The Future Warship – A Scoping Study.

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Synopsis

The current maritime defence sector is held back by a risk averse attitude to technology uptake. This is starting to change in the use of autonomous systems, however this is at the expense of other more wide reaching technologies. In this paper several promising technologies are applied to a frigate design dubbed E-SPARTAN, and their effect compared to a baseline frigate concept, SPARTAN. The designs are then compared across key metrics such as capability, sustainability, through life cost and stability.

The technologies investigated were the large-scale adoption of composites and sustainable propulsion options based on an Integrated Fully Electric (IFE) propulsion system. Through rules based structural design the use of composites was demonstrated to save at least 50% of the structural weight in a like for like comparison, equating to up to 22% of lightship. This weight saving facilitated the increase in mass of the IFE propulsion system, in addition to a 240t battery bank to allow peak shaving and silent running. Alternative fuels were investigated and biodiesel was found to the most effective alternative fuel, increasing engine performance whilst being a sustainable product, producing low emissions and facilitating the use of Marine Diesel Oil (MDO) in operational areas where biodiesel is not available. Other commonly discussed alternatives such as batteries and hydrogen were found to require too large a storage volume and/or mass to be viable for the existing mission profile. The vessel operating costs were shown to be less than the equivalent conventional frigate, this is due to a reduction in non-attributable growth, a reduction in hull maintenance and the flexibility of upgrading an IFE solution.

Overall the changes gave additional capability, with added design and operational flexibility, both key to a cost effective general purpose frigate (GPF). The structure requires less maintenance, due to a reduction in fatigue and corrosion. The build would be more technically challenging, requiring upskilling of the workforce for composite construction, however with life cycle savings circa £21.5M. The proposed changes constitute a stability improvement due to a lower center of gravity and the opportunity to locally optimize the layup and materials to improve survivability and signatures. The design provides additional capability due to signature reduction and silent running, both key for central frigate roles such as mine counter measures (MCM) and anti-submarine warfare (ASW), as well as providing additional sustainability credentials and facilitating operation in emissions controlled areas.

The authors conclude that the implementation of such a radical concept would entail upskilling of the ship construction workforce, but the benefits of such a solution are seen across capability, flexibility and through life cost when considered over a class of vessels.

Keywords: Sustainable, Net Zero, Alternative fuels, Composite, Battery, Integrated Full Electric

Authors' Biographies

Alec Lynn-Rodgers is Chief Engineer – Surface Ships at Steller Systems and a Chartered Engineer. He is a naval architect specialising in optimised marine structures, with a focus on composites and novel manufacture. Alec has experience with RN and RFA assets across the CADMID cycle, from concept through to life extension.

Amy Potter is a Naval Architect at Steller Systems and associate member of RINA. Amy has worked on numerous concept designs since joining Steller Systems after graduating with a Masters in Naval Architecture from Newcastle University. Amy has a particular focus on the application of net zero technologies including IFE, hydrogen and batteries.

Paul Gliddon is a Principal Naval Architect at Steller Systems and a Chartered Engineer. He has experience of the design process from concept design through to build of various naval platforms. In recent years Paul has applied novel optimisation methods and technologies to hull forms to improve fuel efficiency.

David Pearson is a Principal Marine Engineer at Steller Systems and Chartered Engineer. He has experience in a wide range of marine systems, specialising in auxiliaries, and has worked on RN surface and submarine vessels, along with the RFA. David has a particular focus on energy saving technologies in the commercial sector, particularly wind power and energy recovery devices.

Alex Pardoe is a Naval Architect at Steller Systems and associate member of RINA. Alex has worked on several concept designs for UXVs and landing craft with Steller Systems, including construction and trials for Steller's own UXV. He has wide experience in arrangement design in 2D and 3D, including graphical representations of early stage models.

Rick Goddard is the Mechanical Engineering Lead at an R&D company, previously Chief Engineer – Surface Ships at Steller Systems. A Chartered Engineer, he has a background in novel Naval concept development and ship design, focused on stability certification from his time in the Naval Authority Stability Section prior to joining Steller Systems.

1. Introduction

1.1. Innovation Across Defence

Some aspects of defence drive innovation, however in the naval surface ship sector innovation is commonly first seen in industry until well proven and low risk. At this point the naval defence sector absorbs the relevant technologies. Examples of this are wide reaching, from implementation of UXVs to the use of high modulus polyethylene (HMPE) cordage. As assets become larger, a lower level of risk is accepted by the end customer. This means that capital warships are one of the most conservative assets, with limited advances in structural manufacture since the inception of steel warships and only the two newest classes of capital warship in the RN using diesel electric propulsion. This risk-averse attitude is unsurprising given the investment for a new class of warship. However, this provides an opening for other nations to take advantage of technologies to leapfrog western platform capability. The authors hypothesise that for the UK and NATO to remain naval powers they must leverage new technologies to enhance platform capability. The traditional risk-averse approach should be replaced by an agile risk aware approach to procurement and development. This would facilitate rapid platform development, alongside driving technological advancement.

1.2. Opportunities for New Technology

In the past it has been shown that the conservative nature of the industry can be overcome. However, the benefits of technology are commonly hampered by the use of a siloed approach to design. Subject areas are designed and assessed independently, facilitating qualification through specialist areas in the Naval Authority Technical Group. This provides satisfactory results where the design space is well understood. However, it means that emerging technologies are only considered within individual siloes. This can limit the uptake of new technologies with little impact on one silo, but large impacts over the whole design.

If a holistic approach to benefit across the platform is used then the true technological benefits can be seen. As such, in this paper the authors explore the benefits of several novel technologies in the context of warship design. Their effect across the platform design space is assessed to quantify their effect on capability and provide an insight into how they may be leveraged in the future warship.

1.2.1. Composites

Warships are almost exclusively of steel construction, particularly from offshore patrol vessel (OPV) size upwards. The exceptions are specialised vessels like the Hunt and Sandown Classes, where composites are selected primarily to reduce magnetic signature. The large-scale adoption of composites has not been considered technically or financially viable, with the majority of composite vessels <40m in length. Recently, advances in composite manufacture allow single-piece moulding of >100m long offshore wind turbine blades (Mason, 2019). The financial viability of such mouldings for many applications remains questionable due to mould costs combined with limited confidence in procurement and therefore production runs. Wind turbine manufacturers can justify the mould cost due to large production runs and the confidence in sector growth. In general, the lower actual manufacture cost for composites versus steel, offsets the additional upfront costs for moulds and tooling after a production run of 5 mouldings. For a large enough mould for a capital warship, this is likely to require a larger production run, circa 10 units. Whilst governments suggest orders of 10+ frigates or OPVs, such large programmes are frequently hit with budget cuts resulting in fewer platforms, such as for the T26 and Littoral Combat Ship (LCS) programmes (Allison, 2017) (Cavas, 2015). Thus, the upfront investment for a composite vessel entails increased project risk versus steel. If the production run is reduced below that at which the mould costs are recouped, the programme becomes economically unviable. The industry is also established for steel manufacture, so the capital cost to upskill the workforce and establish suitable composite build facilities entails a significant investment.

