Defence Suppliers Forum
Research Technology & Innovation Group (RTIG)

Powering Future Operations:

Net Zero Challenges & Opportunities

December 2020

Executive Summary

This paper reflects the views, inputs and insights from the Defence Suppliers Forum - Research Technology & Innovation Group (RTIG) members concerning the challenges and opportunities for future deployed energy and power provision and use, in the context of the Net Zero 2050 target.

Defence accounts for approximately 1% of the UK's total greenhouse gas emissions, with carbon emissions from defence capability (vehicles, platforms and associated logistics) accounting for the majority of annual defence CO_2e emissions.

There is huge civil and commercial investment in energy and power technology, presenting a great opportunity for Defence (with its comparatively modest investment levels) to capitalise on this, leveraging commercial technology investment for application to Defence platforms and systems. Defence must be positioned to select, adopt and adapt leading commercial energy and power technology to meet future capability needs, where it is appropriate to do so and focus investment on niche capability needs where civil technology developments are not fit for Defence needs.

The current technological state of the art in Energy and Power has not yet yielded a viable alternative to hydrocarbons across all capability needs. It is likely that any solution to the Net Zero capability challenge will be underpinned by a broad set of technologies and approaches. Some applications will align with civil / commercial developments, with others requiring a more defence specific approach. A thorough and detailed review of the applicability of candidate technologies to defence capability needs is called for.

It may be the case that technological solutions alone will not be sufficiently mature to reach Net Zero 2050 for all deployed military platforms at the levels required to maintain and extend operational advantage. It follows that offset strategies be targeted at those platforms and systems for which zero carbon alternatives are most challenging, whether on the basis of cost, technical feasibility or operational considerations such as survivability.

Effecting any form of widespread change across the Defence enterprise to realise the Net Zero 2050 objective requires an openness to, and acceptance of, new ways of working, concepts of operation and a willingness to reframe legacy policies, standards and approaches. The following science and technology (S&T) recommendations are offered for consideration:

1. **Develop a cohesive approach to energy and power S&T across Government:** leveraging the strength of investment in the civil and commercial domains, and identifying where niche technology approaches are needed. Form an energy and power intelligence cell that includes membership from UKRI, key energy and power technology players together with defence system integrators.

2. **Position Defence to influence and "Fast-Follow" rapidly emerging energy and power from outside Defence, with focus on integration to defence applications, and bespoke development for provision of niche capability where necessary.** Identify and explore niche capability needs, unique to Defence, and how S&T must be targeted to meet those needs

3. **Apply a systems approach to evaluating the impact of alternative energy and power technologies on deployed military capability:** Use Wargaming, operational analysis and experimentation to expose and explore the issues associated with the adoption of alternative technologies across a number of scenarios.

4. **Strengthen the access of Defence to expertise & SQEP in energy and power:** To provide Defence the expertise to follow and influence the evolving technological state of the art, positioning Defence for rapid adoption and adaptation of emerging technology for defence applications.

5. **Accelerate the use of monitoring systems to provide live data and insight:** To develop deeper understanding of system energy and power demands and to inform future needs for technology, cognisant of wider developments in digitisation, that will fundamentally change energy use.

6. **Understand where standardisation can be exploited to facilitate the use of alternative energy and power systems - prioritising interoperable, modular and scalable systems:** Engage with international partners, civil and defence industry in setting defence specific standards, only where commercial standards cannot be adopted.

Contents

Glossary of Terms

Bn	Billion
CO_2e	Carbon Dioxide Equivalent
tCO_2e	Tons of Carbon Dioxide Equivalent
$MtCO_2e$	Million Tons of Carbon Dioxide Equivalent
h	hour
J	Joules
kJ	kilo Joules
MJ	Mega Joules
kg	kilogram
kW	kilo watt
MW	Mega Watt
BEIS	Department for Business, Energy and Industrial Strategy
CCUS	Carbon Capture, Utilisation and Storage
CNG	Compressed Natural Gas
DC	Direct Current
DEW	Directed Energy Weapon(s)
DLOD	Defence Lines of Development
eFuel	Synthetic Fuels generated using electricity
EPSRC	Engineering and Physical Sciences Research Council
LNG	Liquefied Natural Gas
MOD	Ministry of Defence
NZ50	Net Zero 2050
Op.	Operation
R&D	Research and Development
RAF	Royal Air Force
RN	Royal Navy
S&T	Science and Technology
StratCom	Strategic Command
UKRI	UK Research and Innovation

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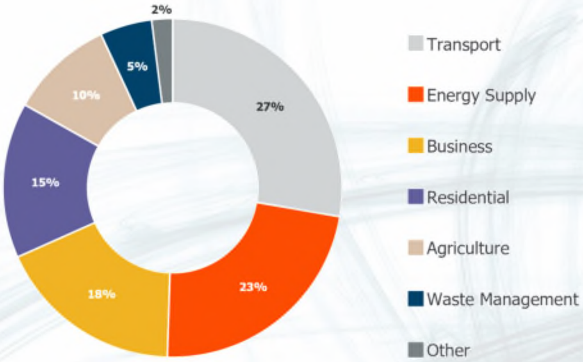
Foreword

This paper reflects the views, inputs and insights from the Defence Suppliers Forum - Research Technology & Innovation Group (RTIG) members across the UK MOD, Industry and UKRI. The information contained is a combination of that derived from public domain sources and inputs from working group members. The recommendations arising are the agreed output from the assembled group, developed through a series of workshops, and are offered for consideration in the shaping of Defence Science & Technology (S&T) strategy pertinent to the future of energy and power technologies for deployed defence capability.

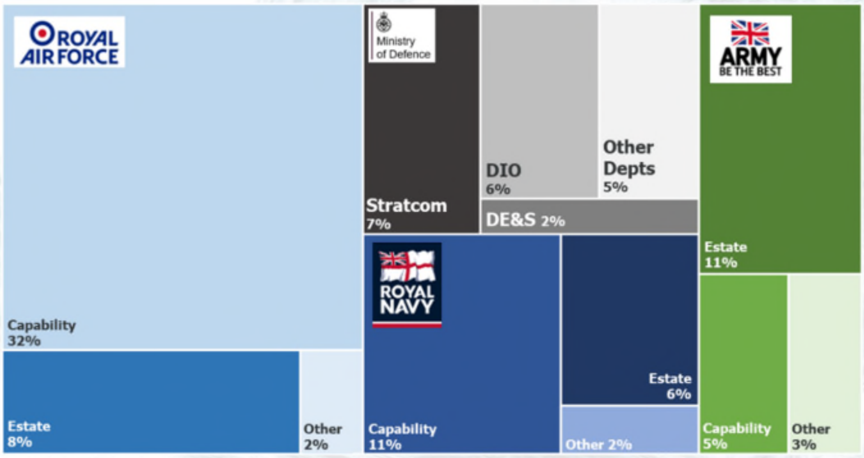
Carbon Footprint of Defence

In June 2019 the UK became the first major global economic power to enshrine its commitment to ending greenhouse gas emissions into law; requiring the UK to bring all greenhouse gas emissions to Net Zero by 2050.[1] In 2018, Defence in the UK generated 2.63 $MtCO_2e$ emissions. Defence accounts for approximately 1% of the UK's total greenhouse gas emissions on an annual basis and (including emissions across all defence activities) is more than double that of all other central Government departments combined[2].



