LATERAL

NAVAL ARCHITECTS

ELECTRIC AZIMUTHING PROPULSION IN SUPERYACHTS:
IS A TRADITIONAL SHAFT LINE A THING OF THE PAST?

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SUMMARY

Electric azimuthing or Propulsion-Oriented Devices (PODs) are already a well-established method of propulsion, common in the cruise ship industry. They are now making waves as a compelling avenue within the superyacht market, offering enhanced manoeuvrability, design flexibility and comfort. The drive to net-zero and increased environmental responsibility, including protection of coastal areas, is driving a trend towards electric energy architecture and less anchoring operations. As a result, electric PODs have become the compelling option for new large displacement superyacht design and builds.

This technical paper will take a holistic approach, investigating how electric PODs affect many different parts of superyacht design. Considered will be the various enhancements in design in terms of more flexible layouts, but also impact on arrangements. There are various POD units on the market offering exciting opportunities and this paper will look at how different units can affect overall performance, as well as implications on noise and vibration, a key design requirement in superyachts. The benefits of manoeuvring and excellent station keeping that PODs provide will be explored, and how the multi-directional forces and moments generated influence the structural design of the aftship. Where appropriate, comparison with the conventional shaft line arrangement will be made, including hybrid combinations that can broaden a yacht's capability.

With the increasing choice of propulsion architecture, this paper will provide insight on the benefits, challenges and impacts of integrating PODs into the design of a superyacht. This insight will enable the wider industry to fully consider the compelling opportunities PODs offers for future projects, reinforcing it as the emerging alternative to a more traditional shaft line arrangement.

1. Introduction

With the IMO marine industry target of net-zero by 2050 on the horizon, this regulation requirement falls well within the lifetime of large yachts currently being built. Adopting an electric energy architecture system offers a potential future-proofing strategy due to the ability to integrate add-on technologies at a later stage. With advancements in propulsion technology combined with the adoption of an electric energy architecture system, the range of propulsion options has significantly expanded. In recent years, Lateral has observed a growing trend toward electric azimuthing propulsion systems.

Azimuthing propulsors or Propulsion-Oriented Devices (PODs) for marine vessels were first explored in the 1980s, with the first POD unit retrofitted to a Finnish support vessel in 1990. Since then, development has continued, and more and more vessel types have adopted PODs as their principal propulsion mechanism [1].

The catalogue of PODs available within the marine market is significant with each sector seeking different operational requirements and performance capabilities, as well as satisfying specific vessel arrangement needs. PODs require a different design approach compared to shaft lines, and this paper seeks to explore an array of topics that should be considered in the technical and general arrangement design, specific to superyachts.

The focus of this paper is on electrically driven PODs. POD arrangements not covered in this paper include ducted units, Volvo IPS drives, engine driven PODs, and cyclorotor units such as Voith Schneider and ABB Dynafins. Although these PODs are available to superyacht design, they represent more specialist configurations & requirements that fall outside the scope of this paper. Additionally, for comparison purposes, references are made to diesel-electric (DE) and diesel-mechanical (DM) systems, as well as DC and AC grid electric architectures. Although these topics are highly relevant to the discussion of PODs versus shaft lines, their complexities require analysis that is beyond the scope of this paper.

2. Categories Of Pod

There are many different types of electric PODs available to the marine market, offering different variations on power, arrangement, and performance capabilities. Figure 1 shows an example selection of manufacturers and a spread of units versus power, ranging from 0.2MW to above 7.0MW.

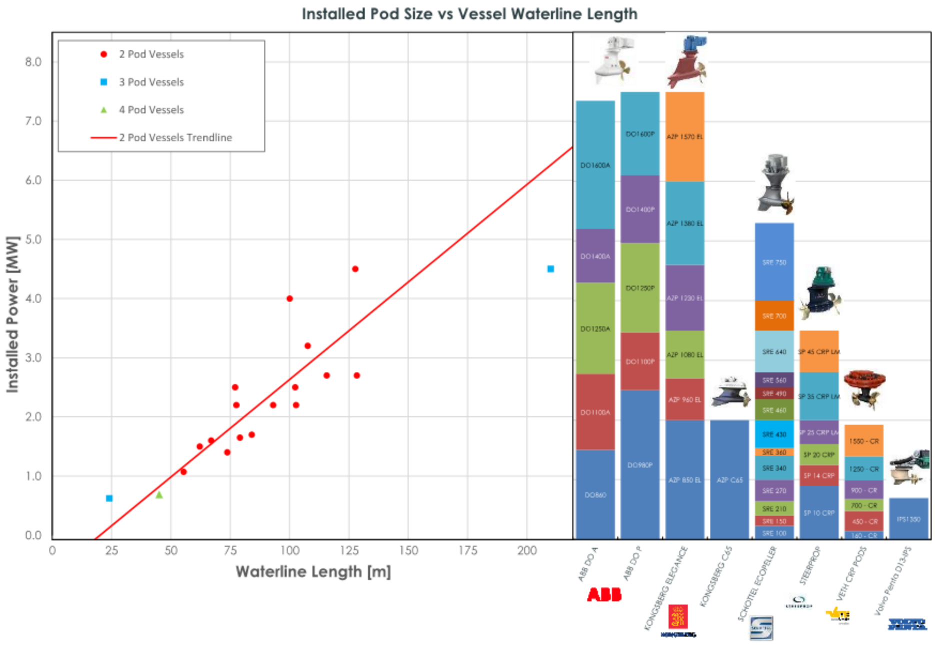


Figure 1 – Examples of PODs from Various Manufacturers & Waterline Length [m] vs POD Total Power [kW]

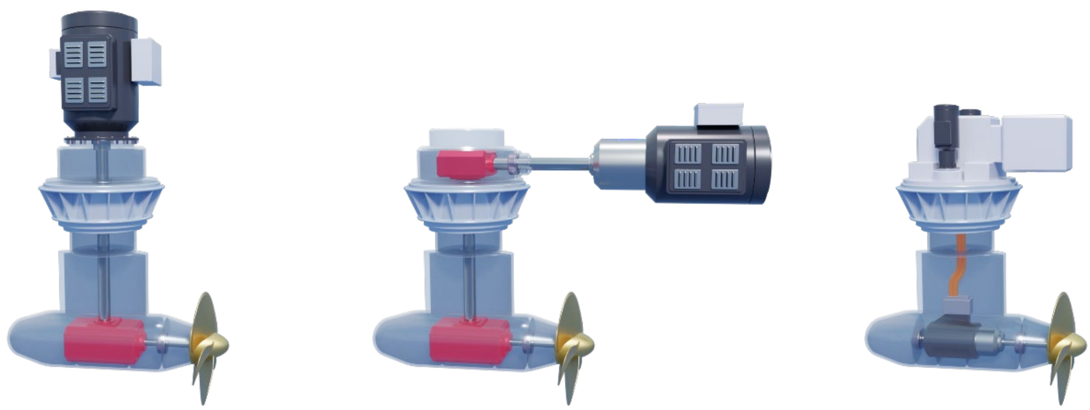
The main category by which PODs can be principally sorted is through the arrangement of the POD's power transmission from electrical generation through to the propeller. These two main categories are:

1. Mechanically gear driven propellers with electric motors mounted above.
2. Electric motors mounted within the propulsion module directly on the propeller shaft.