The financial viability is also affected by programme durations. Large moulds are difficult to transport with a high risk of damage, resulting in on site storage. This entails increased cost with mould size and programme duration, for example with the T26 staggered build of 2 years/vessel (Naval Lookout, 2018), if each hull spent 12 months in mould, the mould would be stored for half the programme length. Further, current moulds are steel backed composite, the steel frameworks are reusable, but the composite is not and goes to landfill.

Established yards manufacturing warships have always built in steel and therefore have the required skills and facilities. Developing new skills and facilities, particularly for composites which are the most onerous, increases CAPEX. Warship programmes are competitively tendered, hence the additional CAPEX for composite construction ensures that without significant technical merit, the steel option is selected.

Composites provide significant structural weight reduction. This can be realised as a reduction in displacement and fuel, or increased payload. Composite vessels have non-attributable through life growth of 0%, as demonstrated by the Hunt and Sandown classes. This is in contrast to ~13% displacement and ~+9% Vertical

Centre of Gravity (VCG) for steel ships over a 35 year life. This drives ship stability, increasing beam over the requirement at the Start of Life (SOL) and resulting in ballasting to mitigate the SOL condition. Composites through life growth is purely attributable growth, enabling optimisation of the hull for SOL. Steel manufacture limits shape, predominantly requiring single curvature. With composites double curvature can be accommodated and more optimised shapes modelled. This can increase efficiency and reduce signatures. Signatures can also be optimised through the composite being non-magnetic and the use of radar reflective, transparent or absorbing materials. Aesthetically, the composite vessels do not need much filling and fairing to get a superyacht-quality finish, whilst steel construction requires costly and heavy filling and fairing to achieve a similar finish. Overall, composites result in more optimised forms for resistance and signatures, with the potential for lower OPEX and CAPEX.

1.2.2. Propulsion

Currently warships are almost exclusively propelled via Combined Diesel Electric and Gas (CODLAG), with T45 being the first RN ship to utilise IFE systems. The power is provided via high voltage AC to the hotel/combat/propulsion systems, the latter comprising twin shafts with Advanced Induction Motors. The Queen Elizabeth Class also utilises this arrangement, whilst the T31 are powered by a standard shaft diesel arrangement.

The shaft diesel solution is cheaper and lighter due to fewer pieces of equipment, and reduced conversion losses. However, it does require doubling up of gensets and propulsion engines for hotel/C4 loads. The primary advantages to IFE is that the hotel/C4 and propulsion loads can be balanced, reducing the total installed power, as well as facilitating balancing of the gensets. This will become more important with the event of directed energy weapons. IFE provides significant benefit where the mission profile contains variable speeds. Frigates can spend long durations at low speed in Anti-Submarine Warfare (ASW), but still need high transit speeds; IFE allows both design points to be met with higher overall efficiency.

IFE is also key in transitioning to sustainable technologies, being agnostic to the power source. There are several options for fuel source with advantages and disadvantages, and all work for specific CONcept of OPerationS (CONOPS). The main challenge is energy density, summarised in Table 1. With military vessels being both weight and space driven, fuels must have high volumetric and specific energy densities. The use of alternative fuels to power the IFE system is considered later in this paper.

Table 1: Volumetric and weight density comparison of alternative fuels to diesel

FUEL	RELATIVE ENERGY VOLUMETRIC DENSITY	RELATIVE ENERGY WEIGHT DENSITY
DIESEL	1	1
LIQUID HYDROGEN	0.198598	0.018012
BATTERIES	0.023467	0.049536
METHANOL	0.464953	0.433737
LIQUID AMMONIA	0.434579	0.325551
ETHANOL	0.492991	0.458150
BIODIESEL	0.911215	0.880090
BUTANOL	0.829439	0.791338
HVO	0.899533	0.825366
FAME	0.866822	0.878053
LNG	1.168224	0.061507
GAS HYDROGEN	2.803738	0.000277

1.3. Paper Approach

To maximise the technological benefits, platforms must be designed for new technologies from the outset. This allows the adoption of new CONOPS that makes the most of new systems. As this drives a departure from the current practice, it is hard to assess the improvement such a vessel could provide over the existing solution. Therefore, this paper compares an existing frigate concept with one including key technology developments. For the purposes of this paper, Steller System Limited's SPARTAN, has been used as a baseline, with the future variant dubbed E-SPARTAN. This approach does limit the benefits that can be realised compared to developing a new concept from scratch as the hull form is effectively fixed. This is an area for future work.

In order to assess the impact of technologies between the two concepts, the driving parameters for warships must be established. With the two designs at concept stage it is hard to quantifiably compare across all aspects of the design. As such, the authors have selected the following areas.

- Operational capability;
- Cost, both CAPEX and OPEX;
- Sustainability.

2. SPARTAN Baseline

SPARTAN has a length of 117m, beam of 17.5m and lightship of 2,630t. The design is forward looking, but still assumes a low risk position and therefore provides a good baseline. In this section of the paper the design of SPARTAN is described in order to provide a baseline.

2.1. Structure

The structure is transversely framed, longitudinally stiffened A grade steel, as expected for a frigate. The midships section has been derived based on Lloyds' Register (LR) Rules and Regulations for the Classifications of Naval Ships (Lloyds' Register, January 2020), notation NS2, considering rule defined panel pressures and global strength. The assumption was made that the superstructure contributes to global strength. The SPARTAN structural weight estimate of 1140t was derived through regression formulae developed by Steller Systems Limited.