UK Government Figures on greenhouse gas emissions by sector (Defence emissions feature across categories)
Source: UK Government – 2018 UK Greenhouse Gas Emissions – Final Figures[3]

Defence emissions have reduced by 45% from the 2009-10 baseline of 4.70 $MtCO_2e$. There is some correlation between this reduction in overall carbon equivalent greenhouse gas emissions and the reduction in operational tempo and overseas deployments (including the draw-down of forces from Op. Telic and Op. Herrick).



Breakdown of FY2018/19 MOD Emissions
Source: adapted from MOD CS&S Strategy Team Briefing and DSFA inputs[4] [5]

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[1] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law
[2] https://www.nao.org.uk/wp-content/uploads/2020/05/Environmental-Sustainability-Overview.pdf
[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/862887/2018_Final_greenhouse_gas_emissions_statistical_release.pdf
[4] MOD CS& Strategy Team Briefing Presentation, provided to RTIG by Cdr Paul Williams, Royal Navy
[5] Defence Strategic Fuels Authority inputs to RTIG

A significant portion of the contribution to GHG emissions from defence results from emissions generated by fuel usage through operations and associated training and logistics activities. The distribution of energy consumption and greenhouse gas emissions varies by service, with the RAF contributing 42% of the overall emissions total, the Royal Navy and Army each contributing 19%. The distribution of fuel use by type reflects a similar trend, with aviation fuel consumption being the dominant contributor.

The Case for Change

Beyond the clear legislative and environmental imperative to address the challenges of Net Zero by 2050, there are other, equally compelling reasons to consider the future of energy & power for deployed capability. A global transition away from conventional hydrocarbon fuel sources presents further motivators for adopting alternative approaches for the supply of energy and generation of power for deployed forces.

Civil and commercial markets in developed nations will move away from the use of conventional hydrocarbons, however the pace at which this transition will take place (and the rate of adoption of low carbon alternatives across the globe) is not yet known. Defence must therefore be positioned to adapt to a future in which the availability of fossil fuels diminishes on an uncertain timeline.

Not only must future alternative energy vectors and power generation systems be considered to address the challenges of Net Zero, but the very nature of the environments in which forces will be deployed in the future is evolving due to the impacts of greenhouse gas emissions and climate change.

The remit of the Ministry of Defence and the UK's armed forces is to provide security and protection to the United Kingdom's people, territories, values and interests, at home and overseas.[6] In so doing, retaining and enhancing capability advantage is of paramount importance, and any moves to address the challenge of Net Zero must retain the sharpest focus on this imperative. Operational capability advantage must come first.

Defence must seek opportunities to secure operational advantages offered by low carbon technologies; including reductions in acoustic and other signatures, reduced overall energy consumption and logistics burden along with improvements in flexibility offered through the adoption of hybrid drives and micro grids.

Whilst the focus of this deep dive is on energy and power associated with deployed capability, it is recognised that a whole force approach to energy, power and emissions management will be required to address the Net Zero target.

This paper does not provide a comprehensive review of energy and power technologies, rather it considers four principle themes of relevance to energy and power for Defence platforms:

Operational Demands & Considerations – Consider impacts on Defence Lines of Development (DLODs) of alternative energy and power technologies and the role of open standards and architectures in the adoption and deployment of future energy and power systems.

Defence platform energy and power needs – Develop contextual understanding of energy and power demands across current defence platforms. Provide insight to how energy and power demands may evolve beyond 2030 and how this may impact on the suitability of alternative energy power solutions.

Energy and Power Technologies – Review technological developments in energy & power, providing a summary of the current state of the art, development targets and limitations.

Investment Landscape – Explore civil and defence market investment in energy and power technologies, and develop insights into current energy and power initiatives being undertaken across MOD.

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[6] https://www.gov.uk/government/organisations/ministry-of-defence

Operational Demands and Considerations

The operational environment is, by its very nature, both demanding and diverse. Military platforms and assets are subject to conditions not routinely experienced in non-defence contexts, and the ability of platforms and systems to operate effectively within these challenging and varied environments is fundamental to effective capability provision.

Beyond the qualifying question of whether alternative energy and power systems have the capacity to meet the performance needs of platforms, in terms of propulsive power, range and longevity of deployment, there are other factors of key importance that must be evaluated when considering the suitability of alternative approaches to satisfying energy and power needs.

A number of these elements can be considered as hygiene factors, or those that form the base level requirement needed to retain operational capability and allow a system to operate in an operational context; such as tolerance of the broad range of operating temperatures, and the rigours of the physical environment. Others, notably Signature, present the opportunity to enhance operational advantage. An obvious, but noteworthy example being the near silent running, and lack of exhaust gas emissions offered by electrical propulsion systems when compared to conventional internal combustion engines.

Operational Demands and Considerations
– Consolidated view from working group participants

Adoption of alternative energy and power systems will have implications across the DLODs[7], and the nature of these implications will vary according to the technology under consideration and the specific needs of the capability for which it is being considered. Defence capability and the associated equipment, platform and systems, support infrastructure, concepts of operation, doctrine and logistics management continue to evolve. The ubiquity of hydrocarbon based energy and power systems in defence applications over the last century or more, dictates that current approaches are heavily influenced by the role of hydrocarbons as the principal means of energy storage and distribution. Any deviation to this approach will have wide reaching considerations extending far beyond the technical feasibility of alternative approaches.

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[7] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/36757/20100602MODAFDownload12004.pdf

Defence platform energy and power needs

A subset of platform types have been considered to provide a contextual understanding of the relative energy storage and power requirements associated with differing platform types in the Air, Land and Naval domains (Appendix 1).

Across the platforms considered, the proportion of platform mass committed to fuel storage ranges between 40% in fixed wing applications to 2% for armoured fighting vehicles, & less than 1% in the case of nuclear powered submarines. Storage volume on platform for fuel ranges between 22% in some fixed wing cases and less than 1% for some naval and land based systems. Power to weight ratio requirements for airborne platforms are typically 1 or 2 orders of magnitude higher than those for naval and land based platforms, ranging from over 400 W/kg for fast jet and rotary wing attack platforms to less than 2W/kg for naval platforms.

Evolving and future platform demands

Whilst the future energy drivers for platforms vary according to role and domain, there is a continually steepening upward trend for energy and power demand both for propulsion and to power increasingly complex on-board systems. There is a balancing influence from increased efficiencies in energy and power transmission networks and smarter systems architectures for the management of on-board energy and power distribution. However, the historical and likely future trend is for on-board demand to continue to increase.

The future adoption of DEW based weapon systems[8] and an increasing focus on electromagnetic warfare capability indicate that this demand increase is likely to get ever greater as future capabilities develop. Other developments such as hypersonic weapons will place additional, and in some instances, unique requirements on the energy and power systems needed.

Future Force Structure

In October 2020, the Rt Hon. Ben Wallace; Secretary of State for Defence and General Sir Nick Carter; Chief of the Defence Staff, presented the Integrated Operating Concept, outlining the vision for future warfare and the nature of the key capabilities that will deliver operational advantage at a strategic level in the future.

