Powering into the Future - Propulsion Options for Surface Combatants

Nick Smith, UK Technical Director, GE Power Conversion
Richard Trumper, Head of Research & Technology, BAE Systems Naval Ships.

Author biographies:

Nick Smith: BEng, CEng, FIET
Nick joined Power Conversion in 1988 where he is now the Technical and Technology Director, and has played a leading role for more than 30 years designing ships' power and propulsion systems for a variety of the world's navies, including Type 23, Type 45, and Wave, Albion, Zumwalt and QE classes for the UK and US, as well as many supporting technology development programmes.

Richard Trumper: PhD, MBA, CEng, MIMMM
Richard joined BAE Systems in 2011 and is Head of Research and Technology for Naval Ships. He is responsible for exploiting innovations and developing future platform technologies that enhance Naval Ships' ability to design and deliver complex warships.

Affiliations: GE Energy Power Conversion UK Ltd. (Rugby, UK) and BAE Systems Naval Ships

Disclaimer: This paper reflects the views of the authors and does not necessarily represent the views of the authors' affiliated organisations or the Institute of Marine Engineering, Science and Technology (IMarEST).

Synopsis

There have been many papers presented over the years claiming to put a definitive, ideal propulsion system forward for a particular vessel, with solutions varying from Mechanical through Hybrid, to Integrated Full Electric Propulsion. The ships associated with these differing propulsion systems also vary hugely, from small offshore patrol boats through larger platforms, such as Type 23, Type 45 and potentially her successor in the destroyer category, to the largest ships ever commissioned to the Royal Navy, the Queen Elizabeth class aircraft carriers. This paper seeks to explore the range of options available, with some of the pros and cons of different solutions, through a lens of differing ship types, and mission/role profiles. The aim is not to conclude a definitive solution, but provide the discriminators/differentiators to be considered when making the selection. Aspects to be considered as part of this analysis comprise a range of differing drivers and constraints including: ship's lifespan, vessel size, operating environment, combat role, likely operating profile, future-proofing requirement, such as the growth and impact of non-propulsion loads, potential crew/maintenance impacts, the desire for fleet commonality and emerging requirements, such as emissions and neutral/zero carbon aspirations as well as affordability and cost of ownership. While none of these aspects alone will provide a definitive discriminator to the selected option, each of them influences the choice in a unique way. Selecting the 'ideal' propulsion becomes an exercise in trading off each of the competing demands in order to find a suitable solution. The replacement for Type 45 will be considered in more detail by the authors, whose companies between them have been the leading suppliers of propulsion systems and shipbuilding for the post-Cold War UK Navy.

Keywords: Power, Propulsion, Net-Zero Emission, Zero-Carbon Emission, Electrical Architecture

1 Introduction

Technology, economics and the need to field competitive vessels have always shaped the design of warships. The British Admiralty started to build oil-fired steam powered destroyers as early as 1908, following trials with HMS Spiteful in 1904 [1, 2]. With oil offering roughly twice the calorific content compared with coal such a move allowed for increased range whilst allowing typically a halving of the number of stokers. Concerns over cost slowed the adoption of oil into the fleet and prolonged the use of coal-fired boilers, even though oil-fired ships offered significant military advantages.

The first commercial diesel-powered, sea-going ship was the MS Selandia [3], commissioned in 1912 and fitted with two reversible four-stroke diesel engines rated at 1,088 HP each, from Burmeister and Wain. Technological developments progressively allowed diesel-powered commercial cargo-carrying vessels to

https://doi.org/10.24868/issn.2515-818X.2020.028

dominate older steam-powered solutions, with thermodynamic efficiencies now exceeding 50% and the ability to exploit heavy diesel oil fuels at low cost.

The desire for higher speed saw the Royal Navy adapt aero-engine gas turbines as early as 1947 with trials at Portsmouth carried out aboard MGB2009 [4]. A subsequent development programme culminated in the 7500 HP G6, designed by Metropolitan Vickers for the Tribal class frigates and County class destroyers, laid down from 1958 onwards. The poor fuel consumption of such engines, when part-loaded, was addressed by mixing initially steam and subsequently diesel and gas turbines of different power levels to address the wide speed operating conditions unique to warships from cruise to sprint.

Considerations for a future power and propulsion architecture must now take account of the need to be flexible and future-proof, to be able to accommodate future technology, both in terms of power generation and consumption, and adapt to evolving environmental legislation.