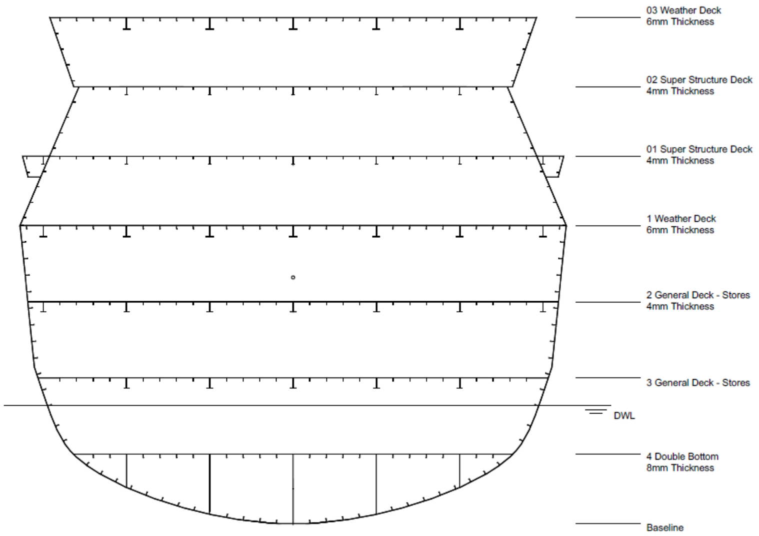

Figure 1: Midship section for SPARTAN steel construction based on LR Rules and Regulations for the Classifications of Naval Ships NS2

2.2. Propulsion System

SPARTAN utilises Combined Diesel Electric and Diesel (CODLAD) propulsion, with propulsors and power generation subdivided into 3 survivability zones, as shown in Figure 2.

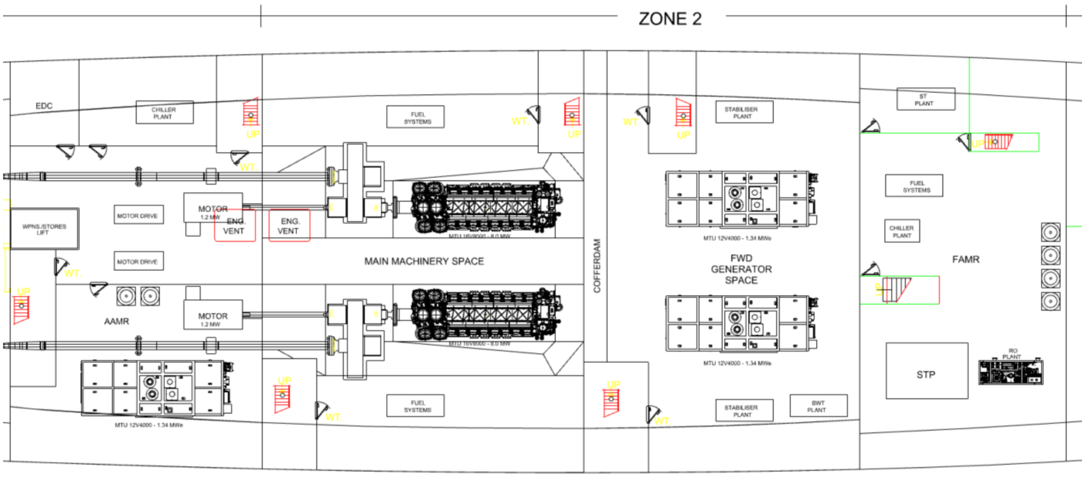

Figure 2: SPARTAN key machinery locations, Zone 3 not shown

The power is delivered through 2 shafts to Controllable Pitch Propellers (CPP). The power and weight for each component of the system are given in Table 2 along with the total installed power for each survivability zone. The total installed power is 21.36MW, giving a sprint speed of 25kts.

Table 2: Spartan Machinery Arrangement

DAMAGE ZONE	PROPULSIVE COMPONENTS	INSTALLED POWER (MW)	MASS (T)
ZONE 3	1x 1.34MW Diesel Generator	1.34	33.50
	2x Electric Motors		11.86
	Total Zone 3	1.34	45.36
ZONE 2	2x 8MW Diesel Engines	16.00	94.40
	2x 1.34MW Diesel Generators	2.68	67.00
	2x Direct Drive Shafts		-
	Total Zone 2	18.68	161.40
ZONE 1	1x 1.34MW Diesel Generator	1.34	33.50
	1x Drop Down Propulsor		-
	Total Zone 1	1.34	33.50
TOTAL SPARTAN DESIGN		21.36	240.26

The mission profile currently used for sizing the fuel assumes a 5065nm range, this has been used as a baseline for E-SPARTAN.

3. E-Spartan Design

E-SPARTAN looks to implement technologies across two main areas, large scale adoption of composites and updating to IFE propulsion.

3.1. Composite Structure

Several aspects are key to successfully implementing composite as a material choice for construction. These are discussed in the following subsections.

3.1.1. Material Selection

When composites are discussed for weight saving, carbon is usually the first thought. In this case, the impact resistance of carbon makes it unsuitable for use on a warship. If a ship received weapon induced damage the carbon would fracture/splinter, providing a hazard to personnel as well as potentially shorting electrical equipment, a risk to platform operability if based on an IFE system. E-Glass offers a reduced weight saving, but greater impact resistance, Kevlar reinforcement could improve this further. Carbon and Kevlar would be cost prohibitive, but could be used locally to complement E-Glass construction.

E-Glass is radar transparent, this means that the Radar Cross Section (RCS) can be tailored. Spaces with large radar reflective structures, such as engines/machinery rooms, can be lined with radar absorbent or reflective material to ensure the internal objects do not show up on radar. Through this approach the RCS could be severely reduced, without the normal considerations of tumble home vs roll angle.

Three main resin systems are available, polyester, vinyl-ester and epoxy. The former two emit styrene throughout curing, this is not sustainable/eco-friendly and would be hard to control on a large-scale structure, thus epoxy is recommended. This has a higher strain to failure and cures via a catalyst, giving more control over cure times, which is useful for large structures. Epoxy is susceptible to UV degradation, this is a function of the chemistry, whereby the aromatic groups in the epoxy react with oxygen radicals. Some epoxies are supplied with UV stabilisers however the effectiveness of these is not proven. It is suggested that the best way to avoid this is to utilise a painted finish, or a vinyl-ester gelcoat. The painted finish is lighter, allows the use of traditional paint schemes and facilitates simpler repair.

3.1.2. Panel Construction

Currently, composite shock qualified military vessels utilise monolithic laminates for at least the hull. This is inefficient as composite panels rely on thickness to give stiffness. This is because a significant amount of physical testing was conducted in the 1970's on monolithic laminates to justify their performance in the Hunt Class, and cored structures have not been tested. If a low-density core was used for a sandwich panel it is reasonable to expect the core to suffer compression in the event of a non-contact underwater explosion. This can be mitigated through the use of higher density foam cores, such as those used on high performance craft. Given the robustness needed in a warship, the skin thicknesses will need to be thicker than traditionally associated with a cored composite.