The operating concept recognises that an evolution of force structure will be required to meet the Defence needs of the future, highlighting the need for smaller and faster capabilities and reducing dependency on fossil fuels. The concept also highlights an increased mix of crewed, un-crewed and autonomous platforms, a greater focus on the role of electronic warfare, information advantage, low observable and stealth technologies[9]. Subsequent speeches and announcements from senior military and MOD figures have reinforced this approach, particularly with reference to the increased proliferation of autonomous and optionally manned systems.

The announcement of the Integrated Operating Concept was followed by a revised MoD Science & Technology Strategy[10], published in October 2020 with an overarching focus on the “Generation after Next” capability and the need for future capabilities to be “greener than ever before” noting that there will be a clean capability agenda mirroring the clean growth agenda at the heart of the UK’s industrial strategy.

The future shape and use of Defence forces is a key consideration when determining what the associated energy and power systems may look like going forward. An increased shift towards greater use of smaller autonomous or otherwise unmanned systems presents a very different set of technology options and challenges to those that would be considered if large manned platforms remain ubiquitous. The growth of digitisation and adoption of synthetic training, for example, provides opportunities for significant reductions in the use of physical assets in peacetime, with a corresponding reduction in emissions.

Recommendation - Accelerate the use of monitoring systems to provide live data and insight: To develop deeper understanding of system energy and power demands and to inform future needs for technology, cognisant of wider developments in digitisation, that will fundamentally change energy use.

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[8] MBDA Insights into requirements of DEW systems

[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/922969/20200930_-_Introducing_the_Integrated_Operating_Concept.pdf

[10] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/927708/20201019-MOD_ST_Strategy_2020_v1-23.pdf

Defence Direction and Sustainability landscape

Lt Gen Nugee is leading the review into the MOD's contribution to Net Zero 2050, considering all the defence elements that contribute to MOD emissions, culminating in a Defence Climate change and security strategy, anticipated in the coming weeks. The recently published roadmap for sustainable defence outlines a vision for reaching Net Zero by 2050[11] outlining some nominal timescales by which individual measures and approaches will need to be in place

It is clear that immediate action is required to position Defence to meet the challenge of NZ50. This action must be appropriately focused, supported by allocation of budgets commensurate with the challenge and underpinned by a cohesive approach across Defence and government.

A detailed analysis of Deployed capability carbon footprint, identifying the contribution to Defence emissions made by each platform and system in operation is needed, to ensure that investment is directed to those areas that represent the optimum trade-off between reduction in CO_2e and ease of implementation. A number of projects, activities and initiatives are already underway across defence. (Appendix 2)

Effecting any form of widespread change across the Defence enterprise to realise the Net Zero 2050 objective requires an openness to, and acceptance of, new ways of working, concepts of operation and a willingness to reframe legacy policies, standards and approaches. This may extend to a cultural shift, whereby energy is treated as a battlefield commodity, in the same way as ammunition, fuel or food and the procurement and equipment planning approach places sharp focus on establishing an energy budget for platforms, systems and subsystems.

Energy and Power Technologies

There are a myriad of alternative energy and power technologies subject to research and development for both civil and defence applications, at varying stages of maturity and readiness for adoption depending on individual application. Central to the consideration of alternative energy and power systems to those currently employed for military capability is the energy density available from the respective storage vectors (predominantly gasoline or derivatives thereof). A synopsis of energy and power technologies considered, their merits and shortcomings are included at Appendix 3.

Industry are considering a broad range of energy and power technologies at various stages of maturity, including very early to mid-stage stage research in areas such as Leptonic fuels and coherence capacitors at Lockheed Martin, and micro deployable reactors and heat drive energy storage at Rolls Royce. Mid and late stage maturity research areas including alternative fuels, electrical actuation / electrical and hybrid propulsion systems and power and energy management systems continue to be explored, developed and implemented by organisations including BAE Systems, Leonardo, QinetiQ and Rolls Royce.

As of yet, there is no solution that is fit for all (civil or defence), no silver bullet technology that provides an overarching solution for all purposes. Commonality of approach is of course of great benefit, however it must be recognised that any solution to the Net Zero challenge will be underpinned by a broad set of technologies and approaches.

Recommendation - Strengthen the access of Defence to expertise & SQEP in energy and power: To provide Defence the expertise to follow and influence the evolving technological state of the art, positioning Defence for rapid adoption and adaptation of emerging technology for defence applications.

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[11] https://secure.teamdefence.info/filerequest.php?id=1007437

Observations

Investment

Global defence R&D investment in energy and power technologies is estimated to be in the order of £4.5Bn per annum, with over 80% of this total coming from the US Department for Defence. In the UK, the latest published ONS figures indicate that defence specific R&D totals approximately £2bn, 5% of the UK's total R&D spending (£37.1 billion or 1.7% of GDP)[12]. In contrast, global energy investments were in the order of $1.8 T in 2018, with low carbon energy and power investment accounting for over 50% of this total.[13]. Worldwide energy R&D combining State and Corporate R&D investment was in excess of $120 billion in 2018.

In the UK, there has been a significant increase in civilian transport investment across various arms of Government including the Department for Transport, BEIS and UKRI in recent years, with Innovate UK reporting over £5 billion of transport related investments between 2006 and 2019. A significant proportion of this investment is relevant to energy and power for deployed systems. Major investments have been made in battery technology, through the Faraday battery challenge; low carbon propulsion technologies through the Advanced Propulsion Centre; and Aerospace.

The UKRI Engineering and Physical Sciences Research Council are reporting substantial investments in clean energy technologies, with current investments of £33m in wind power; £32m in Solar; £24m on Marine, Wave and Tidal; £66m in Fission; £43m on Fusion and £17m on Carbon Capture, Utilisation and Storage (CCUS).

Furthermore, a series of decarbonising transport networks were established by the UKRI Engineering and Physical Sciences Research Council in 2019 supported by £5m of funding, bringing together expertise from across academia and industry[14] covering 5 focus areas:

- Network – H2: A network for hydrogen-fuelled transportation
- Decarbonising the UK's freight transport
- Decarbonising Transport through electrification (DTE), a Whole System Approach
- New Jet Network+
- DecarboN8 – An integrated Network to decarbonise transport

There is huge civil and commercial investment in energy and power technology, presenting a great opportunity for Defence (with its comparatively modest investment levels) to capitalise on this, leveraging commercial technology investment for application to Defence platforms and systems. Defence must be positioned to select, adopt and adapt leading commercial energy and power technology to meet future capability needs.

Recommendation - Develop a cohesive approach to energy and power S&T across Government: leveraging the strength of investment in the civil and commercial domains, and identifying where niche technology approaches are needed. Form an energy and power intelligence cell that includes membership from UKRI, key energy and power technology players together with defence system integrators.

Technology

It is clear that current technological state of the art in energy and power has not yet yielded a technology that can compete with the energy densities provided by traditional hydrocarbon based fuels for all applications. It also appears that the technology gestation period for new and emerging technologies will necessitate a phased approach to de-carbonising deployed capability, with focused interventions for bases, logistics and the procurement and operation of new platforms and equipment.

Technological advances alone are not sufficient to meet the Net Zero challenge, whether for Defence or for society more generally. A whole system / enterprise approach encompassing technology, legislation, policy, doctrine, and culture is needed.