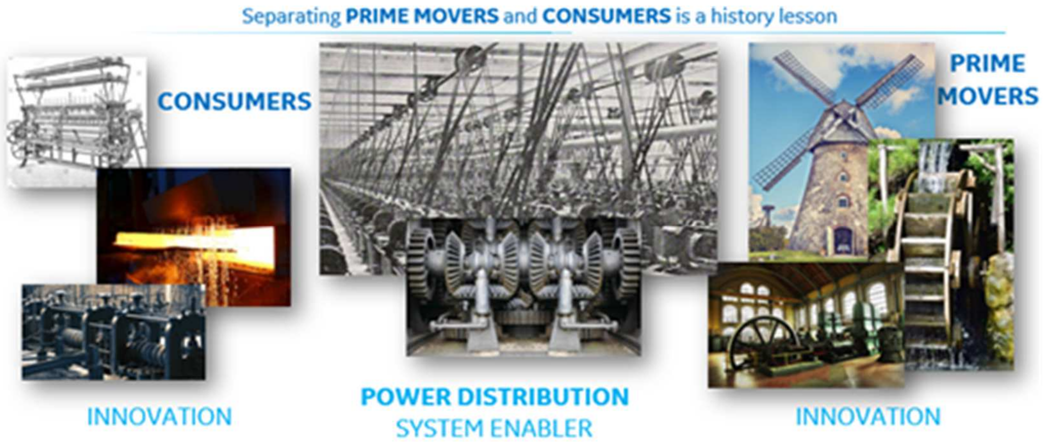

Figure 1: Power Systems Enabling the Future.

Challenges will come in the form of pulse loads for Directed Energy Weapons (DEW) and Electromagnetic Rail Guns, but also higher and higher power-hungry equipment such as radars and sonars. There is also likely to be the requirement to deploy, recover and charge large and small UAVs or UUVs. Mixed in with this are two factors: the reduction in emissions likely to result from operating current power sources more efficiently, or with different fuels; and the ability to accommodate future power sources as they become available, without wholesale ship changes or refits.

There are lessons from history here; separating the production and consumption of power leads to innovation and future-proofing. When windmills or waterwheels drove millstones, there was little innovation. Then the industrial revolution harnessed these sources to deliver mechanical power using a network of shafts and belts to multiple machines. Innovation was rapid and a plethora of industrial machines were born. Once there was a mechanical power network, then innovation could take place with the prime movers too. Water gave way to steam, and weather was no longer a limiting factor.

*The images are General Electric Company (GE) property. All rights reserved

Figure 2: Advances in Technology drive Innovation at the Consumer and Generator on an Existing Grid

The real enabler was the Mechanical Power System, which rapidly evolved to an electrical network, and that remains to this day. Industries and countries rise when they are electrified. It’s not the power stations or the consumers, it’s the grid, both at home and at work, and the super-grid. Power stations and technologies come and go, products and factories change, but at both ends of the grid there is innovation and the ability to adapt to the future.

Ships are no different, install the power network, with the current technology at each end, and it will be flexible and future-proof, with the ability to accommodate new loads and new generation technologies. No one knows the future, but it will be electric, like cars, trains, industry, and even aviation. We can no longer afford to deploy one dimensional prime movers, with a single mechanical duty. Industry has been placing large gearboxes where they belong, in a museum.

2 Approach

Fuel Options

In 1997, a new annex was added to the International Convention for the Prevention of Pollution from Ships (MARPOL). The regulations for the Prevention of Air Pollution from Ships (Annex VI) seek to minimize airborne emissions from ships (SO_x, NO_x, ODS, and VOC shipboard incineration) and their contribution to local and global air pollution and related environmental problems. Annex VI entered into force on 19 May 2005 and was updated in October 2008, with technologies such as Selective Catalytic Reduction (SCR) now being adopted to meet the latest Tier III levels for NO_x [5].

Global Warming concerns and the recognition that the maritime fleet will need to reduce its carbon emissions to help maintain the 2015 Paris Agreement on climate change [6] . In 2018, the International Maritime Organisation (IMO) set a target of 50% reduction in CO_2 emissions by 2050 compared to 2008 levels [7]. The UK Department for Transport recently issued a policy document aimed at achieving a route to zero emission for Clean Maritime [8]. With the average ship life being 25 years, this would suggest that engineering solutions are required for new builds as early as 2025-2030, or timely routes identified to be able to adapt platforms to meet such requirements in the longer term.

Diesel is the current fuel of choice for warships and the majority of cargo carriers and cruise ships, although the use of Liquid Natural Gas (LNG) is growing in popularity as it provides an affordable route to address MARPOL Tier III environmental emissions, but at the expense of requiring larger capacity tanks. Increasing political and legal pressure to achieve reduced CO_2 emissions from the maritime fleet and warships, to achieve either net-zero or zero emissions by 2050 , is now driving the search for alternate fuel sources. Current measures to reduce CO_2 emissions through fuel saving measures, such as slow speed steaming, weather routing, more efficient propellers, adoption of wind power solutions (such as kites, Flettner rotors and sails) combined with low drag hulls, may well achieve CO_2 reductions in excess of 50%, but will not deliver net-zero emissions.