Four main layup methods are used in the marine industry, each with its own merits. These being hand lay roller consolidated, hand lay vacuum consolidated, vacuum resin transfer infusion and prepreg in order of increasing complexity and cost. The first two options require skilled laminators to obtain repeatable structures, whilst the third and fourth are more reliant on the workers correctly following a manufacture process. The final option requires storage of prepreg fabrics at sub-zero temperatures prior to use as well as curing at elevated temperature. Given this, the resin infusion approach gives best repeatability and fibre weight fraction, which is key in such a structure, therefore this method has been assumed going forwards.

3.1.3. Manufacture Strategy

There are two composite manufacture options for warships ~100m length. First, single hull mould, separate superstructure mould and flat tables for internal decks and bulkheads. This entails large costs for mould storage, preparation and disposal, whilst holding high risk for the infusion process, the loss of one moulding could make a project unviable. If this route is taken the mould will need to be steel backed for support, but the mould surface could be 3D printed, this means a plug is not required and the mould can be printed in sections, bonded together, fixed to the steel backing structure and then faired. Further, the print medium could be recycled from ground down industrial waste composite, from old hulls or offcuts. This process is likely to be cheaper than conventional methods of constructing moulds.

The alternative method would be to construct a composite or steel skeleton and then bond on panels to form the shell. The panels can be formed using flexible mould technology, such as that presented by Curve Works BV (Composites World, 2021). This can mould panels up to circa 4m x 10m, similar to the size of a sheet of steel. The mould bed can be programmed to any shape (within the radii limits) and double curvature can be accommodated. The skeleton could utilise longitudinal and transverse bulkheads, laid up on flat tables and slotted together before bonding and over lamination. Then pultruded/moulded stiffeners fitted to link these flat structures and for the side panels to bond to. This approach is labour intensive, however the footprint for manufacture is smaller and it lends itself to offsite panel construction. This could support a larger supply chain, fitting in with the National Shipbuilding Strategy and supporting SMEs as well as mitigating the shipyard's skills gaps. This paper assumes the latter method, noting that with a production run the former may be more labour, cost and weight effective.

3.1.4. Scantlings

The composite structure has been designed using the same loads and methods as the SPARTAN. The panels have been assessed for stiffness and strength according to LR Rules and Regulations for Special Service Craft (Lloyd's Register, July 2021), resulting in the midship in Figure 3.

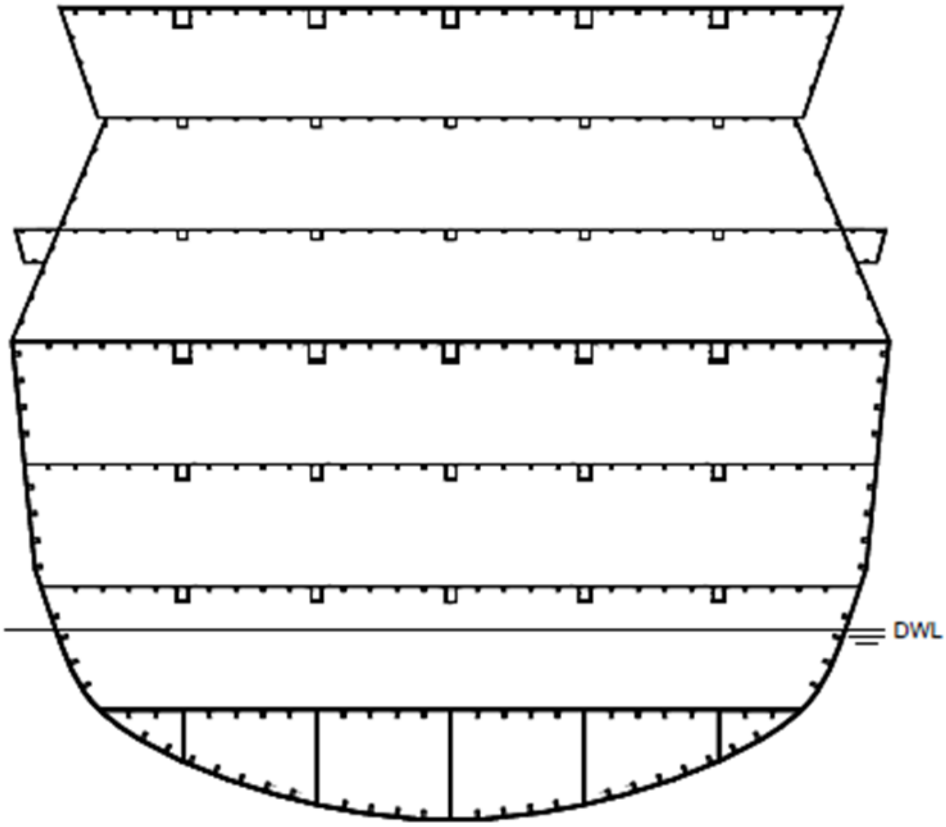

Figure 3: Midship section for E-SPARTAN assuming composite construction.

The panels are mostly cored using H130/H200 Diab Divinycell PVC, the high density gives improved resistance to core compression, and increases the panels' shear stiffness. The composite skins range from 1-7mm depending on the area of the vessel, with solid E-Glass core inserts used in very high load areas, such as the keel or tug points, giving 30-40mm E-Glass.

The stiffening utilises moulded top hat sections, in reality pultruded sections are likely a more cost effective solution. The secondary stiffening could be fitted to the composite panels prior to bonding on to the skeleton, with primaries fitted once the flat panel bulkheads have been connected together to provide stiffness to the skeleton itself.

3.1.5. Weight Estimate

The composite weight estimate was calculated assuming a linear relationship between SPARTAN's structural weight and midship section t/m. Using specific densities for each type of composite material considered, the midship stiffeners and plate elements were calculated to give 2248kg/m and 3103kg/m respectively, compared to 8308kg/m and 16810kg/m for the existing steel design. This constitutes 73% and 82% weight savings for the two structural aspects, averaging at 79%. This assumes the construction and design margins for local reinforcement are equivalent for composite and steel, which is optimistic. As such, a conservative weight saving is 50%, giving a structural mass of 570t, compared to SPARTAN's 1140t, this is pessimistic compared to the 60% saving presented by Hellbratt (Hellbratt, 2016) and gives a combined design and manufacture allowance of 43%.

Initial structural weight saving is a key metric, accounting for 22% of SPARTAN's lightship. However, another benefit of composite is the reduction in non-attributable growth to 0% for displacement and VCG. When this is applied to the structure we see an increase in weight saving to 31% at a 35 year EOL.

3.1.6. Integrated Armouring

One of the advantages of composite is its flexibility, especially with a cored structure. Here the core can be replaced locally with ballistic protection Kevlar panels. These can be localised to areas of the vessel which are critical to survivability, with the remainder left unarmoured. This could lead to more optimised armouring across the platform. Figure 4 shows the location of critical compartments for blast protection.

