Sciberras EA, Zahawi B, Atkinson DJ, Juandó A. Electric auxiliary propulsion for improved fuel efficiency and reduced emissions. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 2015, 229(1), 36-44.

Electric auxiliary propulsion for improved fuel efficiency and reduced emissions

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Abstract

Auxiliary drives can provide an alternative propulsion system for marine vessels giving the potential to achieve improved environmental performance during low speed sailing. In this work, two case vessels were considered for analysis, a Roll On-Roll Off (RoRo) ship and a harbour tug boat. Actual sailing operational profiles were used as the basis for energy considerations to assess the potential for lower emissions. An energy-centric simulation model was built to estimate the emission of various pollutants, considering different machinery setups. Results have shown that savings are possible especially for vessels which run on residual fuels, where auxiliary drives provide a way of exploiting the advantages of cleaner sources for manoeuvring instances.

Keywords

Marine vehicles, permanent magnet machines, variable speed drives, air pollution

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Introduction

Emission reduction is a worldwide high priority with regulatory efforts aimed at boosting technologies or solutions which address this issue. Shipping is recognised as one of the most efficient transport methods yet the scope for further emission reductions is still significant especially given the likely predicted growth in shipping activity around the globe.[1] This is especially true when vessels are operating close to shore, such as during in-harbour manoeuvring where ship manoeuvring takes place in the vicinity of habitations. A reduction in emissions during this period will have a direct impact on human health and surrounding air quality.

A major driver towards reduction of these emissions is environmental legislation. Within the European Union (EU), EU Directive 2005/33/EC limits the Sulphur content of fuels used by a vessel while berthed in an EU port to 0.1%. In addition, a vessel in regular service between member states in EU waters is limited to 1.5% Sulphur content.[2, 3] The International Maritime Organization (IMO), under the revised MARPOL Annex VI, is also progressively reducing Sulphur limits. The introduction of Emission Control Areas (ECA), where even more stringent Sulphur limits are imposed, is a further requirement that must be taken into consideration. ECAs include the Baltic and North Seas as well as North American coastlines. In ECAs, SO_x limits are down to 1% from July 2010, being further reduced to 0.1% in 2015. Globally, Sulphur limits are currently restricted to 3.5%. This limit is progressively being reduced down to 0.5% in 2020[3, 4] (subject to a feasibility review by IMO before 2018). Potentially therefore, vessels may need to carry different fuels to use in different limit areas. A vessel not meeting these limits may be prohibited from operating, or face significant penalties.

Diesel engines account for the vast majority of prime movers found on ships with Heavy Fuel Oil (HFO) being the fuel of choice due to its lower cost.[5] The burning of this fuel however generates significant emissions. Furthermore, main engines are typically sized for the continuous at sea power rating, hence when they operate in harbour at reduced speed, they are operating at low load factors, with associated increases in emissions, Specific Fuel Consumption (SFC) and sooting.[6]

A hybrid propulsion system consisting of at least two energy sources addresses this mismatch between peak and actual power demands by exploiting the advantages of two separate systems, whose operating points are optimised for different power requirements.[7] Though typically associated with automotive vehicles, marine hybrids in the form of mechanical parallel hybrids such as COmbined Diesel And Gas turbine (CODAG) and serial electric hybrids such as diesel-electric submarines have been used in naval applications for a large number of years.[6]

Most seagoing vessels which employ mechanical main propulsion with diesel engines already have a link to the onboard electric system in the form of a mechanically driven shaft generator. In almost all cases, this is a conventional wound-rotor synchronous alternator mounted along the propeller shaft line to generate electricity at the cheapest possible cost from the main engine.[6, 8] This arrangement can be further taken advantage of by reversing power flow through the electric machine to provide an electric motoring capability at the cost of additional complexity, namely the need for a bidirectional power converter in order to permit controlled four-quadrant operation of the machine. The shaft generator in this configuration can operate as an auxiliary propulsion drive. This can help meet the stringent emission limits by exploiting the flexibility of the electric system to provide power from compliant sources while in sensitive areas.

This paper aims to examine the feasibility of providing alternative propulsion at low ship speeds by means of the onboard auxiliary electric power system. Although the generators run on fossil fuel, they provide the opportunity to use a different fuel than that used in the main engine. This fits the definition of a hybrid system in that the advantages of different systems can be exploited to achieve the same output. The study is based on actual operational ship data obtained from two different vessel types on a typical operational voyage, a Roll On-Roll Off (RoRo) ship and a harbour tug boat. The auxiliary drives are considered as a retrofit modification for the two vessels with simulation models built for the propulsion systems. Results show that significant fuel savings and emission reductions can be realised through the use of auxiliary propulsion, depending on vessel type and operational profile.

Auxiliary drives

In this work, auxiliary drives are understood to be a bidirectional electric drive consisting of an electric machine, power electronic converter and control algorithms, mounted in parallel to the prime source of propulsion power, as illustrated schematically in Figure 1.

