, ensuring availability of power
- The energy management system also controls the load sharing, but includes the batteries
- Load sharing is performed in order to reduce fuel consumption and maintenance costs, as opposed to power management, which shares loads in accordance with power availability. In case of a conflict between availability and optimisation, availability prevails, due to the layer control structure indicated in *Figure 21*.

PERFORMANCE FEEDBACK

Keeping the captain in the loop is part of the design philosophy of the automation system for the hybrid tug. In order to capitalise on the benefits of the hybrid solution, the system needs to be used as designed. The energy management system provides real-time feedback on the performance of the hybrid system to the captain and fleet manager. The energy dashboard is the human-machine interface for the captain, and is part of the alarm, monitoring and control system (AMCS). It provides feedback on system health and performance, and can advise whether the system is being used correctly *(Figure 22)*.

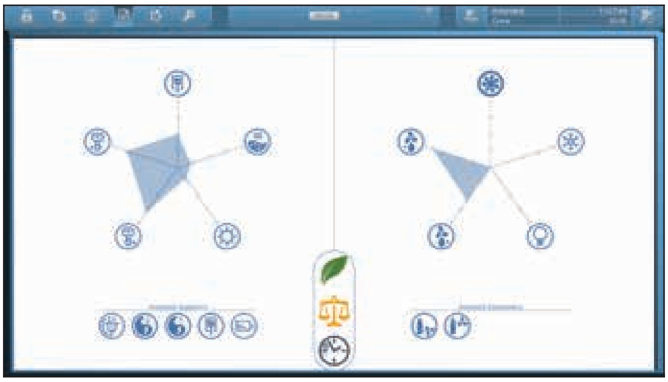

Figure 22: The energy dashboard, which provides performance feedback to the captain

The fleet manager receives feedback via a remote monitoring system. In this web-based application, the fleet manager can select the relevant key performance indicators (among others, fuel consumption, position and maintenance values) *(Figure 23)*.

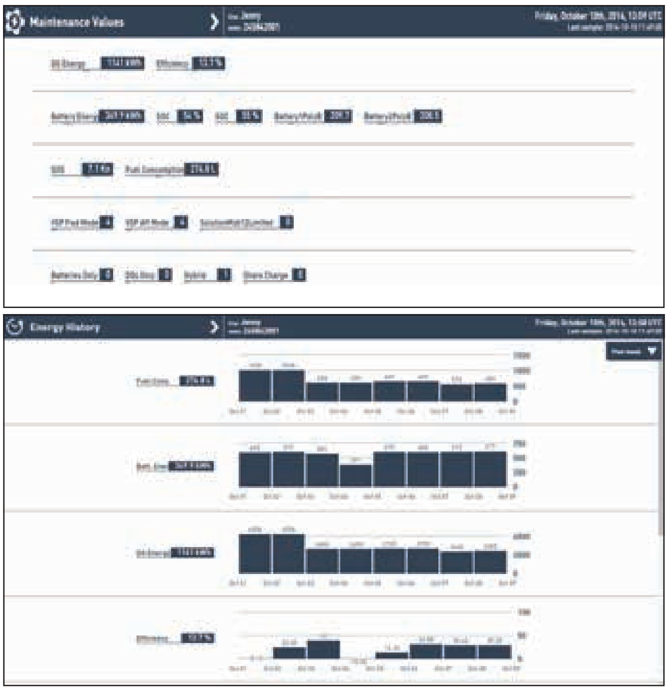

Figure 23: Output from web-based monitoring system

CONCLUSION

The low-emission tug can be delivered compliant with IMO Tier 3 requirements, suitable for ECAs. The uniformity and perfect loading of the propulsion system ensures low maintenance and fuel costs. Transient sailing and manoeuvring can be performed with zero emissions.

The hybrid system employed on the vessel is extremely fuel-efficient in terms of mobilisation and towing capability, superior to that of vessels using direct diesel or diesel-electric systems. The system results in lower fuel consumption and fewer running hours for the engine, which should also mean less maintenance costs and less downtime due to longer maintenance intervals.

The propulsion system is highly manoeuvrable, and the vessel's power train has a remarkably short reaction time. By using the batteries as a booster, maximum bollard pull can be achieved within six seconds. The relatively small size of the engines frees up more space below deck, providing optimum flexibility in respect of the division of space, including piping.

As a result of its podded drive and the double elastic mounting and acoustic enclosure of its gen sets, the vessel will provide the highest comfort level for its crew.

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