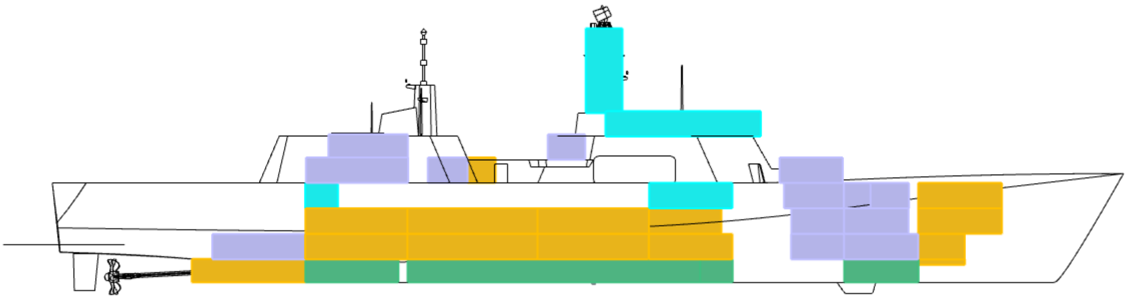

Figure 4: Armoured Zones on E-SPARTAN. Orange - Machinery Spaces; Green: Fuel Tanks; Purple: Munitions/Armament; Blue: Operations

3.2. Propulsion System

In order to specify the propulsion arrangement, it is first necessary to define the fuel source as this drives machinery selection.

3.2.1. Alternative Fuel Comparative Study

The IFE propulsion system gives an opportunity to produce the electrical power using fuels with lower environmental impact. Typically this would be associated with batteries, ammonia and hydrogen, however there are other options that are more achievable in terms of availability and density. The authors conducted a high level review of the alternative fuels utilising three parameters relative to the SPARTAN baseline, energy stored, volume and weight. It should be noted that the transmission efficiency refers to the efficiency of the machinery required to convert the fuel into usable energy onboard. The propulsive efficiency and shaft efficiency are assumed to be independent of fuel type. The weight and volume of the fuel tanks required and additional supporting systems such as cryogenics have not been included. Table 3 summarises the results.

Table 3: Summary of fuel volume and weight required for equivalent fuel energy to baseline vessel

Fuel	Transmission Efficiency (%)	Fuel Weight increase (%)	Fuel Volume increase (%)	Range increase (%)
Diesel (baseline)	0.3	0%	0%	0%
Liquid Hydrogen	0.8	404%	5452%	167%
Batteries	0.9	4161%	1919%	200%
Methanol	0.3	115%	131%	0%
Ammonia	0.3	130%	207%	0%
Ethanol	0.3	103%	118%	0%
Biodiesel	0.3	10%	14%	0%
Butanol	0.3	21%	26%	0%
Hydrated Vegetable oil (HVO)	0.3	11%	21%	0%
FAME (Fatty Acid Methyl Esters)	0.3	15%	14%	0%
LNG (Liquid Natural Gas)	0.3	-14%	1526%	0%
Hydrogen @700bar	0.8	-64%	621%	167%

The baseline design stored 13910000MJ of energy within the diesel tanks onboard. LNG and Gaseous Hydrogen show a decrease in fuel weight, however the current storage requirements and auxiliary systems required make the utilisation of such fuels in warships infeasible. The low energy density of batteries makes the implementation of a fully battery electric warship infeasible, even considering the battery energy density projections into the 2030s. Out of the remaining fuels biodiesel had least effect on storage volume and weight, with a 32.5t increase in weight and 59m^3 in volume. The volume challenge exhibited by the different fuels is summarised in the below extract from the UKNEST Warship Net Zero Conference (Oldershausen, 2022).

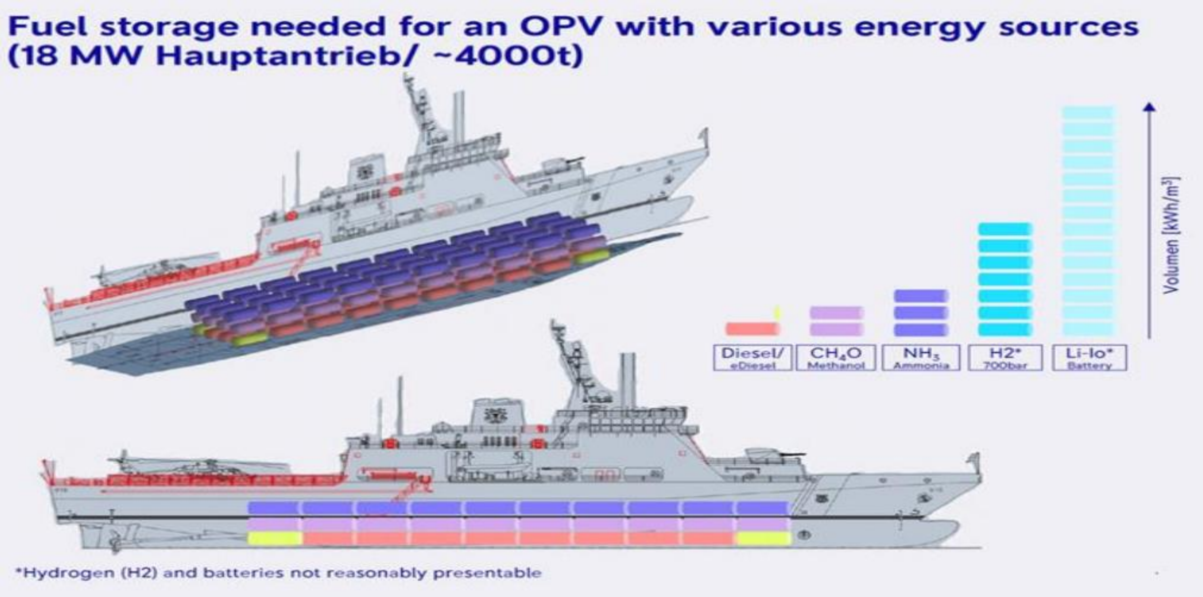

Figure 5: Extract from UKNEST Warship Net Zero Conference 2022 (Oldershausen, 2022)

Whilst biodiesel may not seem as beneficial as the other alternatives, it has many benefits over conventional diesel. It is made from organic matter and is therefore renewable, it is also sustainable if this matter is produced in a sustainable manner (S.Boudh, 2020). Biodiesel also emits lower emissions than conventional MDO with the US EPA stating 11% lower CO and 10% lower particular matter emissions (US EPA, 2002). These emissions can be removed from the exhaust using scrubbers, such as those seen in IMO Tier III engines. Biodiesel is compatible with standard marine engines, but provides greater lubricity and has a lower ignition point than MDO, thus improving engine performance (A.Soomro, n.d.). The fuel is also biodegradable and nontoxic and therefore would have a lower impact on the marine environment in the event of a fuel spill.