The prime difference from a conventional shaft generator system is the bidirectional power control equipment which permits a propulsive capability. This consists of a voltage source inverter which uses Insulated Gate Bipolar Transistor (IGBT) power electronic switches to convert the onboard AC fixed voltage and frequency supply into a variable output via an intermediate DC link. The use of an IGBT converter also permits reactive power flow from and into the drive to be controlled (up to the kVA rating of the drive). Such variable frequency drives are now commonplace in industry due to their much greater operational flexibility and improved harmonic performance compared to conventional thyristor controlled drives.[9]

The electric machine is therefore fully controlled by the converter in all its operational modes, permitting motoring or generating action at the required power factor (unity power factor when operating as a motor and providing reactive power to the load when operating as a generator). Permanent magnet machines offer higher power density and efficiency compared to conventional wound-rotor machines[10] which allow for more compact installations, especially important in the cramped spaces of an engine room. A more in-depth description of the electrical machines and converter considered in this paper is given in the Appendix.

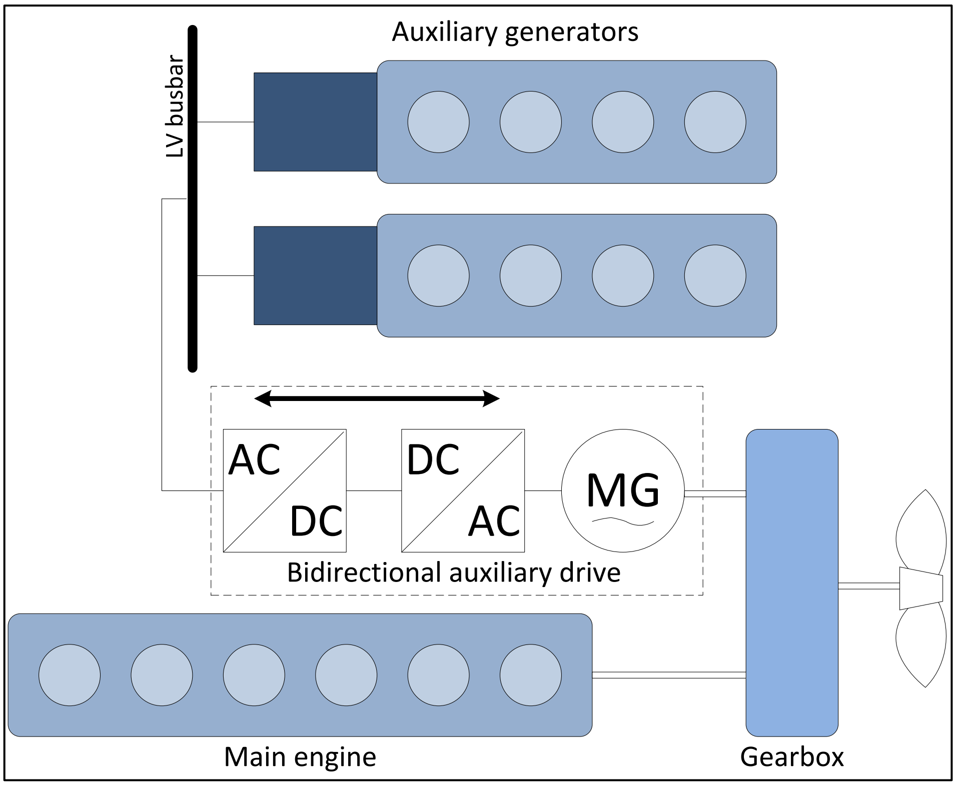

Figure 1. Generic diagram of auxiliary drive.

The placement of the drive along the propulsion chain determines the speed rating of the machine, in turn affecting the size, weight and cost of the system. For the same power rating, low speed machines require higher torque, which translates to a higher current requirement and hence bigger conductors. Higher speed machines are generally smaller and lighter due to the reduced torque/current requirements but need mechanical reduction gears in order to be matched to the speed required by the propeller.

In case of a slow speed diesel engine system, a direct drive is typically provided between the engine flywheel and propeller, avoiding the need for any gearing.[6] This reduces transmission losses to a minimum – hence any auxiliary drive installed with a gearbox would introduce additional losses and encroach on existing physical space. In a medium or high speed engine installation, a step-down gearbox is a necessary part of the propulsion package in the form of the Main Reduction Gearbox (MRG). In this case, the presence of the MRG can be exploited since this does not introduce any (additional) losses or components, and an even higher speed machine can be utilised by providing the MRG with a Power Take-Off/Power Take-In (PTO/PTI) facility. This consists of a secondary gear on the MRG, permitting two-way mechanical power flow to and from any connected auxiliary machinery.[11-13]

Vessel Data and Operating Profiles

Data from two separate vessels, namely a RoRo vessel and a harbour tug is used as the basis for the analysis presented in this paper. In close collaboration with the vessel operators, operational data was obtained from which the propulsion characteristics and operating profiles were documented and logged. These two vessels were selected because of the availability of data. They represent two different categories of vessel with their own individual machinery arrangements and operating profiles. The main particulars of the two vessels are given in Tables 1 and 2.

Table 1. RoRo vessel particulars.

Vessel length	138.5m
Gross Tonnage	18,979T
Main Engine rating	14,480kW at 500rpm
Service speed	20.2kt (10.4m/s)
Propulsion system	Controllable Pitch Propeller (CPP) at a nominal speed of 150rpm

Table 2. Tug vessel particulars.