Mechanically driven PODs are categorized into two main shafting and gear configurations: Z-drive and L-drive, see Figure 2. In L-drive arrangements, the motor is mounted directly onto the top of the vertical shaft within the steering module. The motor itself can be distributed either horizontally or vertically. Z-drive arrangements introduce an additional change in transmission direction, with the motor mounted horizontally to the side of the steering module. The various configurations have potential advantages and dis-advantages for the development of a general arrangement.

PODs with electric motors mounted inside the propulsion module eliminates the need for gear transmissions, as the motor is directly connected to the shaft line that drives the propeller.

POD electric motors can also be split down into two main categories; Synchronous motors & asynchronous motors. Synchronous motors maintain rotor speed equal to the stators magnetic field. Generally, they use either permanent magnets or an excitation machine. Permanent magnets are mostly used with smaller inaccessible units, typically of PODs used on superyachts. Excitation machines are more typical for large high-power units where access to the components is simple, and a higher torque is needed. The other motor type, asynchronous motors or induction motors operate with a 'slip' between the rotor and stator files making them cost-effective for small to medium sized vessels, as well as offering simple, reliable and maintenance-free operation at the expense of slightly lower motor efficiency [2], [3].



L - Drive
Electic motor mounted above the steering module

Z - Drive
Electric motor mounted above the POD and to the side of steering module

Electric motor
in propulsion module

Figure 2 - Illustration of the Key POD Arrangements

The differing POD arrangements between the two main categories also lead to variations in propeller configurations. Electric motors mounted within the propulsion module are typically restricted to fixed pitch propellers (FPP). In contrast, mechanical configurations offer more flexibility, allowing for the use of controllable pitch propellers (CPP). CPP's are beneficial because the propeller pitch can be adjusted, allowing for optimal efficiency across different RPMs. This adjustment can improve fuel efficiency and the propeller's cavitation behaviour. However, to operate a CPP requires additional control systems inside the propulsion module which can mean larger or alternative geometry affecting the overall hydrodynamic efficiency of the POD.

There are also PODs on the market, such as the VETH [4] range which are fitted with contra rotating propellers (CRP). With this arrangement two propellers are mounted on the same axis, rotating in opposite directions, with the rear propeller working in tandem with the energised flow from the front propeller's swirl. The benefit from this arrangement is that these PODs can offer a higher power density than more conventional single propeller PODs, which is particularly beneficial for lower draught requirements.

A limitation of PODs is the reduced top speed capability when compared with shafted vessels. Figure 3 presents a selection of yachts from the global superyacht fleet, plotting vessel length against top speed from Lateral's Large Yacht Statistics Database. As examples of podded superyachts are relatively few until now, the available data points are limited. Two trend lines are displayed: one for yachts powered by PODs and another for those using conventional diesel mechanical shaft line propulsion. This shows that on average, similarly sized yachts equipped with PODs have a maximum speed 2 kn slower than those with shaft propulsion.

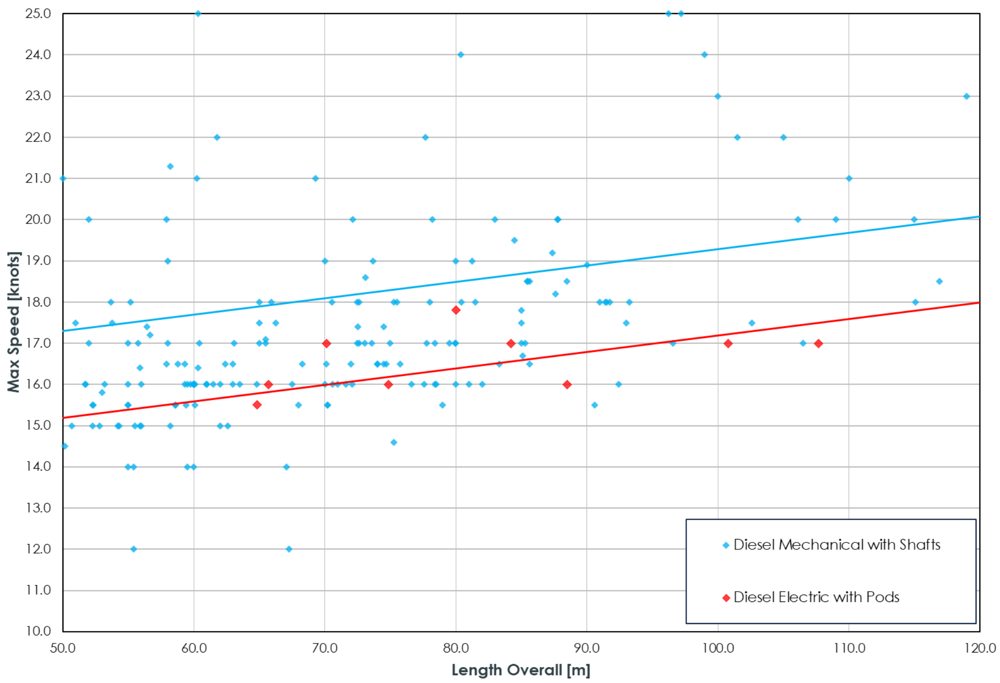


Figure 3 - [5], Speed vs Length, Diesel Mechanical with Shafts vs Diesel Electric with PODs

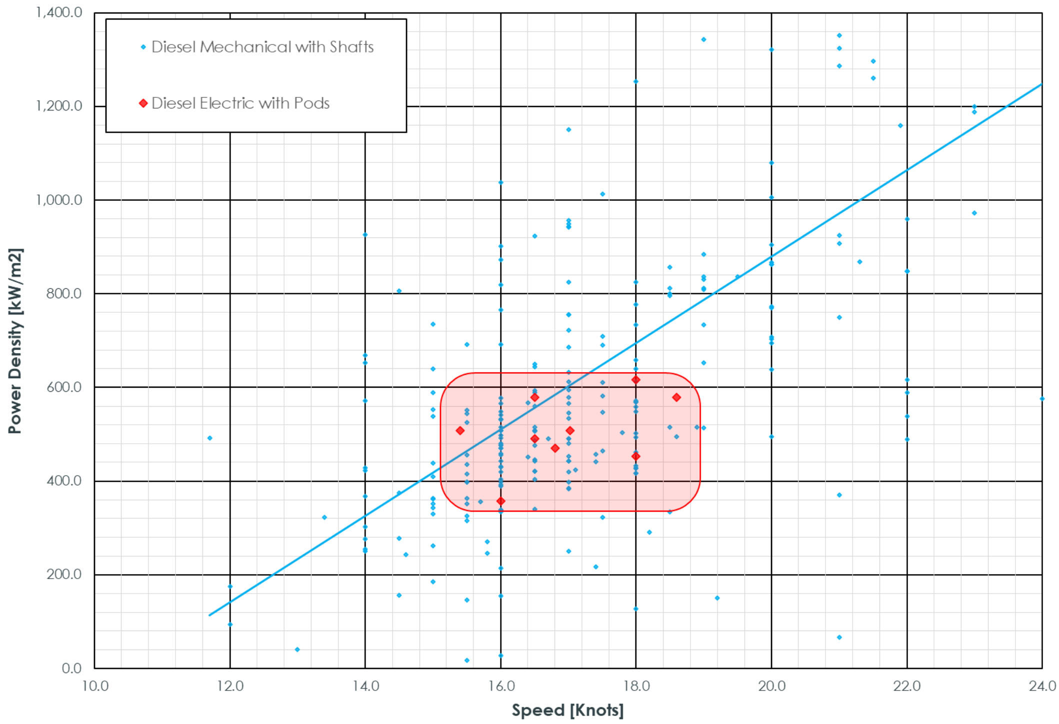


Figure 4 - Power Density vs Speed (Limit Line)

When evaluating the reduced top speed performance of vessels equipped with PODs and the power density of the propeller disc, it is evident that PODs typically reach a limit around 600 kW/m². In contrast, shafted vessels exhibit a much higher range of power densities (See Figure 4).