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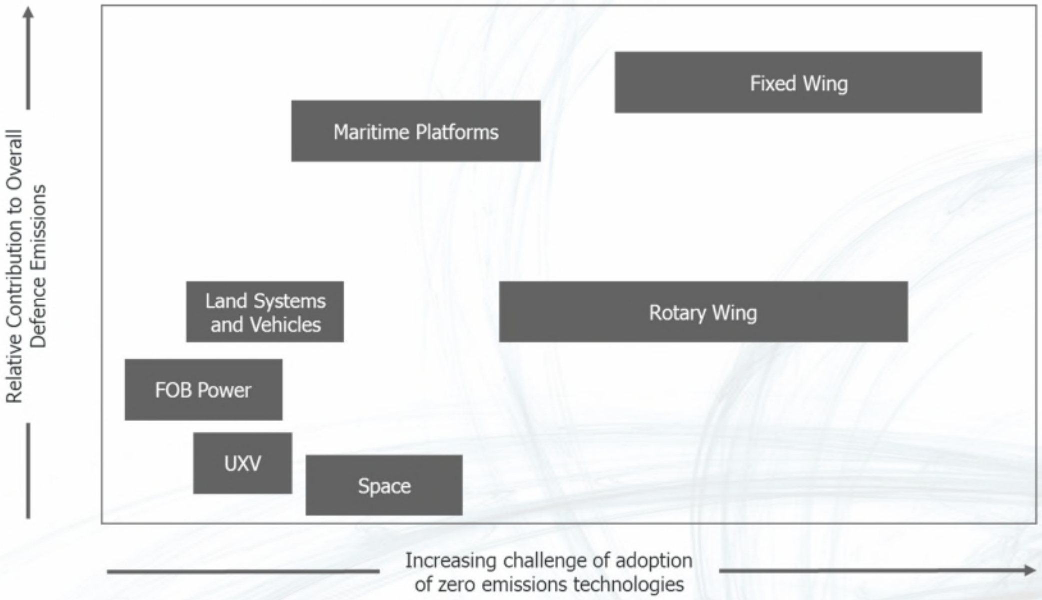
[12] https://www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2018

[13] World Energy Investment 2019, https://www.iea.org/reports/world-energy-investment-2019

[14] https://webarchive.nationalarchives.gov.uk/20200930160159/https://epsrc.ukri.org/newsevents/news/networks-to-prepare-uk-transport-for-a-low-carbon-future/

Beyond the Net Zero imperative, there are a multitude of other factors that must be considered in realising effective and sustainable change, not least of which are the through life monetary and environmental costs associated with alternatives to traditional hydrocarbon fuels and the clear imperative to maintain capability advantage.

The relative ease with which deployable platforms and systems can be brought to a zero carbon emissions position and their relative contribution to overall defence emissions can be considered as a continuum



Challenge and Benefit of Net Zero across capabilities
For Illustrative purposes only

The least disruptive alternative energy storage vector for current and next generation platforms may be through the adoption of Net Zero emissions fuels. The adoption of alternative fuels perhaps has the least impact on existing platforms and systems (in terms of retrofit), represents a modest change (relatively speaking) to the technologies and systems employed and the doctrinal and logistics considerations associated with re-supply, transportation and storage management.

It is however widely accepted that production of bio-fuels in the quantities required for meaningful widespread adoption is limited both by land availability and the impact of diverting land usage to fuel crop growth in preference to conventional agriculture. Artificial synthesis of hydrocarbons utilising Carbon Capture and Storage technologies may be a viable long term solution, but is dependent on securing both efficient means of capturing and storing atmospheric carbon (to be Net Zero in use) and having vast quantities of cheap, reliable and readily available energy generation, due to the underlying conversion inefficiencies of eFuel technologies. At the moment the current and emerging technology options to provide this primary energy provision are through renewables, fission or fusion. Adopting this approach as a whole force solution is fundamentally limited at the present time by the commercial availability of cheap, plentiful, renewable or nuclear energy.

Options for deployable local clean energy, power and fuel generation, whether through micro-reactors, renewables or other means should be given consideration, assessing the opportunities to reduce the logistical burden of getting fuel to the front line and replace with “tactical energy nodes” whereby local energy generation and conversion to the appropriate storage vector (e.g. electrical storage, synthetic fuels etc.) reduces reliance on logistics transport. Estimates vary, however it is widely considered that getting a single litre of fuel to the front line consumes in the order of 8-10 litres to get it there through the logistic chain in some operational environments, along with an additional cost of committed materiel, manpower and ultimately lives[15]. It is proposed that a number of Defence platforms and

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[15] UKDSC Cross Sector Innovation – Energising Defence Whitepaper, CSI3-RP-0001-v3.0, June 2020

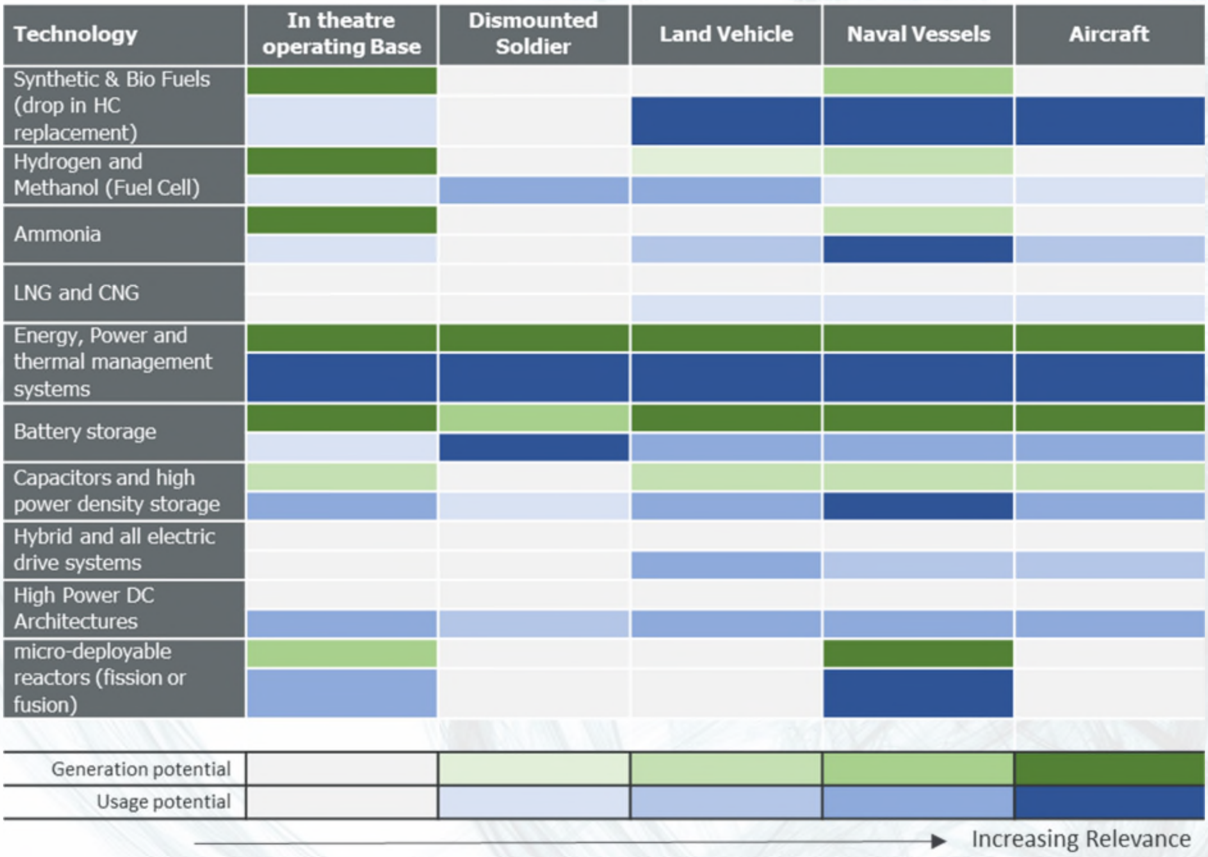
forward operating bases be considered not only in terms of energy usage, but their potential for energy generation and provision for use by other platforms and systems.