Vessel length	25.36m
Bollard pull	53T
Main Engine	2×1,469kW at 1,600rpm
Propulsion system	Fixed Pitch Propeller (FPP)

Most importantly for the analysis, vessel operational data was logged in order to design and assess the performance of the auxiliary drive system. An example of the measured speed and power profiles for the RoRo vessel is given in Figure 2, from which a typical manoeuvring average was obtained across a number of similar voyages. The RoRo's profile focuses on the in-harbour manoeuvring time between the point of port entry and berthing. This involves a manoeuvring period of around six minutes sailing at 3.09m/s (6kt). The use of the auxiliary drive to provide propulsion will be examined during this period of operation. The operating profile for the tug boat is given in Figure 3, including actual port and starboard engine measurements together with boat speed profile. Operational data was collected every second and averaged over the length of each individual operating condition, giving piecewise linear approximations of the profiles. In the absence of standardised operating profile for marine vessels, this averaging process gives a representative profile of the vessel's operation, which is more indicative of typical operation and energy consumption patterns.

In the tug case, the (longer) operating profile shows a larger variation in power levels which can be related to the tug's mode of operation at the time. The periods of lowest power are the *standby* periods when the tug is idling and waiting for vessel approach. During *transit* periods, the tug is sailing between stations with moderate power values. Finally during the *assist* period, peak power is demanded from the engine for towing and when assisting vessels. Auxiliary propulsion will be examined during tug standby/idling and transit periods.

The highlighted periods in Figures 2 and 3 are the times when the main engine is lightly loaded and comparatively low power is needed for propulsion. Due to the (approximately) cubic nature of the propulsion characteristic (tug propulsion characteristic shown as Figure 4), lower ship speeds mean substantially lower power demands, as is the case when slow-steaming.[14]

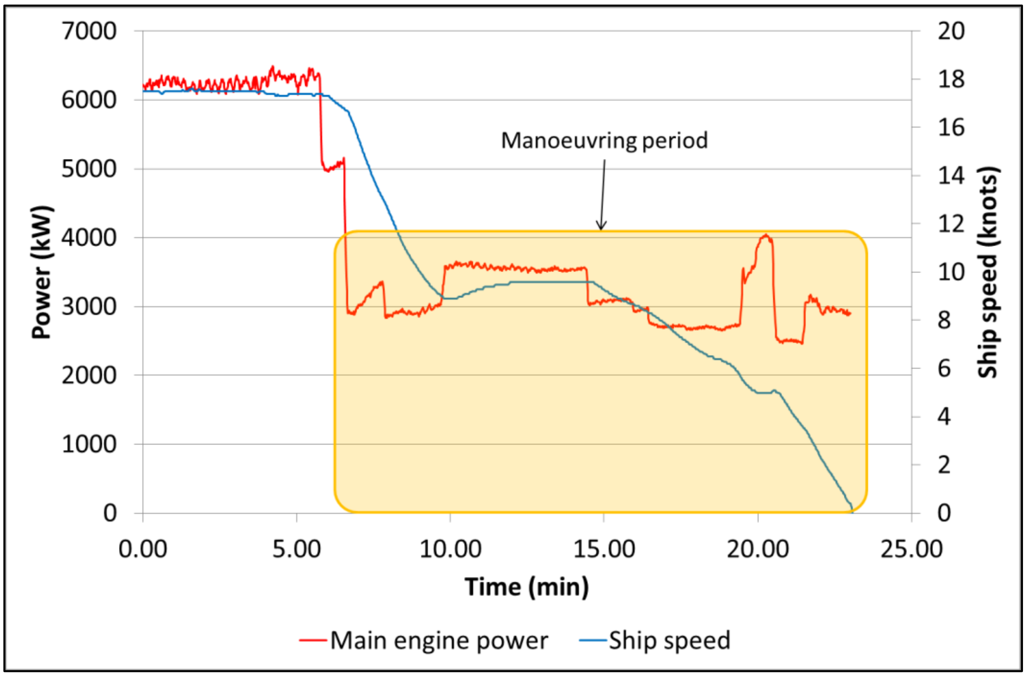

Figure 2. Measured RoRo manoeuvring speed and power profile.