Lateral are not POD designers, but from our experience with implementing Podded solutions we see various factors that could be leading to power limitations of PODs. These include:

1. The strength of the POD strut related to the forces and moments generated from the propulsion. A larger, stronger strut will reduce the propulsive efficiency of the POD.
2. The propeller hubs on PODs tend to be large due to the internal gearing.
3. The propeller RPM in PODs tends to be higher than with shafts at a similar power: Looking at specific examples of Lateral's model tests, the propeller RPM of a POD tends to be around 12% - 15% higher.

Considering these various factors a balance needs to be achieved across various limitations in the design of the PODs.

For example, if high top speed is a priority for a client, and POD only propulsion is restricting the vessel capabilities, hybrid propulsor options can be possible.

3. Impacts on Hull Design Principles

A crucial factor for any vessel, including superyachts, is the underwater hull design, as it primarily affects resistance and seakeeping performance, but also influences the ship's overall efficiency and comfort. For superyachts, this balance is key to minimising environmental impact, running costs and enhancing onboard comfort for clients. This section outlines the key design considerations for optimizing POD integration across five main areas:

1. Draught Design Loop
2. Transom Design, Slamming & Seakeeping
3. POD Transverse Position & Rotational Constraints
4. Longitudinal Position & Buttock Shape
5. Weights

Draught Design Loop

A design consideration for yachts with PODs is the speed limitation due to the lower power density of PODs compared to shaft lines (See Figure 4). Superyachts often operate near coastlines, bays, and reefs, making draught an important design constraint.

With shaft line arrangements, it is easier to stay within draught limits while maximizing top speed, as the delivered power from the main engines and propeller design can be optimized for the best propulsive efficiency. Local hull modifications in way of the propellers for shafted vessels are also an option when draught limitations are imposed. In contrast, for podded propulsion, increasing delivered power typically requires a larger POD unit, which demands a deeper draught to remain above the hull baseline, and propeller tunnels are not an option.

If a deeper draught is not an option, which could be due to limits set in the contract based on operational area, or due to Naval Architecture principles relating to block coefficient, then the remaining option is to reduce the contract speed (See Figure 5).

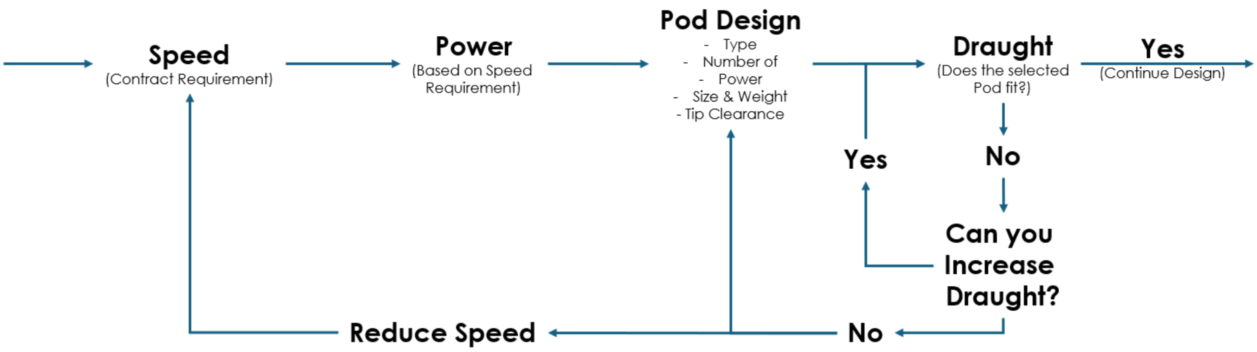


Figure 5 – Simplistic Draught Loop Visualisation

Transom Design, Slamming & Seakeeping

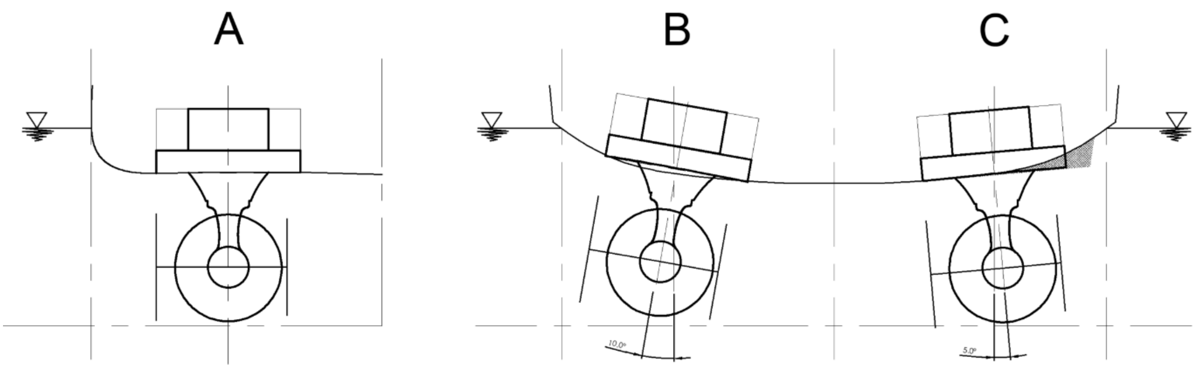


Figure 6 - Varying POD Arrangements & Section Shapes

An interesting design loop which stems from various requirements of PODs is the transom design, depth, immersed area, and overall shape. Transom and aftship hull design is key to performance and there is room for optimisation if there is design freedom in this area. A shaft line vessel can allow freedom in transom shape and design. However, POD integration requires a more prescribed section shape.

Figure 6, Arrangement A, shows the preferred hull design for POD mounting, with a U-shaped section with shallow deadrise angle and turn of bilges moved further outboard.

If the section shape has more upwards curvature and no obvious round of bilge, the PODs will be much more difficult to mount, and transverse POD tilt may have to be introduced to align with the shape of the section. This is more challenging from an installation point of view, and forces the machinery inside the ship closer together, taking up valuable room in the aftship, typically used for beach clubs and guest spaces on yachts.

If the section shape is too rounded, the additional tilt could cause angles which are outside of the manufacturer's recommendations, as Arrangement B shows. Reducing this tilt angle to within an acceptable range would require the addition of a fairing piece or header box, as shown by the hatching in Arrangement C. Based on Lateral's experience, this can add in the region of 1 - 2% resistance,

For the avoidance of stern slamming, the same transom design principles apply for both shaft line driven and podded yachts. Avoiding shallow, flat section shapes is key to minimising slamming. This is more challenging for podded yachts where there is a need to mount PODs on a flatter section shape.

The obvious solution to this is to make the transom deeper, thus avoiding any emergence in waves. However, deeper transoms can be directly linked to increased resistance, and a deeper hull would give less available space to fit a POD within the desired draught. A fine balance needs to be struck between minimizing transom immersion for better performance but avoiding being too shallow and inducing slamming instances which will cause vibration throughout the vessel.