3.2.2. Selected Arrangement

With the selection of biodiesel, IMO Tier III diesel gensets can be used to provide electrical power. This is an advantage over fuel cells or similar as it is a well-known and proven method of generating power and is understood by existing RN ships' staff with minimal training required to manage the change in fuel type. The resultant machinery arrangement is detailed along with the breakdown across survivability zones in Table 4 and Figure 6.

Table 4: E-SPARTAN Machinery Arrangement

DAMAGE ZONE	PROPULSIVE COMPONENTS	TOTAL INSTALLED POWER (KW)	MASS (T)
ZONE 3	2x 1.786MW Diesel Generators	3.572	31.60
	1x Electric Motor		40.05
	1x Main Shaft		-
	Total Zone 3	3.572	71.65
ZONE 2	2x 7.2MW Diesel Generators	14.200	234.00
	1x Electric Motor		40.05
	1x Main Shaft		-
	Battery Bank		163.20
	Total Zone 2	14.200	437.25
ZONE 1	1x 1.786MW Diesel Generator	1.786	15.80
	1x Drop Down Propulsor		-
	Battery Bank		76.80
	Total Zone 1	1.786	92.60
TOTAL INSTALLED POWER		19.758	601.50

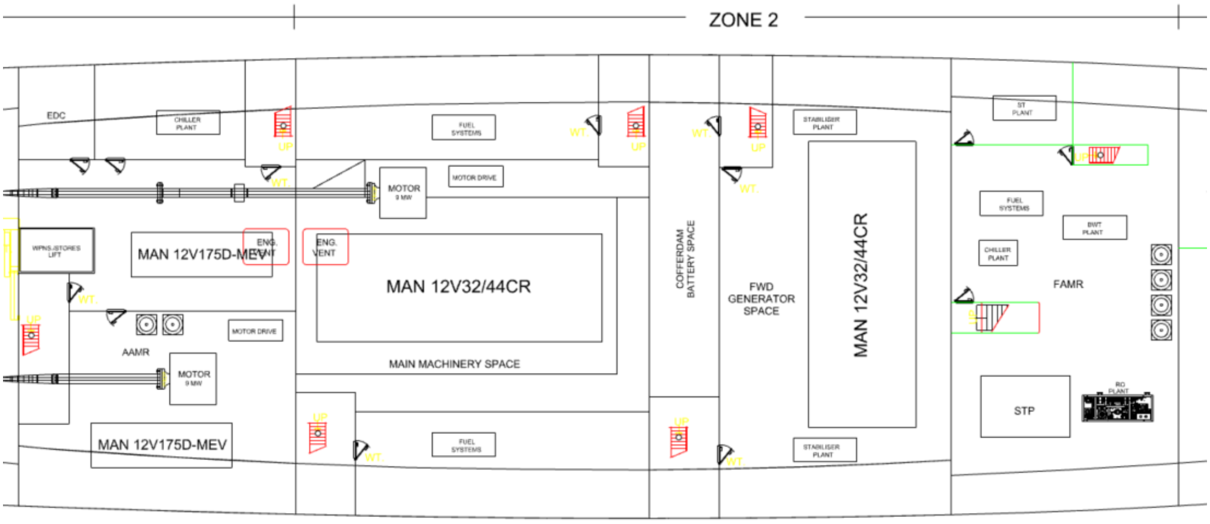

Figure 6: New E-SPARTAN Main Machinery Spaces, note Zone 1 omitted for clarity

3.2.2.1. Batteries

Due to the reduction in structural weight, post consideration of the increased machinery weight associated with the IFE arrangement installed, E-SPARTAN remains ~240t lighter than SPARTAN. This does not provide a tangible reduction in emissions or speed increase, therefore batteries will be fitted using this spare weight to provide a silent running and peak shaving capability to the platform. The batteries also provide instantaneous power, reducing lag and supporting directed energy weapons. Conservative calculations have been performed using data from leading battery cell manufacturers, Innolith AS and Steatite, for currently available cells and the likely increase in energy density over the next decade. It should be noted that any frigate designed now is unlikely to be at full operating capability within this decade.

Table 5: Required Volumes of Batteries for varying Energy Density based on data provided by Innolith AS and Seatite

YEAR	ENERGY DENSITY (WH/KG)	ENERGY DENSITY (WH/L)	STORED ENERGY (KWH)	REQUIRED VOLUME - INCLUDING 20% ADDED PACKING MARGIN (M^3)
TODAY – 2022	279	500	66960	160.7
	315	800	75600	113.4
	350	950	84000	106.1
	380	1050	91200	140.2
2024	400	1125	96000	102.4
	475	1375	114000	99.5
2030+	1000	3150	240000	91.4

The battery banks will be split between Zones 2 and 1. In Zone 2, the original cofferdam has been extended to provide a sealed battery compartment (see Figure 6), and in Zone 1 there are two void spaces in the double bottom that will provide the additional volume. With these three spaces there is an available 240m^3 of space, sufficient for all the aforementioned densities. The duration the batteries can provide silent running for is dependent on ship speed as shown in Table 6 assuming the current energy density (279Wh/kg).

Table 6: Potential Silent Running Capability

SPEED (KTS)	ENDURANCE (HRS)	ENDURANCE (DAYS)	RANGE (NM)
1	230.0	9.6	230.0
2	204.1	8.5	408.3
3	176.6	7.4	529.9
4	155.7	6.5	622.6
5	139.1	5.8	695.6
6	122.5	5.1	735.1
7	104.6	4.4	732.2
8	89.3	3.7	714.6
9	76.0	3.2	683.6
10	64.1	2.7	640.9
15	27.0	1.1	405.1
20	10.8	0.5	216.1

As batteries densities improves over time, the silent running capability of the vessel will increase. Table 7 demonstrates how the silent running capability at 12 knots has the potential for a 1.4 fold increase over the next 2 years and a 3.5 fold into the 2030s. The battery densities used in this study have been taken from data provided by Innolith AG.

Table 7: Impact summary for increase in battery energy density over the next decade

YEAR	BATTERY ENERGY DENSITY (WH/KG)	ENDURANCE (HRS)	RANGE (NM)
TODAY -2022	279	24.8	298.0
2024	400	35.6	427.2
2030+	1000	89.0	1068.1

3.2.3. Weight

The changes to the structure and the propulsion arrangement have resulted in displacement and centroid changes. The displacement reduction for the structure is partially offset by the increase in propulsion system weight due to the increase in power management equipment and the fact gensets are heavier than the equivalent direct drive engine. The remaining difference in displacement is related to the batteries, defining the total battery weight of 240t.