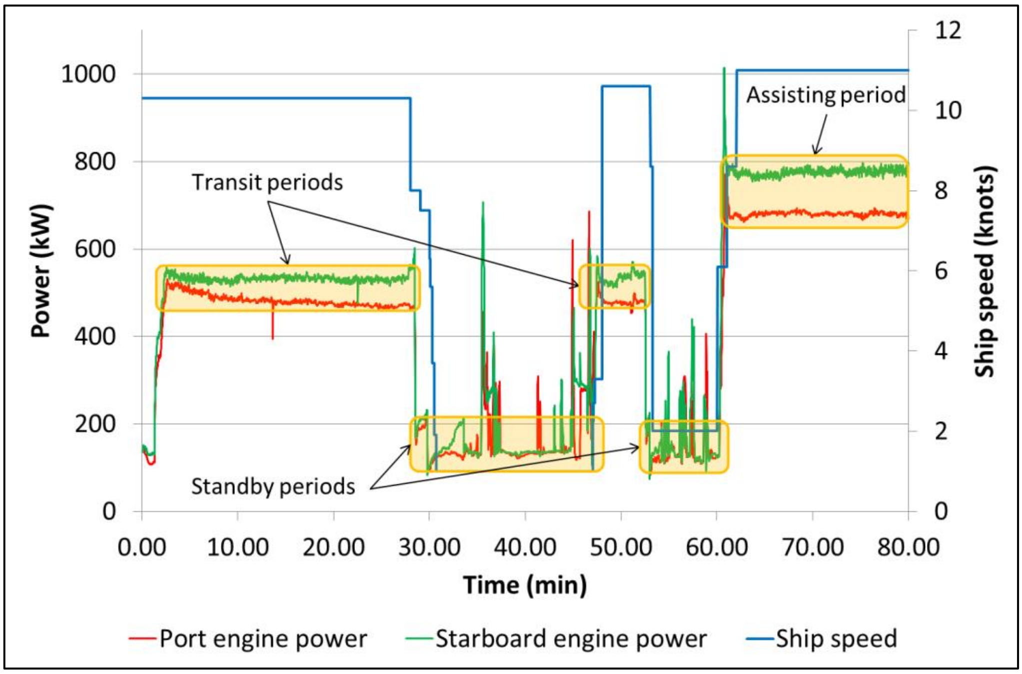

Figure 3. Measured tug operating profile; in-harbour operation.

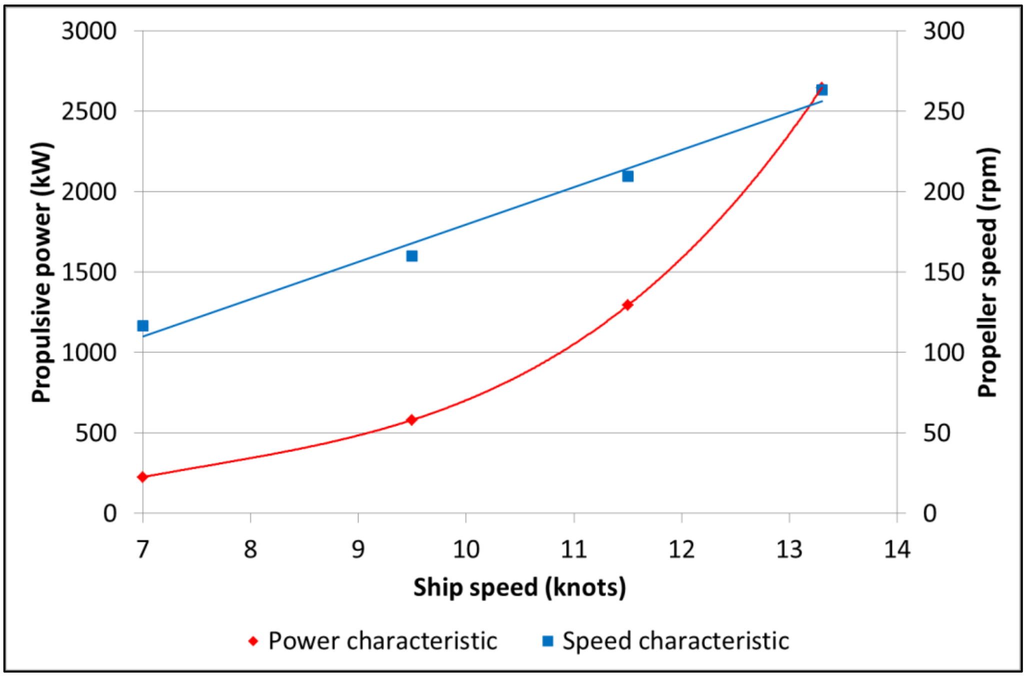

Figure 4. Tug propulsion characteristic.

Combinator mode propulsion

In the RoRo case, propeller pitch adjustment is used to vary ship speed while maintaining constant propeller revolutions. With the auxiliary drive directly replacing the main engine in this setup, a significant power demand over 1MW would be required even at just 3.09m/s (6kt). In order to fully exploit the benefits of the (necessary) power electronic converter, the adjustable speed capability of the auxiliary drive should be utilised in order to operate in combinator mode, i.e. adjustable pitch *and* variable speed.

Reducing shaft speed and increasing propeller pitch gives improved efficiency by reducing the required shaft power. Based on Computational Fluid Dynamics (CFD) simulations the adjusted power demands were determined, tabulated in Table 3. This demonstrates the significant power savings obtained by taking advantage of the controllability introduced by the bidirectional drive when compared with constant speed operation. These figures are then used for the adjusted propeller demand to obtain the averaged operating profile.

Table 3. RoRo propeller power demands at different speeds with adjusted pitch (combinator mode).