Recent studies [9, 10] have explored potential solutions for the maritime cargo-carrying fleets by considering bio-fuels synthesised from bio-mass sources, from Natural Gas (NG) with associated carbon capture or using renewable energy (e.g., solar, hydro or wind) to electrolyse hydrogen from water and either liquefy, compress or combine with nitrogen to synthesise ammonia to simplify storage and transport. Figure 3 compares the through-life costs of a variety of candidate maritime fuels and considers Unit Procurement Costs (UPC) and Life Cycle Costs (LCC) over twenty five years using the projected future costs assessed in [9] and factors in the cost associated with carbon credits (assuming a cost of \$27 per tonne of CO_2) for a light frigate-sized platform.

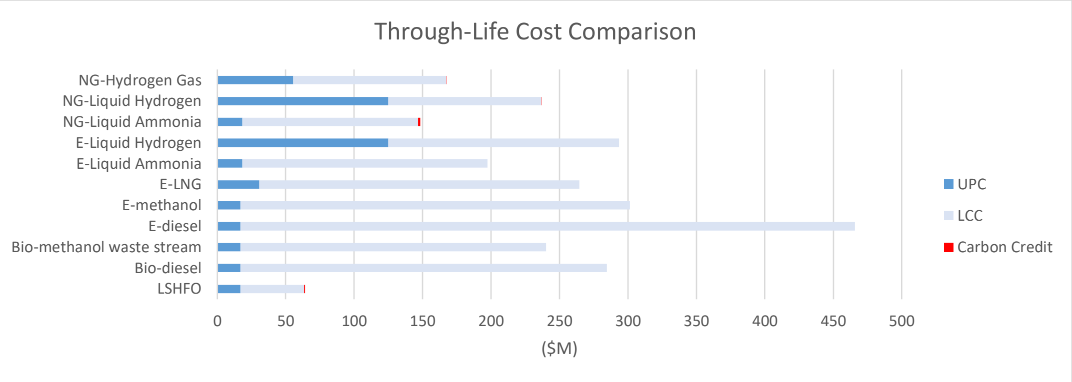

Figure 3: Comparison of the Through Life Costs of Alternative Fuels.

The unique operating requirements of a warship are such that a low flash point fuel such as hydrogen would not be considered a safe solution. The relatively low energy density of hydrogen results in large volume tanks, which are expensive, to store liquid hydrogen at -253°C or under high pressure (70MPa). Replenishment at sea will be particularly challenging for cryogenic liquid hydrogen; while hydrogen gas transfer is possible, the time taken to refuel the gas tanks of a warship is likely to be protracted.

Ammonia would appear to be a potential zero emission candidate to replace diesel, offering a mature industrial base, high flash point fuel (but toxic to marine life) capable of being burnt in existing diesel engines and also gas turbines without substantial modifications. However, such a move is likely to be at a fuel cost of almost three times that of diesel at current projected prices (the future price point for diesel is likely to be very dependent on supply and demand, and taxes!). Adoption of liquid ammonia as a fuel will require larger fuel tanks to deliver equivalent range at cruise speed and be insulated to cope with low temperature (-33°C) or pressure (1MPa). The potential to produce green ammonia directly using renewable energy is likely to open up a wider supplier base and allow excess energy from solar and wind to be more effectively captured which would help stabilise future prices.

Liquid fuels such as bio-diesel, methanol and ethanol, whilst also being candidates for net-zero emission, are likely to be more expensive than ammonia and as they will be reliant on bio-mass feed stocks may well become unaffordable when required in large quantities unless other sources of bio-mass can be utilised.

Power Architectures

The electrification of the world is gathering pace, and ships are no different. Motors and drives have become smaller and more cost effective, electric propulsion has been applied to aircraft carriers, frigates, destroyers and smaller vessels. For example, commercial Flexible Offshore Service vessels predominantly have a four prime mover diesel-electric power and propulsion solution. In the underwater space, small autonomous and remote operated vessels also employ electric propulsion, as do conventional submarines. Even nuclear submarines are turning to electrification for efficiency gains and reduction of refuelling costs.

Hybrid and Integrated Full Electric Propulsion (IFEP) have become prevalent modern naval architectures as they can:

- Cruise and generate power on shared diesels, for economy, efficiency and range;
- Fight on gas turbines, for power and speed;
- Isolate prime movers from shaft-lines to facilitate quieter vessels.

Mechanical systems do not share engine power between propulsion and services power needs. They need to add engines for resilience, which leads to higher running hours, fuel and running costs. Hybrid systems share Diesel Generator (DG) sets across propulsion and services, but not main Gas Turbine (GT) prime movers, so they do have some power flexibility, but not from the most powerful engines.