Transverse Position & Rotational Constraints

Finding a balance for the transverse position of the PODs is an important design consideration. The units themselves can be quite long, so when they are rotated 90 deg for sideways thrust, they can span a large width of the ship. The example arrangements in Figure 6 shows the extents of the PODs and propellers when rotated, and the local beam waterline constraint. It is important to avoid any clashes between the PODs themselves when rotating, and so pushing the PODs further apart transversely seems to be the obvious solution. It is also beneficial to increase the separation between the POD units to enhance manoeuvring and improved dynamic positioning capabilities, a key benefit of PODs. However, the separation between the units is limited by the envelope through which the propulsors can rotate within, and this should not exceed the local beam waterline of the vessel. As with a typical superyacht arrangement, bathing platforms and tender garages are near to the propulsors where guests and crew could be operating, and therefore keeping the propulsor arrangement within the design guidelines is important. Striking this balance becomes more challenging with a narrower beam or a design with a tapered transom.

Longitudinal Position & Buttock Shape

PODs require a dedicated technical space within the yacht's hull to house supporting systems. This space needs adequate headroom for maintenance, which often pushes the POD unit further forward in the hull. Aligning the POD with the hull buttock shape is important because many manufacturers will specify limits on the “tilt” angle of the POD. Typically, Lateral will initially position the POD with a tilt angle at half the buttock angle for best alignment to the flow.

As PODs tend to operate in a "pull" arrangement, with propellers in front of the unit, the resulting propeller position is further forward than a typical shaft line vessel. This pushes the buttock lines in the aftship further forward which can have an influence on the longitudinal centre of buoyancy (LCB) optimisation.

Weight

Anecdotally it is widely accepted that DE propulsion architectures are heavier than DM ones. To make an assessment Lateral have looked at two vessels of similar GT with comparable top speeds. Figure 7 compares systems that contribute to the two different arrangements; one vessel is a conventional DM with shaft line and rudder (Vessel A), the other is a DE with PODs (Vessel B).

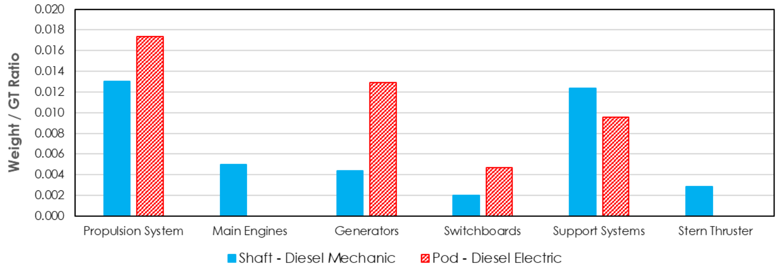


Figure 7 - Weight / GT Ratio Comparison Between DM Shaft & DE Pod Systems

Combining all the weights together shows the propulsion system on Vessel A contributes to 0.40 t/GT, whereas on Vessel B the system is 0.45 t/GT, confirming the DE POD propulsion is heavier in this example. The main differences lie in the propulsion systems, main engine, generators and stern thruster. The propulsion system for Vessel A includes the shaft lines, propellors, gearbox and steering system, whereas the Vessel B includes only the main POD unit, propeller and steering module. This not only shows that a POD arrangement is more weight dense, but also the weight distribution is more focused to the aft POD spaces.

For the main engines and generators, with Vessel A, alternators are only required on the hotel generators. With Vessel B additional alternators are required on all engine blocks. This increases the weight of the generator system, meaning cumulatively a higher weight in total. There are also additional switchboards and power management equipment needed to control the electric load transferred through to the PODs.

An area where Vessel A is heavier is the stern thruster for manoeuvring. Due to the excellent station keeping qualities experienced with PODs, there is no need for stern thrusters which are large and heavy units.

Figure 7 does not show how structural arrangements impact a vessel's weight. PODs transmit thrust in all directions due to their 360° rotation, requiring the POD ring above the propulsion module to be reinforced to handle the dynamic loads and moments. These forces differ from the linear forces typically seen with traditional shaft lines and thrust blocks. While it's challenging to determine which structural setup is heavier, changes in weight distribution and the location of the vessel's longitudinal centre of gravity (LCG) can affect hull design.

Design Verification & Model Testing

Due to recent advancements in CFD capability, much of the optimisation process for resistance and propeller design can be done numerically, and this too can now be expanded to include

POD arrangements. Due to the complexities of POD integration and performance, CFD has in fact become essential in the design process. However, it is still possible to make use of model testing for final design verification.

For shaft lines model test facilities have a large array of stock propellers and parts which can be called upon for different designs as required, giving a good match between model test setup and real world. For PODs, this is a little less simple as it is not only the propeller, but also the POD unit which needs to be provided, and at the correct scale. Therefore, there can be limitations on what model testing can be done on stock units, without the added cost of making a bespoke POD housing and propeller model for the yacht in design.

4. Resistance AND Efficiencies

Comparison of performance between podded and shaft line vessels is complex because of the various components which make up the required power demand and a holistic approach must be taken considering the following concurrently:

1. Bare Hull Resistance
2. Appendage Resistance
3. Propulsive Efficiencies & Power Delivered
4. System Losses
5. Brake Power at the Power Source

To aid discussion, two vessels have been assessed; Vessel A is powered by 2 main diesel engines as the power source. It is a DM yacht with 2 shaft lines (incl. shaft brackets and rudders) coupled to the main engine through a gearbox. Vessel B is a POD driven DE yacht, with diesel generators as the power source. It has a modern DC grid electric architecture, although an AC system would also be viable. Both vessels are assessed over a sensible operational speed range for an 88m yacht.

The propulsion power demand (required brake power at the power source) is a robust method to make a comparison as it considers the resistance, propulsive efficiencies and system losses of Vessel A vs Vessel B.

<u>Bare Hull Resistance</u>

The starting point for assessing any ship's required brake power is its bare hull resistance. This can vary with different propulsion systems due to their associated weight and distribution differences which result in varied hydrostatics that can affect bare hull resistance. For this assessment however, it has been assumed Vessel A and Vessel B have the same bare hull resistance.

<u>Appendage Resistance</u>

The added resistance due to the appendages varies between shaft line yachts and podded yachts. In Lateral's model testing experience, the absence of a shaft, A & P brackets, and rudders on podded vessels can reduce the appendage resistance by up to 50% depending on the rest of the arrangement. This variation in appendage resistance across the speed range is illustrated in Figure 8. In the case of Vessel B, a total resistance reduction of approximately 8% is observed at top speed in this example.

Furthermore, some arrangements of PODs will require a header box, which may be supplied as standard by the manufacturer. In Lateral's experience, these can increase resistance by 1-2%. A header box is considered in Vessel B's resistance.