Ship speed (m/s)	Ship speed (kt)	Propeller power at 500rpm (kW)	Adjusted propeller power at 350rpm (kW)
0	0	2,190	751
3.6	7	2,700	1,085
5.1	10	2,980	1,676

Generation

With the auxiliary drive replacing the shaft generator (if any) the same functionality must be provided in terms of electrical power generation. With a bidirectional converter this is possible without precluding motoring operation. Although the PM machine will exhibit higher efficiencies compared to the conventional wound-rotor generator, it must be remembered that the power converter is a necessary component and the additional losses due to the power electronics must be considered for a holistic drive efficiency figure to be obtained. As the auxiliary drive installations are considered as a retrofitting option, engine downsizing was not considered in this study. This would mirror current developments of *full* hybrid tugs, which utilise energy storage to obtain emission reduction.[15]

Modelling

In order to make use of the available operational data and obtain estimates of the emissions produced by the various machinery setups, a complete system model was built. The averaged operational profiles of the two vessels (obtained from the data of Figures 2 and 3) are used as inputs to the model. This determines the instantaneous power demands on the propulsion system and defines the total energy required by the vessel over the operational scenarios considered in this study. The emissions produced are a function of the energy consumption and the various sources of the energy itself, i.e. main engine or auxiliary engines.

Electric drive model

The electric machine is modelled using the standard d-q (direct and quadrature axes) equations (1)-(6):

$$i_q(t) = \frac{1}{L_d}\int\left[v_q(t) - R_s i_q(t) - L_d i_q(t)\omega_e(t) - \Psi_f \omega_e(t)\right]dt \tag{1}$$

$$i_d(t) = \frac{1}{L_q}\int \left[v_d(t) - R_s i_d(t) + L_q i_d(t)\omega_e(t)\right]dt \tag{2}$$

$$T_e(t) = K_t i_q(t) \tag{3}$$

$$\Psi_f = K_t \frac{2}{P}\frac{2}{3} \quad (4)$$

$$P_{in}(t) = \frac{3}{2}\left(V_d(t)i_d(t) + V_q(t)i_q(t)\right) \quad (5)$$

$$P_{out}(t) = T_m(t)\omega_m(t) \quad (6)$$

where the subscripts d and q refer to the direct and quadrature axes, respectively. R_s is the stator resistance, L_q and L_d are the quadrature and direct axis inductances, respectively, P is the number of pole pairs of the machine, Ψ_s is the stator flux linkage and K_t is the torque constant.

Equations (1) to (6) allow accurate simulations of drive behaviour but present a computational penalty in terms of long simulation times. The solution adopted in this investigation was to create an efficiency chart of the machine according to the operating points demanded by the particular propulsion system topology, generating a look up table of overall efficiencies, obtained from the ratio P_{out}/P_{in} calculated using the detailed simulation model. The detailed d-q simulation is therefore performed across all operating points of interest as defined by the drive topology, by varying the load torque (T_l) and the desired speed setting ω*. The parameters associated with the machine model are obtained from manufacturer data available in product catalogues. This methodology therefore permits commercially available machines and converters to be easily represented.

Losses across the power electronic converter are treated by utilising an efficiency plot as a function of percentage loading, similarly obtained from manufacturer catalogues, allowing quick simulation without a detailed representation of device switching action. The effect of voltage perturbations across the DC link of the inverter are modelled as a proportional gain[16] given by equation (7).

$$V_{dq}(t) = \frac{V_{dc}(t)}{V_{dc\_nom}} V_{dq}^{*} \quad (7)$$

where V_{dq} is the actual stator voltage, V_{dc} is the DC link voltage, V_{dc_nom} is the nominal link voltage and V_{dq}* is the control (desired) stator voltage.

The combination of calculated machine efficiencies and converter losses permit the total drive loss at each identified operating point to be determined by means of interpolation for any intermediary point.

Combustion engine model

The purpose of this model is to determine the fuel consumption and emissions produced by engine operation. The approach adopted was to consider the cumulative energy demanded from each prime mover as the integral of instantaneous power loadings.

The emissions produced by the engines to generate this energy (kWh) are obtained by means of emission factors.[5] These emission factors are particular to individual engine types, and also vary according to the fuel used. They represent averaged quantities and hence inherently address issues of absolutism and artificial accuracy in the simulations. Since no journey will be identical to another even when under similar conditions, this averaging (combined with the averaged power profiles) gives a sound basis for comparison and evaluation of improvements brought about by auxiliary drives or hybridised sources. A further variable is the different percentage loadings on the engine, which is addressed by using different emission factors for different operating modes.[5]

Power loading

The allocation of power demands to the different subsystems is at the heart of this or any hybridised drive system. This directly determines the energy generated by each prime mover and hence the resultant emission figures.

The vessel speed demand in the form of a speed time-series is used as an input to the model. This speed demand is converted to a propulsive power demand by means of a speed-power look up table obtained from vessels' sea trials data. As a result, the power demand profile is a direct representation of the real propulsive power without any additional model uncertainties. This speed-power look up table takes into account the combinator mode power demand.

The load is allocated to the electric drive by a control logic decision block by assuming a threshold figure corresponding to the drive's rating. This maximises the time spent in auxiliary propulsion such that main engine load is reduced to zero once the power demand drops below the drive's rating. Throughout the operational scenario, the vessel's auxiliary electrical demand is imposed as an additional load on the auxiliary generators.

Such a simulation setup is energy-centric by design where the consideration of interest is the power loss across the various propulsion chain components. This permits the comparison of different auxiliary drive topologies and strategies without requiring detailed simulations capturing transient behaviour. The overall schematic of the developed model is illustrated in Figure 5, showing the topology of the various sub-models described in the previous sections.