Table 8: Changes to displacement and Vertical Centre of Gravity

ITEM		ADDITION OR REMOVAL	WEIGHT (T)	VCG (M)	VERTICAL MOMENT (T.M)
ORIGINAL SPARTAN LIGHTSHIP			2630.3	8.01	21069
ORIGINAL DESIGN	Diesel Engines	-1	94.4	3.63	-343
	Electric Motors	-1	11.9	1.00	-12
	Diesel Generators	-1	130.0	3.63	-472
	Steel Hull Structure	-1	1140.9	8.15	-9298
NEW DESIGN	Diesel Generators	+1	281.4	3.63	1022
	Electric Motors	+1	80.1	1.00	80
	Batteries	+1	240.0	4.68	1123
	E-Glass Structure	+1	570.4	8.15	4649
	Additional Power Handling Systems	+1	205.2	4.68	960
ESPARTAN LIGHTSHIP			2630.2	7.14	18778

3.2.4. Fuel Consumption

The reduction in non-attributable growth, as discussed in Section 3.1.5, means the vessel can be designed for SOL. In terms of Vertical Centre of Gravity (VCG), this equates to a beam reduction to pass End of Life (EOL) stability requirements. This is the most effective way to reduce resistance and therefore installed power, propulsion machinery mass and fuel burn. However, this has not been considered in this paper as it entails a redesign of the SPARTAN hullform. The displacement growth reduction to 0% means that E-SPARTAN sees a lower through life lightship than SPARTAN, resulting in an effective weight saving. This can be translated into a resistance reduction and thus fuel saving. Whilst not as significant as if the beam was reduced, this equates to 8,106t of diesel over a 35 year life or a 5% reduction, equivalent to a saving of £7.7M over a 35 year life assuming the Global 20 Ports average bunkering rate for MDO of £945/t, and a 0.84 USD to GBP exchange rate between GBP and USD (Ship&Bunker, 2022).

4. Impact on CADMID Cycle

Composite requires investment in the manufacture process and upskilling of the workforce, however once this is in place if moulds can be avoided then it is a simpler process requiring movement of less material than steel and avoiding the difficulties of bending plate. Further, secondary bracketry can be bonded in with no effect on external structures, whereas as welding pipe supports can affect external paint, this has the potential to simplify the build process. The composite will not be susceptible to corrosion and therefore only damage will need to be rectified. The use of a gelcoat could negate the requirement for antifouling, which means it does not need reapplying. The IFE system allows equipment to be located with reasonable shipping routes and therefore reduces refit time and cost, improving upgradability through life.

The vessel VCG has reduced for E-SPARTAN due to the structural weight reduction and the placement of batteries low down. This will improve the static stability of the platform. Further, the reduction in non-attributable growth will also lead to improved EOL stability.

The move to a fully electric propulsion arrangement has allowed an improvement in the survivability of the design, with the propulsive power better distributed through the vessel.

Through the use of composite, less material is required which will reduce the carbon footprint of construction due to reduced transport costs. However, this is offset by the difficulty in recycling composite hulls. EOL disposal could entail grinding up the hull to 3D print the next generation of composite warships moulds, the alternative is likely landfill. This is offset by the fact composite hulls do not exhibit fatigue or corrosion like steel hulls, this means that at the design EOL they could be upgraded for continued service or sold on to other countries for continued operation. This could mean that with minimal structural repair work the vessels could operate for beyond twice the design life. This does require thought as to shipping routes for the main propulsion machinery and combat systems to facilitate refit, something not necessarily optimised in the current generation of warships.

The ability to utilise the large battery bank for protracted zero emission running means that in sensitive ecosystems where emissions are to be severely restricted, such as the Artic or Norwegian fjords, the vessel can operate without requiring a military dispensation. However, this operation is limited to circa 5 days assuming operation at 6kts, and further reduces with increases in speed. The use of biodiesel electric IFE means that the multiple design points for a multi-role frigate can all be designed for, as opposed to a single design point for direct drive diesel. Overall this can achieve a higher efficiency than a direct drive diesel. This is further aided by the battery bank which allows gensets to be operated at peak efficiency and used to charge the battery bank, when fully charged, a genset can be switched off and the battery bank used to fill the power gap. This increases efficiency of the whole propulsion and combat systems.

Whilst it has been demonstrated that alternative eco-fuels are not a viable solution without reducing capability, the use of biodiesel reduces the reliance on fossil fuels and facilitates a cleaner burn and allows compatibility with standard diesel should biodiesel not be available on operations. This coupled with IMO Tier III compliant gensets will reduce the emissions of the warships when running in pure diesel electric mode. The modular nature of this propulsion system will also allow through life upgrade as technologies become more viable with advances in battery technology and hydrogen storage etc.

4.1. Cost

4.1.1. CAPEX

The key differences between SPARTAN and E-SPARTAN CAPEX are in the structural build costs. The propulsion system will be more expensive due to batteries, but is not expected to be an order of magnitude different from the equivalent warships currently in build. Estimates have been made for the structural construction cost, these equate to circa £8.5M for the steel hull and £10M for the composite, an increase of £1.5M, 18%. This assumes the facilities and skills for both are equally available and that 20% of composite build cost is materials, as advised by AC Marine and Composites.

In reality the cost for the first generation of composite warships of this size would be increased due to up-skilling and equipment for yards to move to composite on this scale. The use of smaller boat builders/composite manufacturers like AC Marine & Composite, NORCO, Carbon Instinct etc to manufacture subcomponents, could help mitigate the level of investment required, alongside the in house experience of BAE SBCE or Damen. The investment could be offset by export of the composite manufacture of large hulls. This could be in the defence arena, but is equally valid for the superyacht market.

4.1.2. OPEX

Through life costs will be dramatically reduced through the use of composite, the reduction in cost is due to no requirement to repaint/finish the structure due to corrosion or welding of tertiary structure. Such repairs cost the US Navy circa $3B annually across the US fleet (Parsons, 2014), however it should be noted that Non-Destructive Examination (NDE) of the structure following extreme load events may be required to identify delamination or failure within the laminate, which would entail a reasonable cost, if not comparative to corrosion repairs. The nature of the IFE system and designing for retrofit of new generation technologies will enable cheaper upgrade through life compared to the T23 LIFEX project and T45 PiP. The former’s power and propulsion upgrade costing £7.8M per ship, and entire package £600M for 13 ships (Navy Lookout, 2018). From the above, estimated through life maintenance savings could easily be ~£20M. The fuel savings associated with the reduction in non-attributable growth have been shown to result in a saving of £7.7M over the 35 year design life. This equates to ~£28M of OPEX savings, offsetting the additional build cost.