Defence capabilities have a number of requirements that differentiate them from civil and commercial systems, and whilst it is considered necessary to leverage and adopt developments made in the civil and commercial sectors, there will be limitations on the degree to which this can be achieved. It follows therefore that S&T investment is targeted to those niche capability needs that drive specific technology approaches for defence.

A rigorous approach is required in determining the key, niche Defence needs that necessitate focused investment, where the acceptable system trade-offs will differ to those for civilian applications, such as:

- Ruggedized, high specific energy and power density batteries (e.g. specialist high energy primary batteries)
- High energy architectures and pulsed power technologies for Directed Energy Weapons
- Compact power sources for Unmanned and Autonomous Systems (enhanced endurance capability)
- Complex Weapons (kinetic & non-kinetic)

Recommendation - Position Defence to influence and "Fast-Follow" rapidly emerging energy and power from outside Defence with focus on integration to defence applications, and bespoke development for provision of niche capability where necessary: Identify and explore niche capability needs, unique to Defence, and how S&T must be targeted to meet those needs



Relevance of energy and power technologies to deployed systems
Source: derived from RTIG energy and power workshop participation

It may be the case that technological solutions will not be sufficiently mature to reach Net Zero for all deployed military platforms at the levels required to maintain, and indeed extend, operational advantage by 2050. It follows that offset strategies be targeted at those platforms and systems for which zero carbon alternatives are most challenging, whether on the basis of cost, technical feasibility or operational considerations such as survivability.

Recommendation - Apply a systems approach to evaluating the impact of alternative energy and power technologies on deployed military capability: Use Wargaming, operational analysis and experimentation to expose and explore the issues associated with the adoption of alternative technologies across a number of scenarios.

Estimates for the efficacy of forested areas in terms of carbon sequestration vary, with figures ranging broadly dependent on the ecology and maturity of the forested area in question. Taking an estimate of 10,000lbs CO_2e per acre per year[16] (equivalent to 11.1 tons/hectare) would require carbon offset totalling over 160,000 hectares, or 1,600 square km, an area the size of Hertfordshire, or 2/3rd of the defence estate (~240,000 hectares, approximately 1% of the UK's land mass). It is noted that the level of carbon sequestration achieved through forestry operations varies based on the maturity of the forested area and ultimately reach a stage of maturity whereby they no longer take up additional carbon, at which point the resulting carbon then needs to be protected or harvested to enable regrowth.[17]

The role of Open Standards

There is a need to consider the role of open standards and architectures in the future of energy and power for deployed capability. It is well understood that open standards and commonality of approach enable interoperability, flexibility and modularity.

Open standards to provoke technology innovation:

Open standards that draw out the resilience and performance requirements associated with defence use, addressing the operational considerations noted previously, can be used by commercial investors to target their future product development and hence to provoke technology innovation. They should assume and be resilient to technology evolution, and as such focus should be placed on points of interoperability; the core infrastructure for connection, with maximum flexibility through modularity, scalability and effective data access and exploitation.

An open standard should be such that a third party can introduce a change to the system without requiring direct involvement from the original equipment manufacturer. Success relies on clear, early & persistent standards, including forecasting the likely nature of future power needs for anticipated defence scenarios (particularly to distinguish between high energy, high pulse power and other relevant needs).

A gap analysis between defence and other industry / commercial standards will enable industry to develop effective portfolio solutions with market- and application-specific variants. For example, to account for military robustness & resilience requirements. This should determine areas where existing defence and commercial standards can be leveraged for the chosen applications and identify where there are gaps that require additional development. It will increase MOD ability to 'adopt and adapt' commercial technology and make the defence market increasingly accessible to commercial technology providers.

Open standards to enable better design, modularity and operational sovereignty:

Collaborative whole-system design can enable significant savings, more efficient power management and a shorter design cycle, requiring an agreed approach to determining the 'right' power profile for the system that allows interaction and trading between system components.

Success relies on excellent commercial frameworks and approaches that deal with risk and liability management throughout the product / system lifecycle, rewarding all for whole-system excellence and encouraging collaborative innovation. This requires a joined-up Defence view of systems to be procured, their scenarios of use and position within the whole system, beginning with including a requirement for commonality in defence procurements.

Recommendation - Understand where standardisation can be exploited to facilitate the use of alternative energy and power systems - prioritising interoperable, modular and scalable systems: Engage with international partners, civil and defence industry in setting defence specific standards, only where commercial standards cannot be adopted.

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[16] https://medcraveonline.com/FREIJ/FREIJ-02-00040.pdf

[17] https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

Electrification

There is undoubtedly a groundswell of interest and investment in the increased electrification of systems, whether at a system and subsystem level, or indeed as a whole platform means of providing energy, power and propulsion. Platform subsystem functionality that would historically been provided by hydraulic or pneumatic systems, for example, are increasingly being replaced by electronic systems, yielding significant benefits in overall efficiency. The proliferation of electrical systems offers further benefits through the smart management and distribution of energy and power across networks, whether at a platform, Forward Operating Base, or deployed force level.

There are limitations on the extent to which batteries can satisfy the burgeoning energy and power demands for military platforms. The current state of the art lithium cells are in the order of 10 times less energy dense per unit mass than hydrocarbons (including provision for conversion losses). By way of illustration, approximately 2% of a Main battle Tank mass is taken up by fuel storage, which obviously reduces as fuel is consumed. To get the same level of stored energy on board, with the efficiencies offered by electric propulsion would require around 20% of the platform mass to be dedicated to batteries, to allow the same level of power output and endurance. There is of course the added complication of recharging time or otherwise having the capability to hot-swap battery packs to maintain operational tempo. In the case of those platforms where mass is at even more of a premium, this becomes less and less attractive.

The UK has deployed methanol fuel cell hybrid power systems in place of diesel generator sets with notable increases in efficiency, reduction in volume of fuel used, lower cost and other operational benefits such as silent running. [18]

Methanol and other Fuel cell technologies may offer an attractive middle ground that benefits from the hugely enhanced efficiency of electrical distribution and propulsion systems and the energy density of methanol, which several times greater than that of current state of the art lithium cells.

Conclusion

Military capabilities have unique attributes and requirements that differentiate them and their energy and power needs from those of commercial vehicles and systems, yet Defence alone does not have the resources, SQEP or, indeed, the time to develop new technologies to meet the challenge of Net Zero from the ground up.