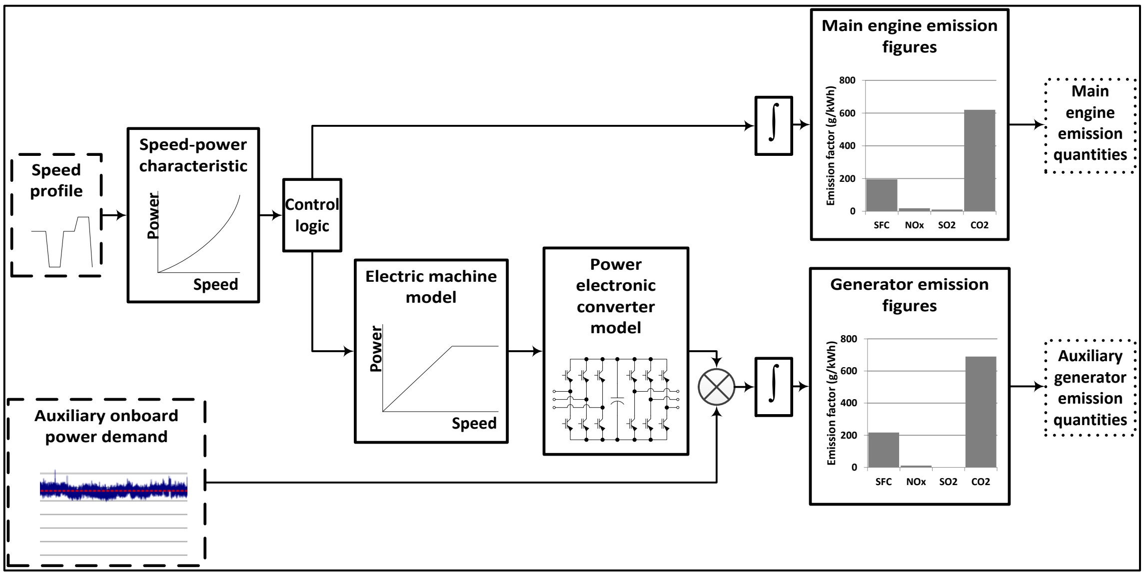

Figure 5. Propulsion system model schematic.

Results

RoRo vessel

For the RoRo vessel, three different machine topologies were considered as the auxiliary drive, as listed in Table 4. Machines A and B are radial flux PM synchronous machines while C is an axial flux PM machine. Machine A is mounted directly onto the propeller shaft while B and C are mounted on the high speed side of the reduction gearbox. All three drives were sized for propulsion at manoeuvring, taking into consideration the use of combinator mode as outlined previously. The speed rating of the machine is determined by the installation topology, and hence whether mechanical reduction gears are used.

All machines have similar (high) efficiencies, making savings highly dependent on the operating profile and propulsion setup. The direct drive setup (Machine A) will have lower losses due to the absence of a gearbox. The other two drives are modelled with a constant 2% power loss at each gearing stage.[6]

Table 4. Auxiliary drive selection for RoRo case.

	Machine A	Machine B	Machine C
Rated power (kW)	893	875	746
Rated speed (rpm)	173	400	3600
Rated torque (Nm)	49,296	20,900	1,980
Mass (kg)	12,470	4,680	340
Installation location	Direct	MRG	MRG+PTO
Machine type	Radial flux	Radial flux	Axial flux
Torque p.u. mass (Nm/kg)	3.95	4.47	5.82
Torque p.u. volume (kNm/m^3)	32.4	24.3	15.7
Efficiency at rated (%)	96.4	96.5	96

The results for the RoRo case are summarised in Table 5 for the six minute averaged manoeuvring period. The savings between the three drives are very similar, with Machine A showing marginally higher savings due to the reduced mechanical losses compared to the other setups as expected. The savings in fuel consumption, CO_2 and NO_x emissions are around 45% of the original conventional case. On the other hand SO_x emissions are significantly reduced, due to the use of marine gasoil (MGO) with a much lower Sulphur content (0.1%) as opposed to the heavy fuel oil used in the main engines. Conversely this cleaner fuel is more expensive than the HFO and hence fuel savings (monetary) are not commensurate with the actual consumption savings due to the higher cost of the MGO.

Table 5. Simulated results for RoRo case.

	Current estimate	Machine A		Machine B		Machine C	
Fuel consumption (kg)	28.15	15.12	-46.29%	15.15	-46.18%	15.33	-45.54%
Fuel cost (€)	14.41	10.90	-24.37%	10.92	-24.23%	11.05	-23.33%
CO_2 emission (kg)	89.63	48.07	-46.37%	48.18	-46.25%	48.73	-45.63%
NO_x emission (g)	1.35	0.76	-43.62%	0.76	-43.50%	0.77	-42.85%
SO_x emission (kg)	1.53	0.08	-94.98%	0.08	-94.97%	0.08	-94.92%

Tug boat

For the tug study, two PM synchronous machines (listed in Table 6) are considered. In the first case, the machine (Machine A) is sized to provide auxiliary propulsion in the standby mode of operation. In the second case, the machine (Machine B) is sized to provide power during the transit periods. In either case, only one installation topology is possible since the existing driveline involves an azimuthing thruster with an integral step down gearbox. Hence the machine will be directly mounted on the high speed engine-side shaft.