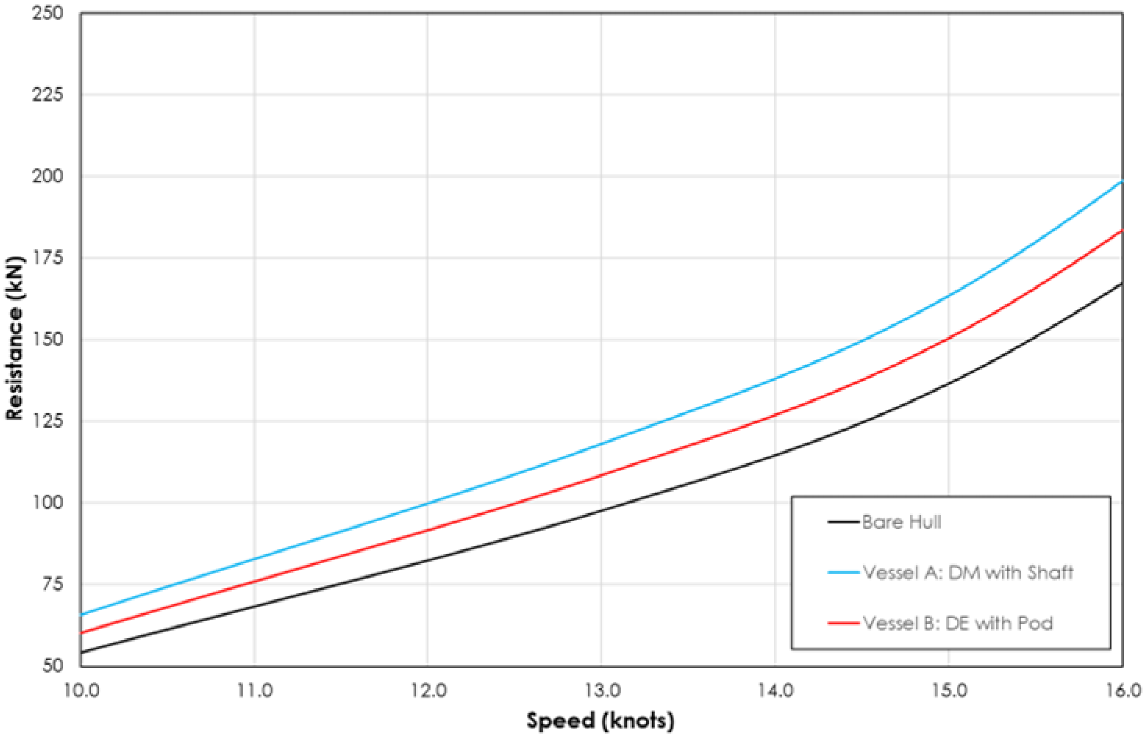


Figure 8 - Resistance Comparison; Bare hull, Appended Vessel A & Appended Vessel B

Propulsive Efficiencies & Delivered Power

To convert total resistance to delivered power at the propulsor, we must consider the propulsive coefficients which make up the total propulsive efficiency. Total propulsive efficiency, or Quasi Propulsive Coefficient (QPC) is considered as the combination of: Hull, rotative, and open water efficiency. Figure 9 shows a comparison of the QPC of 6 various POD types suitable for Vessel B as a percentage of an example fixed pitch propeller shaft line system, suitable for Vessel A. The shaded blue section shows the spread of the upper and lower QPCs stated by the various suppliers. Other PODs may offer QPC efficiencies outside of this range.

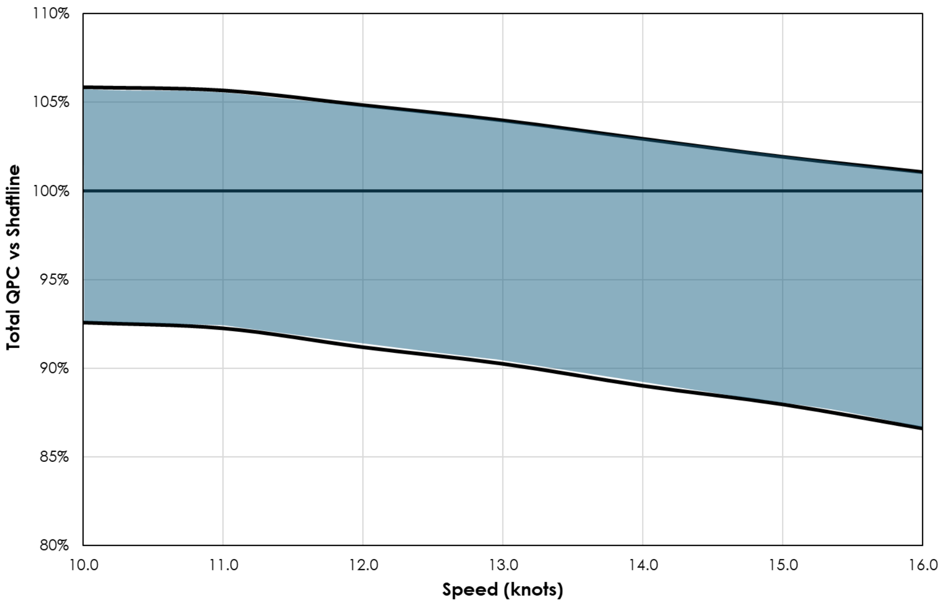


Figure 9 - A Spread of Speed vs QPC of 6 Various POD Units Compared to a Conventional Shaft line

Figure 9 shows a wide variation of POD QPC, with a spread of up to 15% and a notable decline compared to the shaft line as speed increases.

These observations can be explained by one of, or a combination of the following:

1. Resistance of the POD unit is accounted in the QPC for the 6 POD types.
2. Design & geometry of the POD unit will influence QPC, for example:
    - Strut length, width & chord (aspect ratio).
    - Motor position. PODs units with electric motors in the propulsion module tend to be larger.
    - Hub design off the propulsion module.
    - Twist of the strut.
    - Variation of fins and appendages attached to the POD unit.
3. In general POD on superyachts tend to operate in a "pull" mode which means undisturbed flow can enter the propellers leading to better rotative efficiency [6].

4. Across many podded projects, Lateral have observed that open water efficiency tends to reduce through this speed range, unlike a shaft line.

In relation to point 1, it should be noted that suppliers typically consider the resistance of the POD unit within the QPC. This approach does not compare with shaft lines, where the resistance from the shaft line and support bracket is accounted for in the appendage resistance.

In general, Figure 9 highlights the wide variety in QPC performance from various POD suppliers. It is the responsibility of the Naval Architect to advise the client on the most suitable arrangement for each specific superyacht on a case-by-case basis and consider the advantages and disadvantages where appropriate.

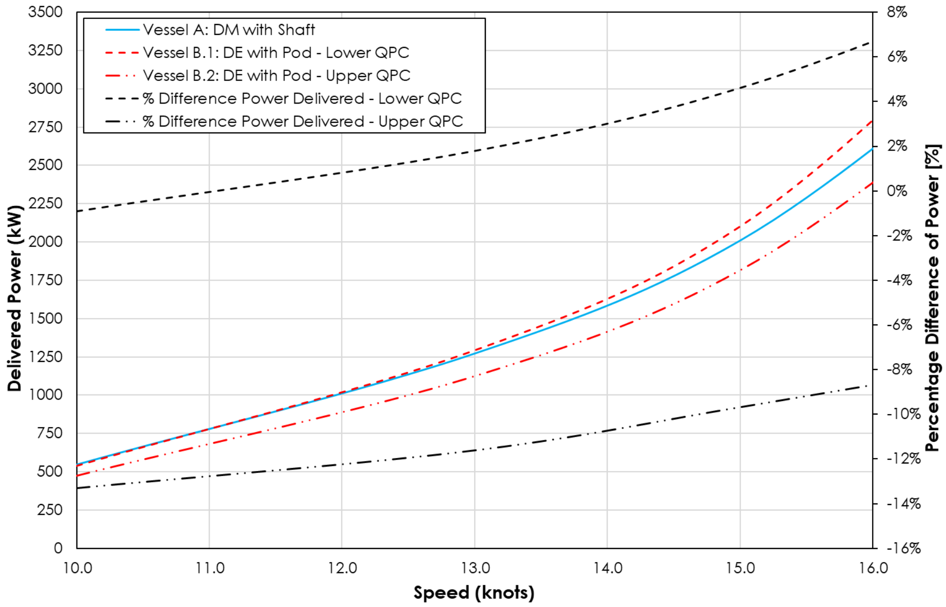


Figure 10 – Delivered Power at the Propulsor, Vessel A vs Vessel B

In Figure 10, the upper and lower QPCs for the 6 PODs selected have been applied to generate two curves for delivered power for Vessel B. With the low QPC efficiency, Vessel B.1 requires 0 - 6% more delivered power across the speed range compared to Vessel A. With the high QPC efficiency, Vessel B.2 requires 8 - 14% less delivered Power. This variation highlights the importance of understanding the individual components of QPC, and the impact various PODs have on the delivered power requirements.