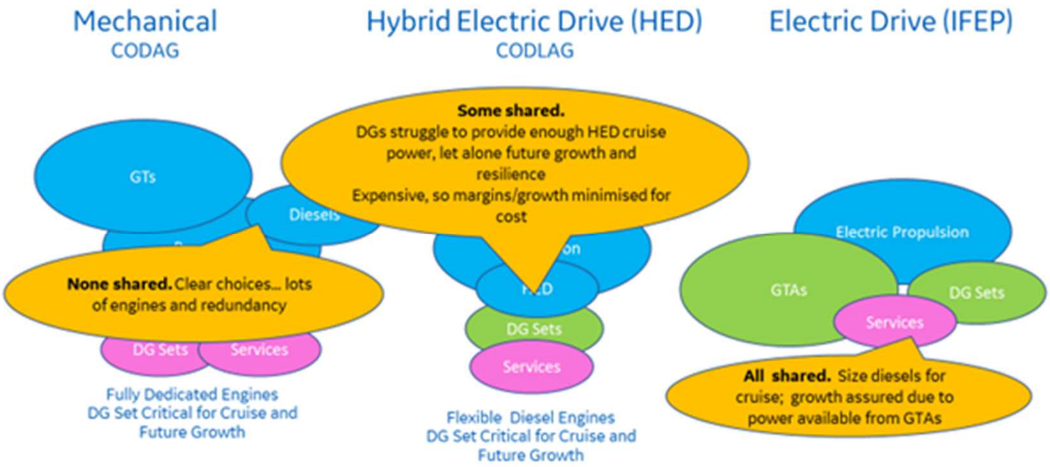

Figure 4: Mechanical versus Hybrid and Fully Integrated Electric Propulsion.

Hybrid DG set selection is challenging to get right, especially with CODLOG, and single GT hybrids. They need to provide efficient cruise, including hull margins, and an engine out/under maintenance cruise. They also have to provide electrical ship services, including future electrical growth margins. Naval DGs may be comparable with GTs on cost per MW, but their volumetric and gravimetric power density is much lower, so there is real pressure on initial ship design, fit and installation costs. In fact, Hybrid is the hardest system to get DG sizing right, especially from a margin/ future-proof perspective. This is illustrated in figure 5, where the two large squares represent installed electrical power on hybrid and IFEP systems with equal power demands (orange arrows).. All the pressure is on the DG sizing for CODLOG hybrid, which only provides 25% of the installed power.

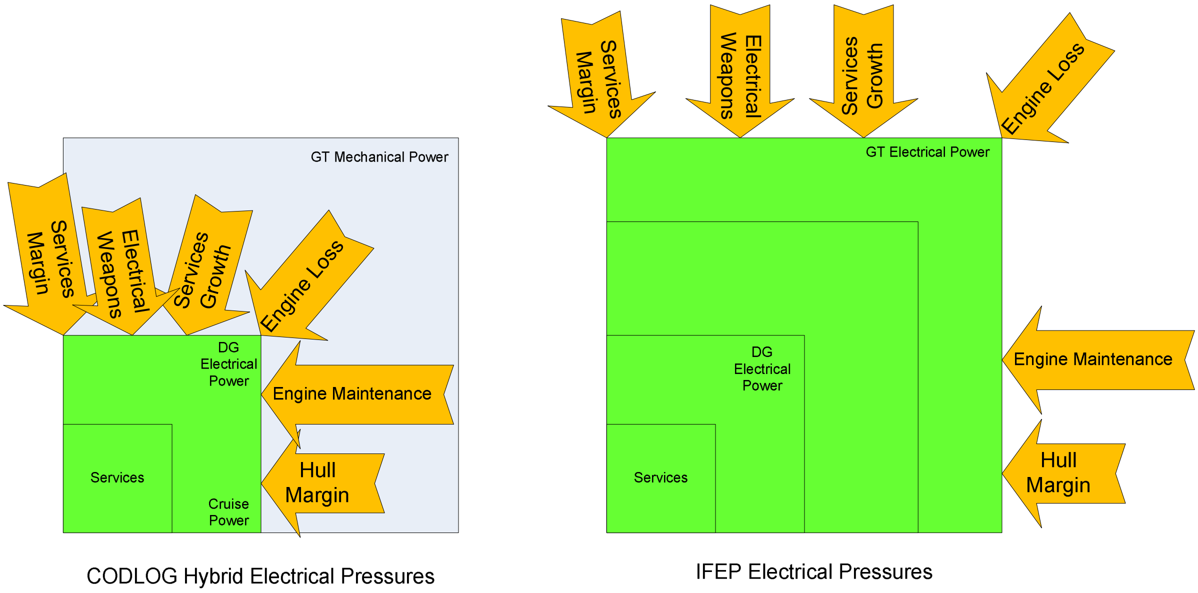

Figure 5: Electrical Loading Pressures on Hybrid and IFEP Generator Installations

Hybrids use their GT to sprint and back up cruise propulsion, but not electrical power; IFEPs use their GT to sprint, back up cruise propulsion and electrical services, including future growth. Type 23 has undertaken through-life power upgrade to diesels, and so has Type 45, which although IFEP, due to her unique GT, broke the normal rule for both IFEP and Hybrid, which is efficient cruise on diesels, sprint on GTs.

Even for the same powering requirements, Mechanical usually requires seven to eight prime movers; Hybrid typically requires five to six, whilst Full Electric only needs four, if sized correctly. Hybrid and Full Electric have to be sized to run on efficient prime movers and sprint on compact ones, hence they should have the same diesel fit power, but the Full Electric enables fewer engines, as all of its prime movers are capable of providing power for all loads. Hybrid retains large amounts of mechanical propulsion.