Table 6. Auxiliary drive selection for tug case.

	Machine A	Machine B
Tug operation (under auxiliary propulsion)	Idling	Transit
Rated power (kW)	160	628
Rated speed (rpm)	600	800
Rated torque (Nm)	2546	7500
Mass (kg)	1125	3040
Size (mm)	508×588	750×1365
Volume (m^3)	0.119	0.603
Machine type	Radial flux	Radial flux
Torque p.u. mass (Nm/kg)	2.26	2.47
Torque p.u. volume (kNm/m^3)	21.4	12.44
Efficiency at rated (%)	95.5	97.2

Table 7 shows the results of the tug case simulation for the standby and transit auxiliary propulsion cases. In these cases, the use of auxiliary drives has not resulted in any reductions in consumption and emissions, instead these have increased. This was an unexpected result since it was assumed that due to the greater variability in the operating profile (see Figure 3), an overall improvement in fuel consumption and emissions would be observed.

This outcome can be explained by the fact that the use of the auxiliary drive in the tug case adds additional losses to the propulsion chain. The main (mechanical) propulsion system returns better consumption figures than the electrical auxiliary system at higher loadings, such that over the complete scenario study, the net overall performance in terms of emissions was inferior to the original case with no auxiliary propulsion. This is in agreement with the observation made by Vossen in [17]. Contrary to the RoRo ship, the main engine on the tug runs on the same fuel as the auxiliary engines, hence no emission savings are realised by the possibility of running on different, cleaner fuels.

Table 7. Simulated results for tug case.

	Standby operation			Transit operation		
	Machine A	Current estimate	Difference	Machine B	Current estimate	Difference
Fuel consumption (kg)	37.34	36.66	1.85%	177.04	175.24	1.03%
Fuel cost (€)	26.92	26.43	1.85%	127.65	126.35	1.03%
CO_2 emissions (kg)	118.76	116.70	1.77%	563.00	558.00	0.90%
NO_x emissions (kg)	1.88	1.58	18.88%	8.89	7.54	17.90%
SO_x emissions (kg)	0.19	0.18	4.71%	0.90	0.86	3.82%

Conclusion

The use of alternative power sources for propulsion onboard vessels gives the possibility of improving prime mover operation during otherwise suboptimal periods, potentially reducing emissions and fuel consumption. Auxiliary electrical drives permit bidirectional power flow such that an electric drive installed along the shaftline can be used as a shaft generator as well as propulsion motor.

Powered by onboard auxiliary diesel generators, this paper considered the possibility of providing low speed propulsion via such an auxiliary drive during manoeuvring periods when vessels are close to shore or in-harbour thus having an immediate impact on human health. Two case vessels were considered, namely a Roll-On Roll-Off (RoRo) ship and a tug boat for which appropriate auxiliary drives were selected. Real operational data was obtained for the two vessels and used for estimating vessel emissions using energy centric models developed for the hybrid propulsion system. All the machines and power electronic converters considered for the auxiliary drives are commercially available devices, and chosen for retrofitting to the existing engine room setup.

Using averaged vessel operating profiles, energy flows and resulting pollutants were estimated using the developed model to quantify the potential improvements obtained by using the auxiliary propulsion system. Considerable emission reductions were projected in the RoRo’s case, with around 45% reduction in fuel consumption and CO_2 emissions. In contrast, the performance of the tug boat did not show any improvements in terms of fuel consumption and emissions when using the auxiliary propulsion drive. The tug’s main engine in the ship considered in this study already ran on cleaner distillate fuel, hence giving no fuel advantage by switching to the auxiliary generators.

The results show that significant savings are possible by using auxiliary generators chiefly due to the larger main engines used on some vessels (such as the RoRo ship considered in this study) and the resulting disparities between the powers required for manoeuvring. With increasingly stringent environmental rules and laws, the provision of alternate auxiliary propulsion capability also permits transits through environmentally restricted zones (such as ECAs) which might be otherwise prohibited, underlining the benefits of hybridised propulsion systems.

Acknowledgments

The authors would like to thank the other partners in the TEFLES project for their contributions to this work.

Funding

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 [grant agreement nº 266126].

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Appendix

This appendix is for the benefit of readers unfamiliar with the power conversion technologies considered in this paper, namely PM electrical machines and active front end voltage source power electronic converters employing IGBT devices.

Permanent magnet machines

The fundamental principle of operation of any electric machine is the interaction between a current carrying conductor and a magnetic field. In conventional wound-rotor machines, this magnetic field is established by the injection of a field current, with an associated power loss. In Permanent Magnet (PM) machines, the magnetic field is established by hard magnetic materials, permitting increased torque densities and higher efficiencies.[18] The mode of operation of the electric machine is determined by the direction of power flow through its armature windings. Thus if power is flowing from the electrical supply to produce mechanical torque at the output shaft, the machine operates in motoring mode, while if power is fed back to the electric supply, the same machine operates in generating mode.