Defence must leverage the pace and scale of technological advancement from the commercial sector where possible, positioning itself to identify, adopt, adapt and integrate the right mix of rapidly emerging technologies to meet the Net Zero challenge. Defence must also focus resources on the niche requirements, unique to defence, for which civil and commercial solutions will not be suitable.

Defence must seek opportunities to secure operational advantages offered by low carbon technologies; including reductions in acoustic and other signatures, reduced overall energy consumption and logistics burden along with improvements in flexibility offered through the adoption of hybrid drives and micro grids.

The current technological state of the art in energy and power has not yet yielded a viable alternative to hydrocarbons across all capability needs. It is likely that any solution to the Net Zero capability challenge will be underpinned by a broad set of technologies and approaches. A thorough and detailed review of the applicability of candidate technologies to defence capability needs is called for.

It may be the case that technological solutions alone will not be sufficiently mature to reach Net Zero 2050 for all deployed military platforms at the levels required to maintain, and extend operational advantage. It follows that offset strategies be targeted at those platforms and systems for which zero carbon alternatives are most challenging, whether on the basis of cost, technical feasibility or operational considerations such as survivability.

Effecting any form of widespread change across the Defence enterprise to realise the Net Zero 2050 objective requires an openness to new ways of working, concepts of operation and a willingness to reframe legacy policies, standards and approaches. If we change nothing, nothing will change.

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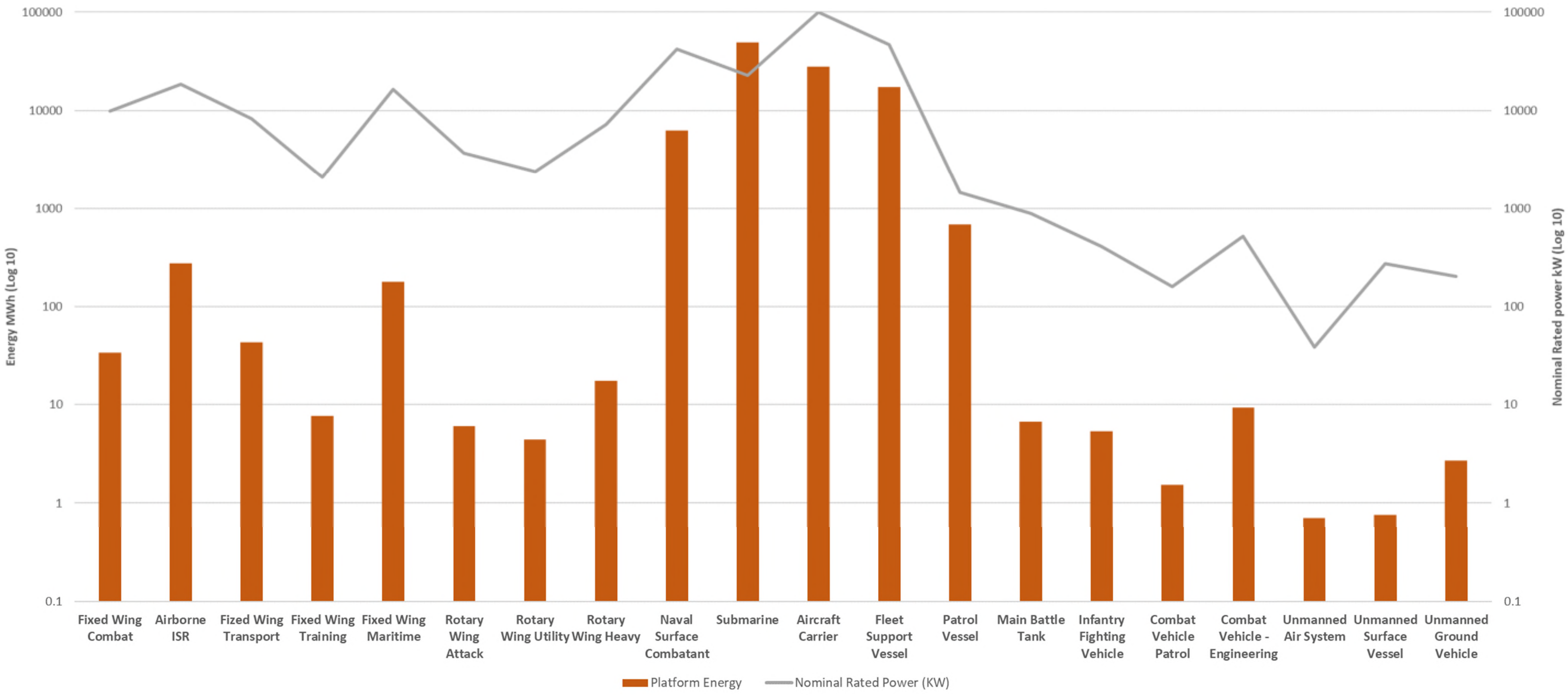
[18] Source: Zero Alpha solutions – Hybrid Power Systems

Appendix 1 – Defence Platform Energy and Power Needs

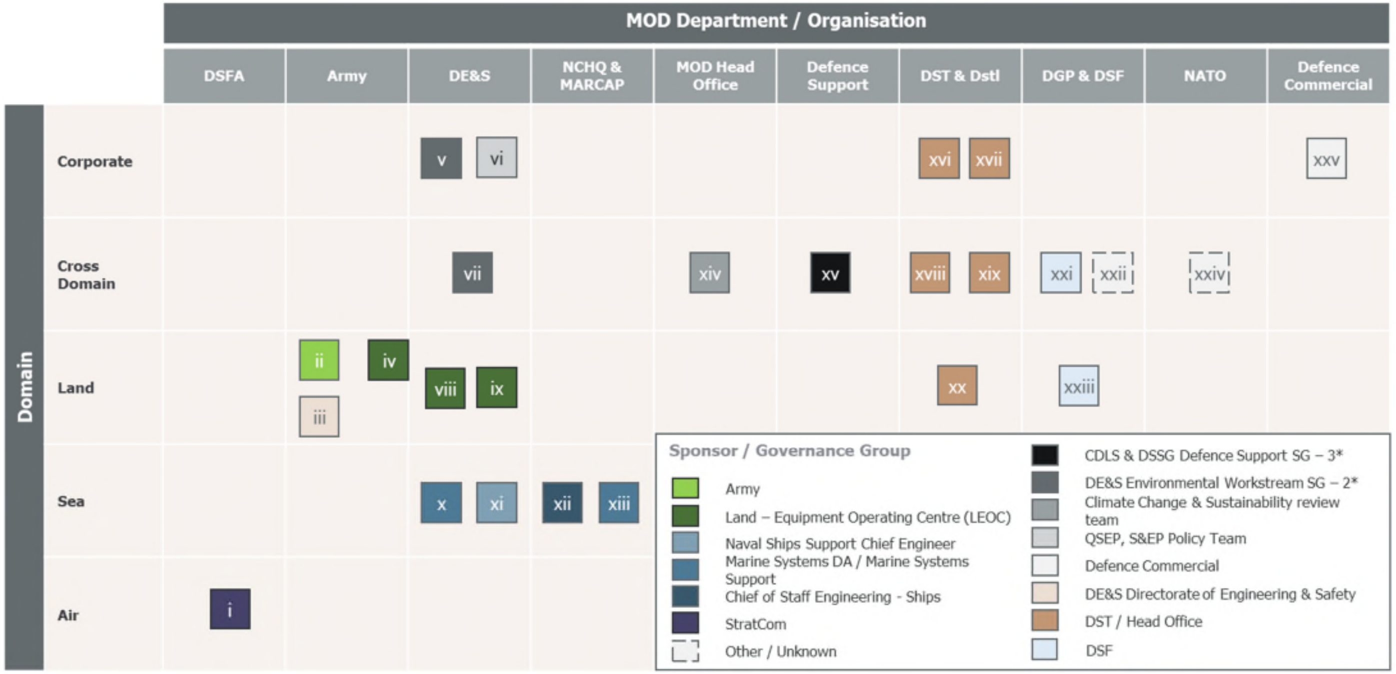
An illustrative view of energy and power requirements across a sample of platform types based on publically available data is provided, indicating the total energy available for use, considering losses due to the inherent thermal efficiency of such systems. Also shown is the nominal power output of the systems in question, noting that some estimates of equivalent power have been determined to account for propulsive power from thrust based systems.