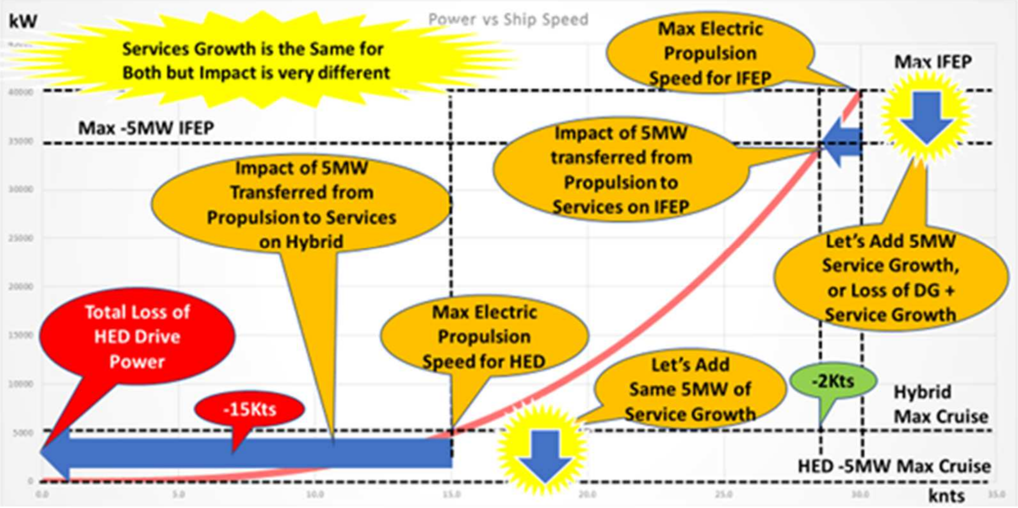

Figure 6: Impact of Electrical Growth on HED and IFEP at different ends of the Cube Law.

Fewer engines, properly sized, should save cost, hours run and maintenance. Combine this with secure single prime mover operation with backup energy storage and the most effective engine fit can be found.

Hybrids require more prime movers but not necessarily more power, but they do have the additional challenge that their electrical generation is at the lower end of the propulsion cube-law curve. Consider the example in figure 6. If 5MW of additional electrical power is required, on a fully electric system this drops the ship speed by a few knots as it is at the steep part of the power curve cube-law. Compare this with Hybrid; the same 5MW increase would sacrifice cruise efficiency/low noise operation, as it affects the other end of the power curve. The impact of future growth is very similar to loss of a DG set in a Hybrid design so mission and growth requirements should be considered from the outset.

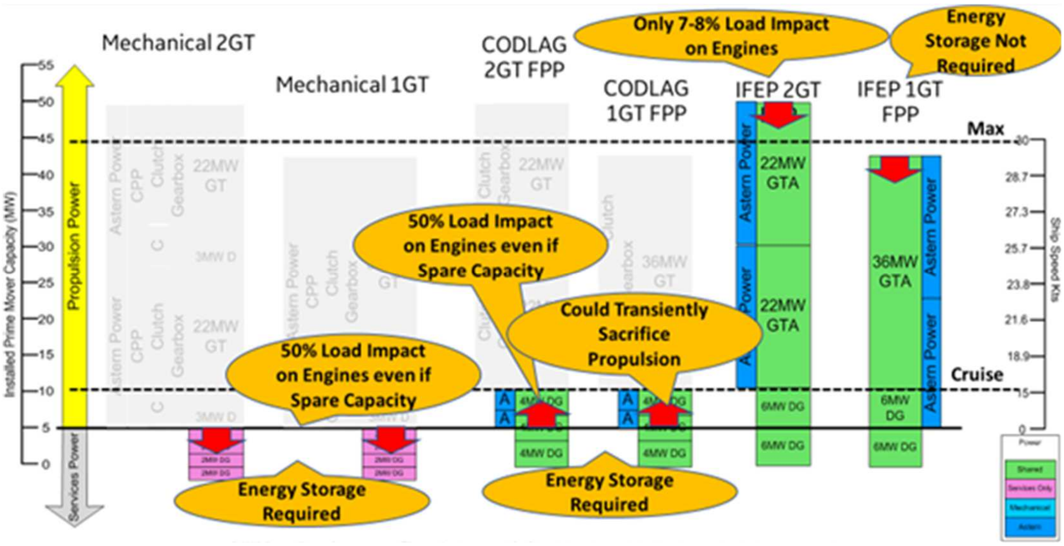

Figure 7: Effects of a 4MW Directed Energy Weapon or similar Transient Load.