The magnets are generally mounted on the rotor, avoiding the need to conduct power to the moving component via brushes, reducing maintenance needs and easing cooling requirements. Radial flux PM machines have their magnets establishing radially directed flux, linking with the conventionally wound stator. In contrast, Axial Flux Machines (AFM), as their name suggests, reorient the magnet placements such that flux is established in an axial direction along the shaft. Such a construction leads to very axially compact machines, permitting stacking of rotor discs in order to achieve the required power rating.[19] Figure 6 shows a cross-sectional diagram of both machine topologies.

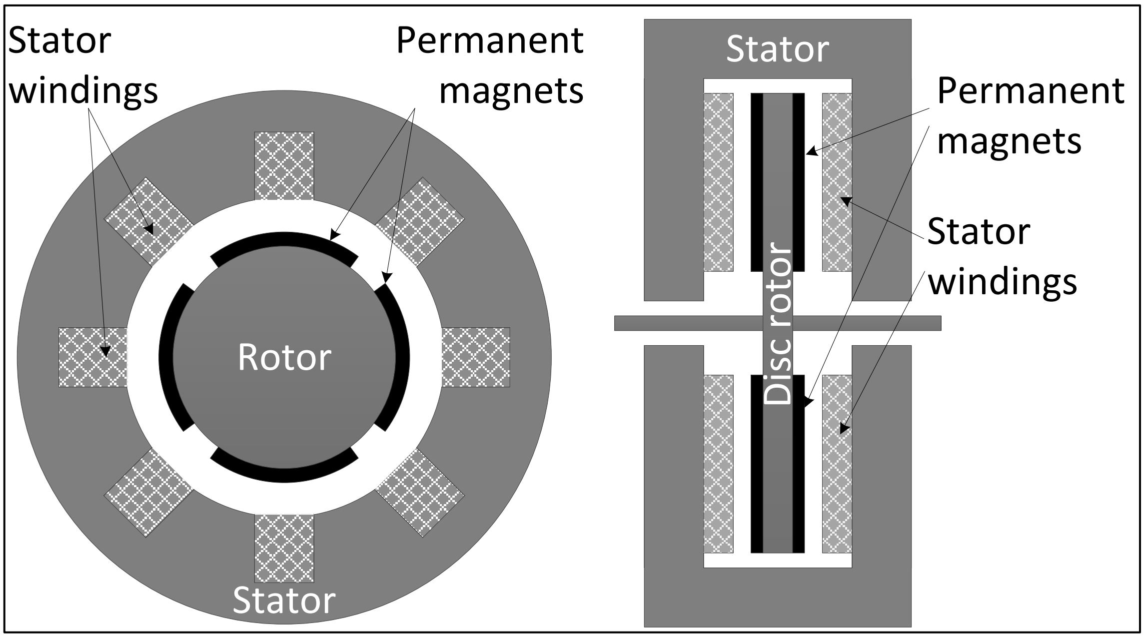

Figure 6. Permanent magnet machine topologies; radial flux machine (left) and AFM (right).

Power electronic converter

In standard industrial drives, a unidirectional converter with a simple diode bridge front-end is sufficient to permit adjustable speed control. With the need for power to be fed back to the supply, the input-side diode rectifier must be replaced by an Active Front End (AFE) converter using IGBTs, as shown in Figure 7. This essentially replicates the inverter output stage at the supply side, with an associated cost increase. It does however eliminate all low frequency harmonics from the ac supply current waveform and permits the input power and reactive power to be controlled, such that optimal supply power factor can be maintained.[9]

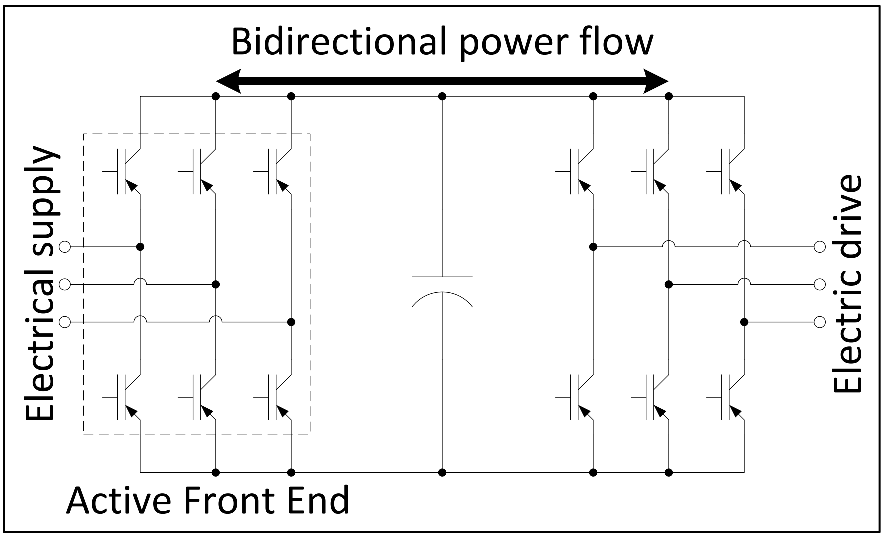

Figure 7. Bidirectional variable speed drive.