<u>System Losses</u>

The focus of this paper is electric POD propulsion. To make a fair comparison it is therefore important to calculate the final break power demand at the power source, to consider the effect of various losses.

For Vessel A both gearbox and shaft line mechanical losses are present which equates to approximately 3%.

For Vessel B, the system losses are broken down into two components, mechanical and electrical losses. Mechanical loses for shafts and gears within the POD are in the range of 0.5% to 4% depending on the POD configuration: direct, L-drive or Z-drive. For the electrical system there are losses due to power generation, distribution and conversion. In Lateral's experience this can be in the region of 6 to 10% for a DE system [7]. It should be noted that electrical efficiencies have been improving, and so these system losses are likely to reduce in the future.

Brake Power at the Power Source

Figure 11 shows the final comparison of the required brake power at the power source for Vessel A at the main engines and Vessel B at the generators.

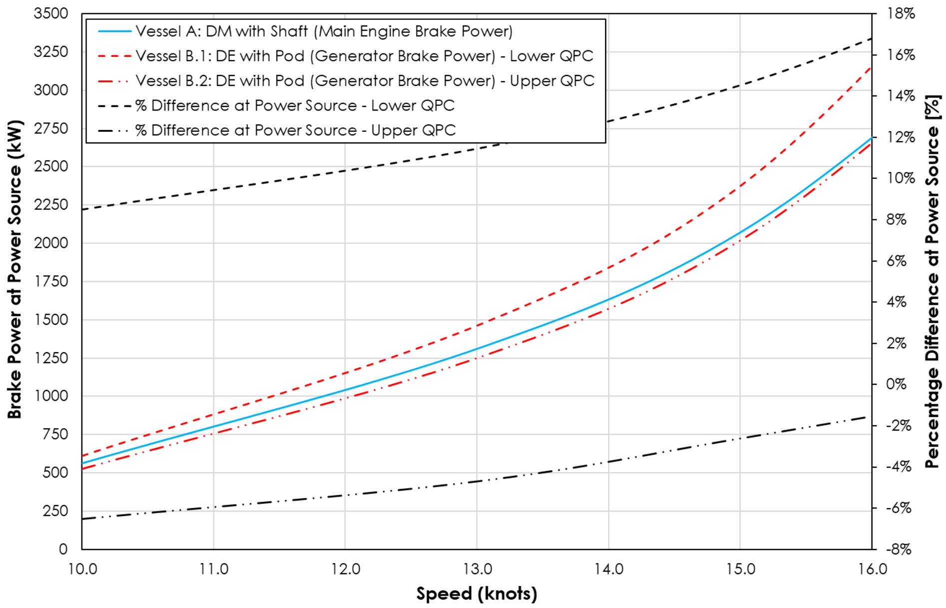


Figure 11 - Propulsive Brake Power, Vessel A vs Vessel B.1 vs Vessel B.2

Figure 10 showed that power delivered to the propellers for Vessel B can be more or less than Vessel A depending on the POD selection. Once system losses are considered, Vessel A & Vessel B.2 show negligible difference in brake power demand. However, Vessel B.1 shows an 8% - 17% increase in brake power required across the speed range.

In this example, the analysis shows that a carefully selected electric POD can achieve a similar propulsion brake power demand as a shaft line configuration. But across the range of 6 PODs investigated, it can be seen that generally the power demand of DE PODs is higher than DM shafts. While the comparison of brake power is a robust approach, there are additional factors that fall outside the scope of this paper. A complete comparison should consider the type, efficiency and operation of the power generation system, as well as how the energy is supplied. This includes consideration of engine loading and specific fuel consumption, use of energy storage systems, as well as renewable power sources and future fuels. These factors are heavily dependent on the operational profile of each individual superyacht and should be evaluated on a case-by-case basis.

5. Noise, Vibration & Structural Considerations

Minimising noise and vibration (N&V) is an important aspect of technical superyacht design. PODs are installed with large, complex seating design in the aftship, usually in areas limited in space and with large shell openings in close proximity.

Structural stiffness and loads transferred from the propeller thrust are a key structural design consideration. For PODs, all loads are applied at the aft end of the yacht, and with 360 degrees of rotation. Contrast this to shafted arrangements where the thrust loads are applied in a linear direction, and closer to the midbody of the yacht where foundation stiffness is generally not an issue. POD integration structural design can therefore be more challenging, with complex Finite Element Analysis (FEA) models required for assessment. Vertical hull stiffness can also be a challenge for PODs as the structure depth is limited by the transom shape and depth, as well as openings at the aft end which are common in superyacht arrangements (See Figure 12).

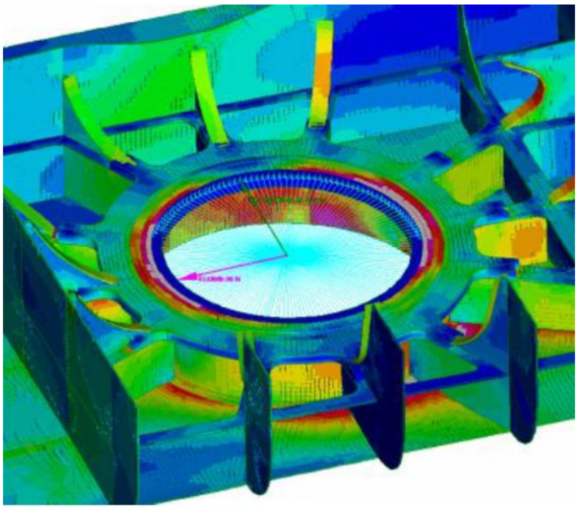


Figure 12 - An Example of POD Foundations

Propulsion systems are regarded as a major source of N&V on yachts. PODs can offer low noise propulsion benefits, especially in units where the motor and shaft is contained underwater within the propulsion module and outside of the yacht. Additionally, the placement of PODs concentrates the cyclic thrust loads within the aft section of the ship, away from typical guest living quarters. With long shaft lines, the mechanical noise is transmitted into the hull via bearings and gearboxes which can be more prone to vibration issues. Overtime, misalignment, shaft imbalance and wear within the bearings can exacerbate any small vibrations, which may be amplified within guest spaces located closer towards the middle of the vessel. PODs, with their external, local mounting and lack of a long shaft line, typically leads to lower vibration levels, though careful design and mounting are required to manage localised vibrations from the PODs themselves [7]. Local N&V characteristics for PODs are related to the specific type and design of the unit, considering the shafting, gearing, mounting and motor location.

Propellers are another source of N&V, and the most effective way to minimize their impact is by reducing the pressure pulses transmitted to the hull. With a lower power density and good tip clearance, pressure pulses can be minimised. Since PODs typically have lower power density than shaft lines and POD designs can allow for variations in strut length, tip clearance can be optimized to achieve the desired effect. For vessels with the most stringent N&V requirements, Lateral targets a tip clearance of 35-40% of the propeller diameter to the hull.