The key capability enhancements provided by the change in structure and propulsion system relate to signatures, key in several GPF roles such as Mine Counter Measure (MCM) and Anti-Submarine Warfare (ASW). Traditionally expensive single role platforms have been used for MCM, however the nature of a composite hull would facilitate E-SPARTAN also being able to conduct such roles, or serve as a mothership for the next generation of autonomous MCM vessels. Whilst SPARTAN could also provide this capability, the E-SPARTAN’s lower magnetic signature would facilitate operation on the fringes of the minefield, increasing effectiveness. The reduction in waterborne noise when operating in battery mode would also aid ASW roles, reducing the likelihood of detection. The use of E-Glass means that the structure is predominantly transparent to radar, allowing tailoring of the RCS. The battery mode enables operation in emissions controlled environments without a military dispensation; as larger areas on waterways become controlled, this gives freedom of navigation compared to existing platforms.

5. Conclusions

In summary, E-SPARTAN gives a cost competitive solution for a new generation of GPF, demonstrating that increased CAPEX (£6.5M - £5M for IFE systems) can be offset by a reduction in OPEX (£28M). This cost saving would offset the cost of upskilling the shipbuilding workforce over a class of ships, resulting in an industry leading capability. The feasibility of composite has been demonstrated via first principle calculations, including for global hull bending, the benefits of this over the operation of a frigate have been discussed, particularly with reference to MCM and ASW roles. The IFE propulsion system provides upgradability through life as alternative zero carbon fuels become viable, whilst the battery bank enables peak shaving of the gensets. The gensets themselves run off biodiesel where available, but can operate using MDO where biodiesel is not available, this does not restrict the operating area of the vessel. The use of IMO Tier III gensets also reduces the emissions of the platform, whilst the battery bank facilitates zero emissions and silent running.

The current assessment is based on SPARTAN as a baseline, however further opportunities for capability and efficiency enhancement have been identified. These include leveraging the reduction in non-attributable VCG growth associated with composites to design the vessel beam for the SOL condition, reducing resistance through life, introduction of radar absorbent materials to reduce effective radar signature and optimisation of the mission profile to maximise benefit of the battery bank. These hold the potential to produce high through life savings, both in terms of emissions and cost.

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6. References

A.Soomro, n.d. *Biodiesel; Definition, Advantages and Disadvantages.* [Online] Available at: https://www.environmentbuddy.com/energy/biomass-energy/biodiesel-definition-advantages-and-disadvantages/
[Accessed 16 June 2022].

Allison, G., 2017. *The Clyde was to build 13 Type 26 Frigates, why has this changed?.* [Online] Available at: https://ukdefencejournal.org.uk/clyde-build-13-type-26-frigates-clyde-changed/
[Accessed 21 June 2022].

Cavas, C., 2015. *Pentagon Cuts LCS to 40, 1 Shipbuilder.* [Online] Available at: https://www.defensenews.com/naval/2015/12/17/pentagon-cuts-lcs-to-40-ships-1-shipbuilder/
[Accessed 21 June 2022].

Composites World, 2021. *Curve Works reaches milestone for modular builds of composite shell structures.* [Online]
Available at: https://www.compositesworld.com/news/curve-works-reaches-milestone-for-modular-builds-of-composite-shell-structures
[Accessed 28 6 2022].

Eckstein, M., 2021. *Rep. Rob Wittman on US Navy ship retirements and a sea-launched nuclear weapon.* [Online]
Available at: https://www.defensenews.com/naval/2022/06/21/rep-rob-wittman-on-us-navy-ship-retirements-and-a-sea-launched-nuclear-weapon/
[Accessed 22 June 2022].

Goddard, R. et al., 2020. *A Novel Approach to the Analysis of Sinking Ships; Combining Vulnerability, Stability and Escape & Evacuation Simulations.* s.l., IMarEST.

Hellbratt, S.-E., 2016. *Time for Light Weight Composite Materials to enter Merchant Shipbuilding,* s.l.: Thüssen Krupp Marine Systems; Kockums AB.

IMarEST, 2019. *Autonomous Shipping - Putting the human back in the headlines II.* Manila Philippines, s.n.

Lloyds' Register, January 2020. *Rules and Regulations for the Classification of Naval Ships*, s.l.: s.n.

Lloyd's Register, July 2021. *Rules and Regulations for the Classification of Special Service Craft,* s.l.: s.n.

Mason, H., 2019. *LM Wind Power manufactures longest wind turbine blade.* [Online] Available at: https://www.compositesworld.com/news/lm-wind-power-manufactures-longest-wind-turbine-blade
[Accessed 21 June 2022].

Naval Lookout, 2018. *Making sense of the Royal Navy's frigate building schedule.* [Online] Available at: https://www.navylookout.com/making-sense-of-the-royal-navys-frigate-building-schedule/
[Accessed 21 June 2022].

Navy Lookout, 2018. *New Engines for the Royal Navy's Type 23 Frgates.* [Online] Available at: https://www.navylookout.com/new-engines-for-the-royal-navys-type-23-frigates/ [Accessed 08 07 2022].

Oldershausen, C. v., 2022. *Alternative Fuels for Naval Vessels.* Portsmouth, s.n.

Olwell, D. D. H., n.d. *Chapter XXII - Effects of Reduced Manning.* s.l.:Naval Postgraduate School.

Parsons, D., 2014. *A fresh Coat of Paint Can Save the Navy Billions.* [Online] Available at: https://www.military.com/daily-news/2014/05/19/a-fresh-coat-of-paint-can-save-navy-billions.html [Accessed 08 07 2022].

Royal Instution of Naval Architects, 2017. *Type 45 to get third diesel generator to overcome problems.* [Online] Available at: https://www.rina.org.uk/Type_45_to_get_third_diesel_generator_to_overcome_problems.html#:~:text=Each%20Type%2045%20has%20an,coupled%20to%20the%20propeller%20shafts. [Accessed 21 June 2022].

S.Boudh, S. S., 2020. Biodiesle as a Rewnewable Energy Source. *Contaminants and Clean Technolgies* .

Ship&Bunker, 2022. *Average Bunker Prices.* [Online] Available at: https://shipandbunker.com/prices/av [Accessed 06 07 2022].

US EPA, 2002. *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions,* s.l.: United States Enviromental Protection Agency, Office of Transportation and Air Quality.

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