Additional loads from high power sensors and pulse power supplies for DEW or Rail Guns will complicate the design space further. For example, figure 7 shows the impact of a 4MW future DEW load on various power generation architectures. Mechanical systems need energy storage, Hybrid can trade propulsion or take a 50% load step on the system, or fit energy storage. Full Electrical Systems can take such loads in their stride, as they represent less than a 10% load step, and in fact can trade propulsion to ensure no load step, with negligible speed impact during the firing.

For a bigger impact, such as a rail gun of 8MW, see figure 8, the Hybrid and Mechanical systems need large energy stores, but it is still only a 14% load step on the full electrical system.

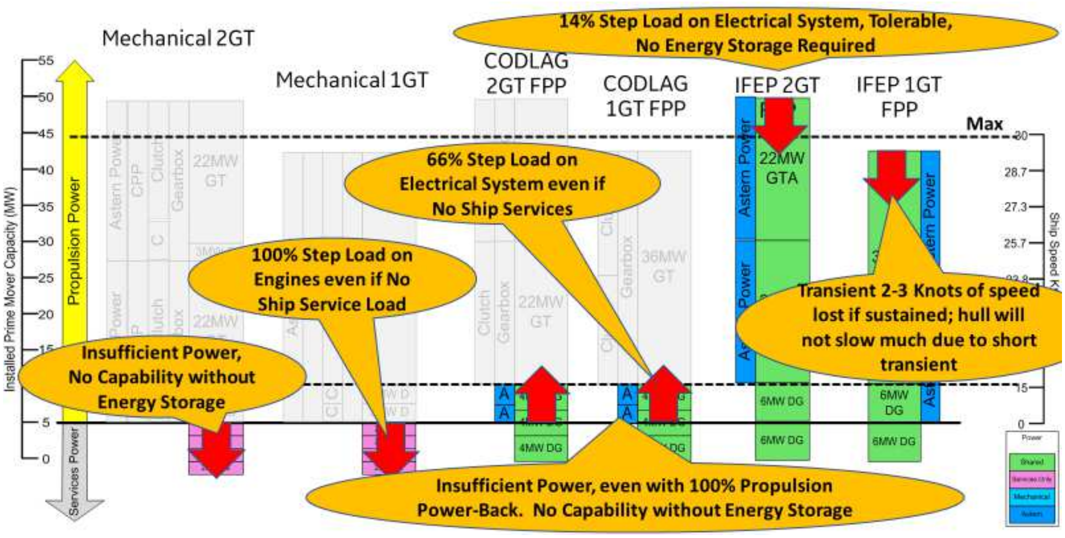

Figure 8: Effects of an 8MW Rail Gun or equivalent

Electric Ships will offer future efficiency and growth potential, not because of their prime movers or their propulsors, but because of the flexibility of their *networks*:

- Mechanical ship fits have no capacity for future growth without margin or refit, not used until needed, with no shared load; their ratio of flexible power/total power is 0%;

- Hybrid ship fits have some capacity for future growth, but it is already a challenge to get good cruise speed on diesels, so margin is often reduced, but they are approximately 20% flexible systems, so there is some sharing;
- Full Electric Systems have the most capacity for future growth, as it is 100% flexible - any prime mover provides for any load but there is still some impact of load sharing on the system;
- Hybrid services growth (e.g., a 5MW load growth) could significantly impact quiet cruise speed and low noise modes, as these are lower power electrical systems and load growth affects the low end of the ship's powering cube-law;
- Full Electric can accommodate the same 5MW load growth much more easily as any prime mover can be used, it impacts the ship's performance at the top end of the power speed curve, losing a few knots of top speed, but preserving low noise cruising;
- Full Electric is a large power system, so can accommodate impact loads much more easily than Hybrid or Mechanical, which need energy store for future loads such as DEW and Rail Guns;
- Full Electric Power systems typically require four prime movers as compared to Hybrid's five to six;
- Single Engine Hybrids are an interesting option, but with one large engine, potentially 80% of installed power could be lost on a single fault;
- Energy Storage is effective, although clearly an additional cost. Mechanical ships need a great deal, Hybrids will need quite a lot, and Full Electric much less or none to accommodate future pulse loads.

A future architecture may incorporate a large integrated Power Grid at the centre and it may initially have GTAs for power density and DGs for economy. They may be upgraded through life to adopt different fuels, or may be replaced through life by fuel cells, flow cells, high speed machines, etc. All of these can be accommodated on a fully rated grid which allows for:

- Fully Flexible Electric to support future growth and accommodate DEW, rail guns, or any future pulse loads, even those not yet conceived, rapid fire weapons, EMP, etc, and accommodate future classical load growth such as high-power sonar and radar systems;
- All power sources to be available to any load, either permanently or transiently;
- Energy Storage will likely be fitted to all solutions - a must on Mechanical and Hybrid, but also for IFEP to deliver resilience and economy, for example, to facilitate single prime movers.