Platform Energy and Nominal Power – Note scales are Log10

This assessment is based on energy and power demands associated with current platforms and systems. However, advances in sensor and on-board systems technologies are driving ever higher requirements for energy and power on platforms. In rotary wing applications for instance, Leonardo estimate that some 90% of the power on the platform is required for lift and propulsion, with the remaining 10% required for other on-board systems including avionics.

Appendix 2 – Sample of UK MOD sustainability activities



Domain	DSFA	Army	DE&S	NCHQ & MARCAP	MOD Head Office	Defence Support	DST & Dstl	DGP & DSF	NATO	Defence Commercial
Corporate			v vi				xvi xvii			xxv
Cross Domain			vii		xiv	xv	xviii xix	xxi xxii	xxiv	
Land		ii iii iv	viii ix				xx	xxiii		
Sea			x xi	xii xiii						
Air	i									

Sponsor / Governance Group

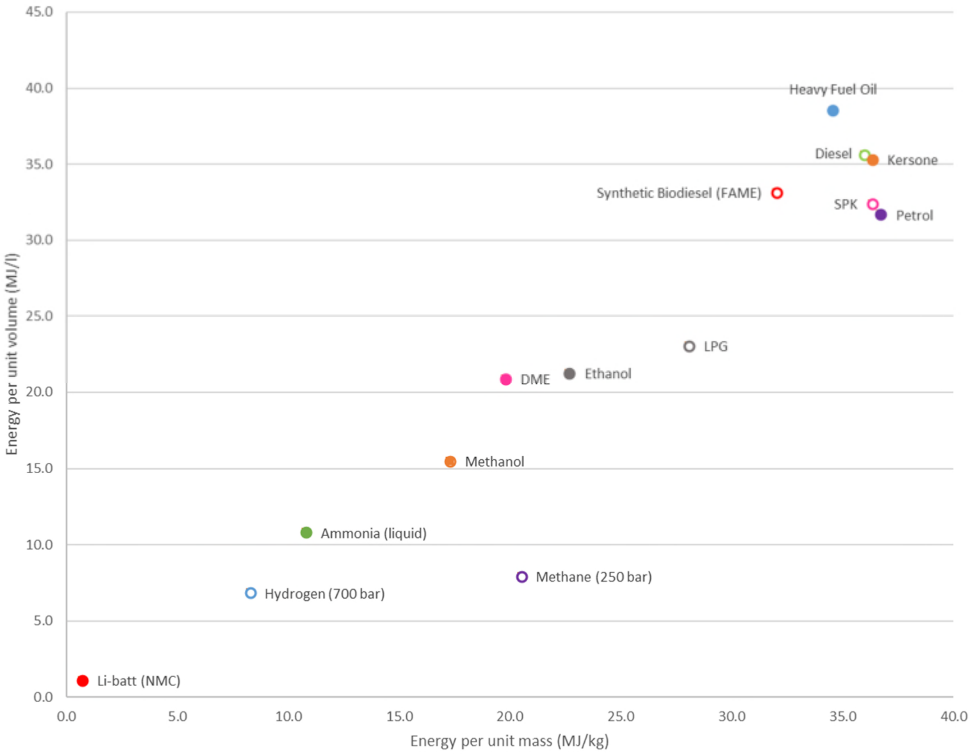
- Army
- Land – Equipment Operating Centre (LEOC)
- Naval Ships Support Chief Engineer
- Marine Systems DA / Marine Systems Support
- Chief of Staff Engineering - Ships
- StratCom
- Other / Unknown
- CDLS & DSSG Defence Support SG – 3*
- DE&S Environmental Workstream SG – 2*
- Climate Change & Sustainability review team
- QSEP, S&EP Policy Team
- Defence Commercial
- DE&S Directorate of Engineering & Safety
- DST / Head Office
- DSF

i – Clearance of SAF (Drop-in-Fuels)
ii – Electrification of the Battlefield
iii – Lithium Ion (6T) Batteries
iv – Hybrid Drive Military Vehicles (TD6)
v – DE&S Environmental Workstream
vi – Defence Standard Development
vii – Equipment acquisition pilot(s)
viii – ULEV Project Phoenix
ix – Manoeuvre Power (MAN-P)
x – Energy Storage Systems
xi – Ships update (multiple)
xii – RB Refrigerant gas WG
xiii – Platform Systems & Naval Arc. CPWG
xiv – Climate Change & Sustainability PMO
xv – Sustainable Defence Support WG
xvi – Logistics Technology Investigations
xvii – Security Systems Surveillance Power
xviii – Emerging Tech. for Defence Power
xix – Climate Change capability degradation
xx – Land Systems DSS, Power
xxi – DSF CMI&I Energy and Power
xxii – UKDSC Energising Defence
xxiii – DSG CMI&I – Vehicle and Operational Infrastructure Power plant
xxiv – NATO harmonized Smart Energy
xxv – Responses to bold statements under climate change and sustainability strategy

Sample of net-zero / sustainability activities in UK MOD
Source: Compiled from RTIG workshop participant inputs

Appendix 3 – Energy and power technologies

In terms of both energy density per unit volume, and energy density per unit mass, there are very few current or emerging technologies that provide a comparable alternative to hydrocarbon based fuels, whether that be sustaining range, performance load capacity or other performance factors. Whilst there are a number that have mass equivalent energy densities or better, the trade off in volumetric storage is significant, particularly in the case of hydrogen storage. Synthetic[19] fuels offer commensurate levels of energy density, however the embedded energy cost in their production is significant.



SPK Synthetic Paraffinic Kerosene; **Li-batt (NMC)** Lithium Nickel Manganese Cobalt Oxide Battery;
LPG Liquid Petroleum Gas; **DME** Dimethyl Ether; **FAME** Fatty Acid Methyl Esters

Energy Densities of selected fuel sources taking into account typical tank weights (lower heating value)
Adapted from: Sustainable synthetic carbon based fuels for transport: Policy briefing, Royal Society[20]

A further dimension in considering the applicability of these alternative energy storage mechanisms are the associated conversion efficiencies. In the case of gasoline and diesel fuelled internal combustion engines and gas turbines, it is typical for overall efficiency to be between 25 and 35%, i.e. between 65 and 75% of the energy contained within the fuel does no productive work and is simply wasted, whether through thermal cycle inefficiency or other transmission and conversion losses. In the case of fully electric systems, these efficiencies can be closer to 85-90%, meaning that only 10-15% of the energy is lost through transmission and conversion inefficiencies.