Large, shafted displacement vessels that require dynamic positioning typically have stern thrusters to assist the main propulsion. As shown in Section 6, the higher station keeping performance of podded vessels will result in less power being used. The combination of less power from the main propulsion, and no stern thruster gives improved N&V.

The design of the POD itself can also influence vibration levels. Hydrodynamic optimisation of the propulsion module reduces turbulence and flow separation, which are key contributors to vibration. Streamlining the shape of the POD helps reduce vibration-inducing forces during operation.

As PODs are electric, they can be paired with DE energy architecture arrangements which can offer many ways to improve N&V benefits over DM arrangements, examples such as energy storage systems, periods of silent operation, enhanced resilient mounting and generator soundboxes to name a few.

6. Manoeuvring and Station Keeping Capability

A key advantage with PODs is the ability to direct thrust in any direction via 360 deg rotation, greatly improving station-keeping and precise manoeuvring, particularly for superyachts operating at anchor or in tight spaces like harbours, enhancing the captain's confidence, operational window and overall onboard experience in higher winds or current. Recent local trends for protection of coastal seabed’s is also driving alternatives to traditional anchoring, such as dynamic positioning.

Vessels equipped with PODs can exhibit superior manoeuvring capabilities compared to those with a shaft line-rudder system, especially at slow speeds. The absence of shaft line, A and P brackets reduces thrust interference, allowing for better thrust generation through a full 360 degrees rotation. Twin POD arrangements can be vectored independently from one another, which leads to improved control during harbour manoeuvres or dynamic positioning operations. For twin fixed shaft line-rudder arrangements the rudders are typically synchronised, meaning that thrust can only be vectored in one direction when helm angle is changed. During slow speed manoeuvring, the rudder only becomes effective when flow across the blade is produced by the thrust generated upstream from the main propeller. As the helm angle is changed to direct the thrust, the water flow becomes misaligned, reducing the effective thrust and ultimately can limit the vessels capability to manoeuvre at slow speeds [8]. When manoeuvring astern with a shaft-rudder arrangement, the effectiveness of a rudder is greatly reduced as the flow over the rudder is slow [9]. There are various reasons PODs provide superior manoeuvring control.

There are also differences between the two arrangements when underway. The improved turning capabilities of podded propulsion have been confirmed through full-scale, full-speed turning circle tests conducted on sister ships—MS *Fantasy* (with conventional propulsion) and MS *Elation* (with podded propulsion). The tests revealed that the POD equipped ship achieved a 38% reduction in tactical diameter, demonstrating significantly enhanced manoeuvrability [10]. This full-scale test has been further verified from Laterals model test experience, where a 36% reduction in tactical diameter was calculated between a conventional shafted vessel and a similar size podded vessel.

Directional instability is a risk with vessels that exhibit excellent manoeuvrability, something that podded superyachts can experience. However, to improve directionally stability generally results reduced turning ability and therefore there is a balance in design required. For a shafted vessel, increasing the movable rudder area will have the largest effect to improve directional stability, something that is not possible with a POD geometry, fixed in design by the manufacturer [9]. From Lateral's experience good POD placement, and sufficient skeg geometry provides sufficient directional stability.

PODs enhance station-keeping performance across the entire 360 deg wind angle spectrum by effectively vectoring thrust in any direction. For comparison, two vessels of equal length & gross tonnage have been assessed through Lateral's dynamic positioning and station keeping tool. Vessel A is a twin shaft-rudder arrangement with a single azimuthing stern thruster and bow thruster. Vessel B is a twin POD arrangement with a single bow thruster. To ensure a fair comparison, the vessels propulsion systems are sized to achieve the same top speed capability and then a 25% MCR power limit is applied to both arrangements in the bollard pull condition. The bow thruster for both arrangements was kept the same. The stern thruster for Vessel A is based on similar vessels, where the size is typically limited due to practical constraints.

As shown in Figure 13, Vessel B has slightly better station keeping performance than Vessel A in wind angles from 0 deg to 70 deg, though they are quite similar as Vessel A is still able to rotate their rudders, in this case limited to 35 deg helm angle to help direct the thrust to support the head wind station keeping performance. However, this results in approximately 40% side thrust compared to the maximum ahead bollard pull thrust [10]. In wind angles greater than 70 deg, and up to 180 deg, Vessel B can hold station in wind speeds up to 30% higher than Vessel A, due to the 360 deg thrust vectoring capability of the PODs.

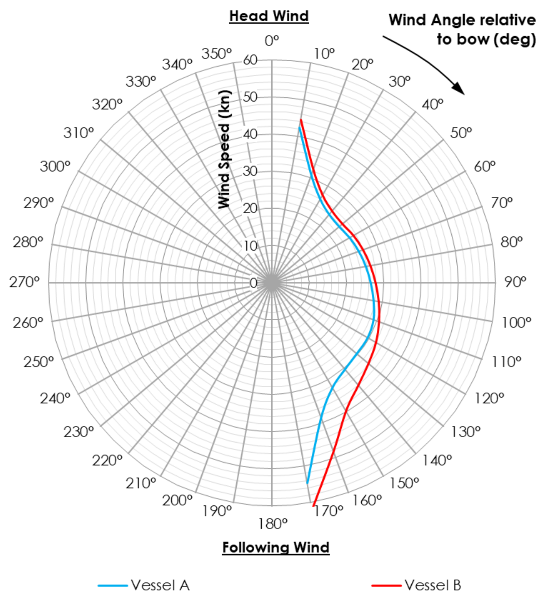
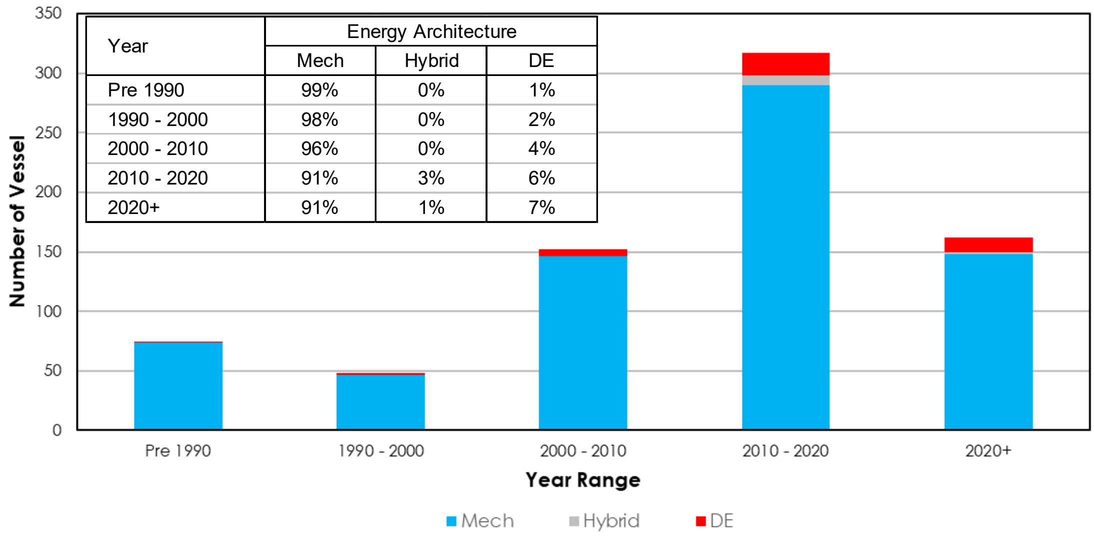


Figure 13 – Polar Plot Comparison; Vessel A Vs. Vessel B

7. Flexibility In Superyacht Design

The evolution of different propulsion systems can enable enhanced flexibility to superyacht design, but there are also limitations and implications on general arrangements that must be considered.