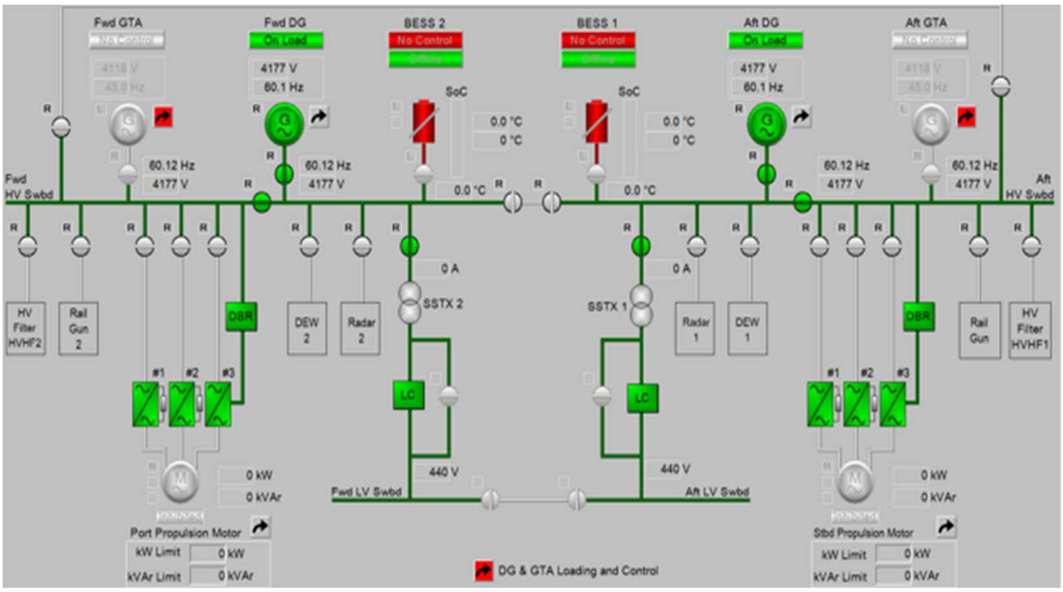

Figure 9: Mock-up of a Next Generation Architecture on current IPMS Mimic.

Figure 9 shows a mock-up of a next generation architecture on a current generation IPMS mimic. With minimal shared prime movers, some modest energy storage, direct high-power connections to rail gun and DEW type loads, and large multi-megawatt radars. The architecture employs a ring rather than linear arrangement, which could be either AC or DC. This debate is secondary to the primary benefit of the network at the centre, being able to connect diverse current and future prime movers and loads. Sensitive loads can be convertor fed, eliminating all quality of power supply issues and allowing the effective use of energy storage and very rapid changeover and reconfiguration. These convertors are not required throughout the system, only at key connection points to keep costs down and capability up. Such a system is 100% flexible and upgradable.

It is the authors' opinion that future Full Electric solutions on a future destroyer would be cost optimised, not by employing large technical advances on day one, but by using a blend of de-risked technologies to enable through-life growth. It will also focus on whole ship procurement, and through-life costs such as lean manning and fuel efficiency. Navies and industry need to polish what they have and optimise cost and capability. If they do that around a fully electric heart, then many future technologies, both loads and energy sources, will be able to be accommodated.

A future destroyer could deploy a mix of helicopters, UAVs and UUVs with small capacity DEW, but they may well still have classic prime movers highly fuel optimised by operation and energy storage assistance. Mid-life they could burn different fuels, and have their smaller prime mover replaced by fuel cells, as well as fitting larger electric weapons and mission systems. At end of life they might replace their gas turbines with static power sources, and large burst firing electrical weapons, shields or pulse generators. They may remotely charge swarms of remote vehicles by directed energy. All of these are possible, but they require flexible electrical power at their heart.

Warships have different mission profiles and roles, but all share a desire for efficiency and lower through-life costs. Cruise on diesels, sprint on turbines, deliver higher efficiency with electric. If mission profiles do not need flexibility, future-proofing is not required, and efficiency and manning is not a concern, then mechanical solutions could be considered, but still need to consider the impact of increasingly stringent emission regulations. Electrical propulsion on Type 23 was originally fitted for quiet operation, but large machines running at part load are quieter than small machines running on high load, so low noise is no longer the preserve of Hybrids, and in fact, fully rated electrical machines eliminate gearboxes, clutches and mode transfer noise.

The propulsion cube-law comes into play with spatial arrangements and grid power; for a Type 23 fitting in a low power motor was relatively straightforward, but as ship speed increases, you need a square of the torque. Motor size is rated primarily on torque, so a few megawatts of hybrid propulsion machine size is not too different to a fully rated IFEP motor, since the Hybrid needs to produce so much low down torque, but never gets to use that torque at high speed/power. Figure 10 shows an IFEP motor connected to a hybrid motor for testing, one is six times the power of the other, but the torque outputs are much closer, hence the similar size of the motor and convertor. What a lost opportunity, carrying around all that motor power potential but limiting it due to the grid capacity!

Figure 10: Full Electric and Hybrid Electric (Foreground) Connected on Test

Availability, cost and capability is vital, it's why the electrification of the world continues. But for a sensible comparison of up-front costs for a power system, the true up-front costs must be considered together. The more integrated the power system, the lower the engine costs both to buy and maintain. Gearboxes are being replaced by Power Electronic Convertors, both for initial and through life costs. Vessels from the ground up with grids on board, not legacy mechanical hulls, with electrical parts substituted within. We need to install the right amount of distribution and power grid, then choose the most appropriate prime movers. We also need to recognise that energy storage has a vital role to play, but not to compensate for a poorly integrated or weak architecture. It should also be recognised that LV (low voltage) grids on ships have been pushed to and sometimes over their limits. The explosive fault level of a 100kA+ LV system is much higher than a 30kA HV (high voltage) system, but generally, there is a greater fear of HV, due still to a lack of familiarity with the risks. The Royal Navy has inherently pioneered such grids on board. It's not about the prime movers or propulsors. Electric is the present, and is certainly the future - quiet, efficient, modern, future-proof, upgradable, lean-manned, for 21st century skills. Most of the pitfalls with its birth into warships were foreseeable and can be mitigated relatively easily. We should enter an era of consolidating the future around a central grid, not seeking some holy grail in the past or future approaches. Divide total installed power by electrical power and that gives you a good measure of how modern your warship is. Switch off any power source and retain at least 50% installed power is another good metric.

3 Conclusions

Warship design and powering will continue to evolve, driven by a mixture of economics, operational requirements and legislation. The move to adopting a net-zero or zero-carbon emission warship may seem like a long way off when considered as a target in 2050, but the impact of Global Warming is growing and, given the long life of such platforms, we will need to be able to technically address this problem within the next ten years.

A range of net-zero or zero-carbon fuels have been identified and a number are already available in significant industrial volumes. All offer lower calorific content when compared with diesel. Some require pressure, or cryogenic cooling to render them liquid, adding cost and volume to platforms that are typically volume-constrained. New designs will therefore need to balance such additional requirements, while retrofitting conventionally-fuelled warships may require more radical surgery, such as hull extensions, to create room for larger tanks and to cope with insulation or pressure.

The Royal Navy has pioneered full electric grids at the heart of its warships, not without some pain. These have been considered as full electric propulsion, or state of the art prime movers, when actually it is the grid in the middle that is the game changer. There are challenges to full electric ships, and there have been many legacy constraints, but going forward, to meet cost, size and performance requirements, these systems need to adopt fewer but more effective prime movers, and trade gearboxes for their electronic equivalent. Designers will have to concentrate more on the system architecture and outcome than the technologies that will come and go. Efficiency and reduced emissions are best achieved by operating at optimum load-levelled sweet spots on fewer prime movers. The more flexible and shared the system, the easier this is to achieve, that is why Hybrid and IFEP win versus mechanical. Mechanical is the most efficient at a single high power rating, Hybrid at more, IFEP at most.

4 References

1. Brown, W.M. (2003), The Royal Navy's Fuel Supplies, 1898 – 1939: The Transition from Coal to Oil, King's College London PhD thesis, (accessed May 2020).
2. E J Dahl, (2001), Naval Innovation: From Coal to Oil, National Defense University, Institute for National Strategic Studies, Winter 2000–01, (accessed May 2020).
3. Denmark: MS Selandia Marks 100 Years of Diesel Propulsion, 12 February 2012, (accessed May 2020).
4. F. W. Armstrong & M. G. Philpot, Future Prospects for Naval Propulsion Gas Turbines, Gas Turbine Conference & Products Show, London, England, April 9-13, 1978.
5. MARPOL ANNEX VI, Nitrogen Oxides (NO_X) – Regulation 13, (accessed May 2020).
6. The Paris Agreement, November 2015, (accessed May 2020).
7. Initial IMO Strategy On Reduction Of GHG Emissions From Ships, Resolution MEPC.304(72), (adopted on 13 April 2018), (accessed May 2020).
8. Clean Maritime Plan, Department for Transport, July 2019, (accessed May 2020).
9. Net Zero Technical report, Committee on Climate Change, May 2019, (accessed May 2020).
10. Techno-economic assessment of zero-carbon fuels, Lloyds Register / University Maritime Advisory Services, March 2020, (accessed May 2020).

5 Glossary

CODLOG	Combined Diesel Electric or Gas Turbine
DEW	Directed Energy Weapons

DG	Diesel Generator
EMP	Electromagnetic Pulse
GT	Gas Turbine
GTA	Gas Turbine Alternator
HED	Hybrid Electric Drive
HP	Horse Power
IFEP	Integrated Full Electric Propulsion
IPMS	Integrated Platform Management System
IMO	International Maritime Organisation
LCC	Life Cycle Costs
LNG	Liquid Natural Gas
NG	Natural Gas
SCR	Selective Catalytic Reduction
UAV	Unmanned Aerial Vehicles
UPC	Unit Procurement Costs
UUV	Unmanned Underwater Vehicles
VOC	Volatile Organic Compounds