Year	Energy Architecture		
	Mech	Hybrid	DE
Pre 1990	99%	0%	1%
1990 - 2000	98%	0%	2%
2000 - 2010	96%	0%	4%
2010 - 2020	91%	3%	6%
2020+	91%	1%	7%

Figure 14 – Popularity of DE Architecture Systems in Superyacht Design [5]

As shown in Figure 14, DE systems are becoming evidently more popular on superyachts. Between 2010 and 2020, they made up 6% of the global market of new builds. This has already been surpassed from 2020 onwards. Within this range, a majority are using PODs as the main propulsor.

A key design benefit is that electric PODs can be disconnected from the engine room as no shaft line is required. Freedom of engine room position opens significant possibilities for yacht layout design. The source of electric power can also be split into multiple smaller components including diesel generators, and energy storage systems. This can lead to alternative technical space distributions such as split or single tier engine room arrangements, providing positive benefits to guest spaces such as beach clubs and spa & wellness spaces on the lower decks.

PODs also eliminate the need for stern thrusters, which are large units that encroach on tank deck technical spaces. Removing them frees up technical space on the tank deck, which in turn helps to maximize interior space above the waterline.

PODs can however be intrusive in the vessel's general arrangement as they are often large and can protrude into areas like the beach club above. Designers must account for technical spaces, known as "POD Rooms," located directly above the steering module to house the additional equipment needed to support the POD system. The size of these spaces depends on the POD's power, transmission configuration and cooling requirements. The transverse position of the PODs and POD rooms can also interfere with exterior staircases connecting the main deck to the swim platform, as well as stern passerelles. Addressing these design challenges early in the conceptual phase is essential for feasibility.

While POD rooms can affect the beach club layout, designers are finding innovative solutions to improve arrangements. Lateral's Free From Bulkheads (FFB) concept reimagines the lower deck by increasing the freeboard compared to conventional vessels of similar size. This approach minimizes the impact of tank deck technical spaces and eliminates the need for watertight bulkheads on the lower deck. The increased freeboard allows PODs and POD rooms to fit below the lower deck, enabling the beach club layout to be optimised for client needs, enhancing the functionality of podded vessels (See Figure 15) [11] [12].

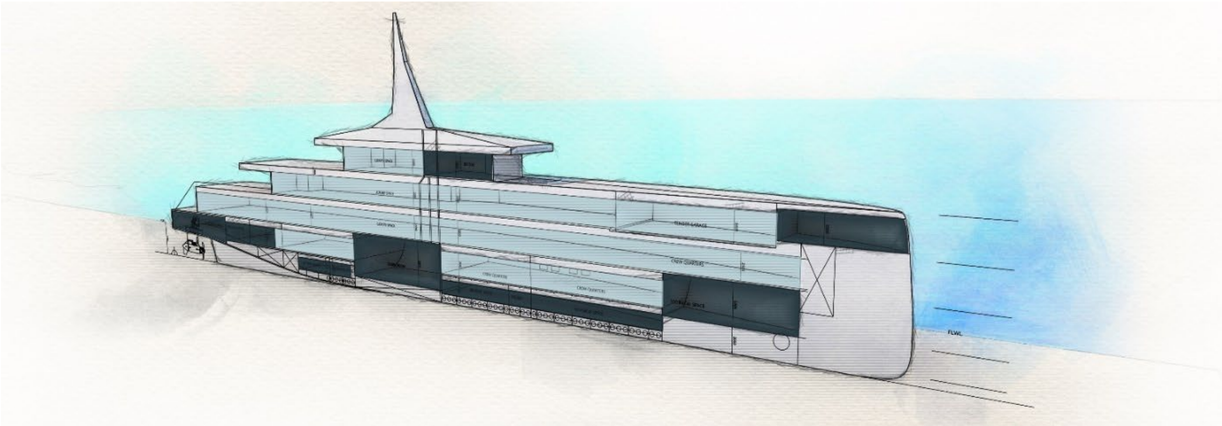


Figure 15 – Lateral's FFB concept

Though PODs are less power dense than a traditional mechanical shaft line arrangement which can limit the top speed of the vessel, Hybrid propulsion arrangements are possible. Arrangements could be two shafts, with one centreline POD, or vice versa as seen on the OPV Turva [13], an offshore support vessel with two PODs and one central shaft line. The hybrid arrangement allows for excellent manoeuvrability at slow speeds and enhanced top speed motoring compared to POD only arrangements.

8. Conclusions

This paper has explored the integration of electric podded propulsion in superyachts, demonstrating the wide variety of options available on the market and how PODs can be a viable alternative to the traditional rudder and shaft line setup for providing primary propulsion and enhanced manoeuvring capabilities.

The integration of PODs presents several unique design challenges and considerations for superyacht hull design. The balance between POD power and draught limitations requires early design assessment, particularly when constrained by operational area or contract specifications. Additionally, transom shape and aftship hull design must accommodate POD installation while optimizing seakeeping and minimizing slamming. POD positioning, both longitudinally and transversely, impacts manoeuvrability and weight distribution, with further considerations needed for system architecture and space for POD support systems. Ultimately, designing around PODs necessitates a holistic approach to achieve performance, efficiency, and operational constraints, while managing the trade-offs in draught, weight, and hull shape.

A comparison has been made of the required delivered power, and propulsion brake power demand, between an example 88m DM shaft driven yacht and a DE podded yacht. While the presented example shows that the electric PODs require equivalent or less propeller delivered power than the shafts, once losses are considered they have an equivalent or higher brake power demand across the speed range. The authors acknowledge that there are many other factors to study when considering the overall propulsion performance of a DE podded system. These factors include how the power is supplied (energy architecture) and operational profile of the yacht. These considerations can provide advantages not considered in this paper and needs to be assessed on a case-by-case basis for yacht projects.

The various impacts on noise and vibration levels from both PODs and shafts has been compared. While the installation and structural stiffness requirements needed for PODs can be challenging, the aft positioning of PODs and their low power density can help keep N&V low and away from guest areas, making them a good option for yachts with strict N&V requirements.

PODs provide a significant advantage for manoeuvrability due to the 360 deg thrust rotation, enhancing station-keeping and enabling precise manoeuvrability. Compared to traditional shaft line-rudder systems, PODs improve slow-speed manoeuvrability, as they generate better thrust without the limitations of helm angle. Underway model tests show PODs provide superior turning performance, reducing the tactical diameter by over 36%. However, while PODs improve manoeuvrability, avoiding the possibility of directional instability needs to be balanced in the design.

The adoption of electric PODs in superyachts has allowed increased flexibility in design. DE systems offer advantages like decoupled engines which can allow flexible engine room location and configurations. This can enhance guest spaces and re-locate noise source. Though PODs eliminate the need for stern thrusters, freeing up technical space in the aftship, they can complicate general arrangements due to their size and the need for additional "POD Rooms" which can impact beach club and aftship design. Understanding the various direct, L-drive and Z-drive configurations is important to help designers find innovative solutions to these challenges, as well as looking at hybrid propulsion setups with the aim to balance manoeuvrability while enhancing top speed capabilities.

While shaft lines are still the leading form of propulsion, with a move to electric energy architecture systems, drive to net-zero and increased environmental responsibility, electric PODs are becoming a compelling avenue in the large luxury superyacht market and should be considered in the early conceptual design for new projects.

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