UKDSC conducted a thorough review of a number of emerging and developing energy & power technologies through Project NAVITAS[21], considering Advanced Fuels, Charging Systems, eFuels, Energy Storage (Batteries), Fuel enhancements, Motor technologies, Power electronics, Powertrain and System enablers. A number of technologies were assessed for technical maturity and any limiting factors associated with adoption for defence purposes.

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[19] Refers to artificially synthesised fuels, including biofuels, biofuel blends and eFuels

[20] https://royalsociety.org/-/media/policy/projects/synthetic-fuels/synthetic-fuels-briefing.pdf

[21] Project NAVITAS, Energising Defence International Market Study, 23rd April 2020, A Frost & Sullivan report for the UK Defence Solutions Centre

Energy Storage Mechanisms

Synthetic Fuels

Synthetic Fuels are carbon based liquid fuels manufactured, via a chemical conversion process, from a carbon source such as coal, carbon dioxide, natural gas, biogas or biomass. They can be considered as two main types:

Electrofuels (eFuels) - These are synthetic fuels manufactured using captured carbon dioxide or carbon monoxide together with low-carbon hydrogen. They are termed electro- or eFuels because the hydrogen is obtained from sustainable electricity sources eg wind, solar and nuclear power.

Synthetic biofuels - Defined as fuels synthesised from biomass or waste or biofuels using chemical or thermal processes, and fuels using biomass and biological processes such as bioethanol produced through fermentation of sugars.

Advantages	Challenges
• High Energy Density (volume & mass) • Implications for platform integration are low • High compatibility with existing logistics and fuelling infrastructure • Wide range of fuels can be produced	• Requires plentiful supply of cheap & sustainable energy • Inefficiency of conversion process • Cost differential to fossil fuels

Hydrogen and Methanol (Fuel Cells)

Fuel cells use hydrogen (or another hydrogen carrying fuel such as methanol) and an oxidising agent (typically oxygen) to produce electricity through a chemical reaction process. Whilst there are many different types of fuel cells, all consist of an anode, cathode and electrolyte that allows ions to flow between the two sides of the fuel cell. Fuel cells have application for power generation, portable power systems, combined heat and power, and as the electricity generating mechanism for electric vehicles.

Advantages	Challenges
• Methanol can be stored and transported easily at ambient conditions • Provide near silent running and limited thermal signature • Clean Burning • Methanol can also be used as a direct fuel • When used in conjunction with energy buffers leads to increased generation efficiencies (demand driven) • Potential to generate Hydrogen / Methanol in theatre	• Methanol is highly toxic • Currently limited to low power applications • Energy density less than half that of gasoline

Ammonia

Green Ammonia, generated from Green Hydrogen, has a number of potential applications as a transport fuel and energy storage medium. Ammonia has approximately nine times the energy storage density of batteries and three times that of compressed hydrogen.

Advantages	Challenges
• Can be stored in large quantities as a liquid at low pressure • Applications for fuel cells, internal combustion engines and gas turbines • When used in fuel cell applications, provides near silent running and low heat output • Easier to store and transport than Hydrogen • Wide range of fuels can be produced	• Energy density (at low pressure) ~40% that of gasoline • Requires plentiful supply of cheap & sustainable energy • Inefficiency of conversion process • Cost differential to fossil fuels • High toxicity

LNG and CNG

Liquefied Natural Gas (LNG) mainly containing methane is stored under low temperature in liquid form, whereas Compressed Natural Gas (CNG) mainly containing methane, are stored at ambient temperature under high pressure in gaseous form. LNG and CNG are widely used in commercial passenger vehicles and, to a lesser degree in locomotives and shipping.

Advantages	Challenges
• Low maintenance costs for vehicles utilising LNG and CNG fuel sources • Existing IC engines readily converted to CNG / LNG use • High efficiency • Applications in high power scenarios • Emissions contain fewer harmful gases than those of LPG or gasoline • Lowest CO_2 emissions of fossil fuels	• Fuel storage occupies a lot of space • Pressurised storage presents additional hazard and significant implications for survivability • Supply quality assurance

Batteries

Estimates of projected energy densities of emerging battery chemistries vary. The Faraday Institution[22] provide a view of current and emerging state of the art for battery technologies. The assessment provided indicates that battery chemistries available in the next 5 years are unlikely to move beyond energy densities above 500Wh/kg and the most ambitious battery options considered in a 10 year + horizon are thought to return energy densities approaching 1000-1300 Wh/kg (approximately 10% of the energy densities of hydrocarbon). This paper considers rechargeable (secondary) batteries, however it is noted that primary (non-rechargable) batteries can offer higher energy content, but can only be discharged once, leading to a higher logistic and through life costs. The use of primary batteries is therefore suited only to those applications where runtime and ultimate performance considerations outweigh logistic and cost concerns.

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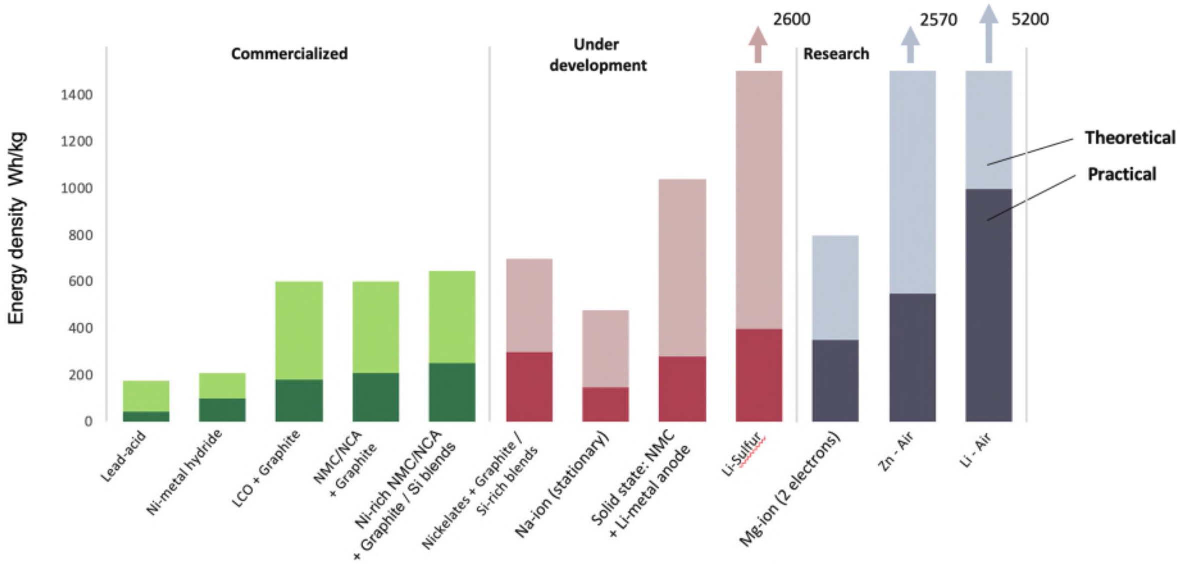
[22] https://faraday.ac.uk/wp-content/uploads/2020/01/High-Energy-battery-technologies-FINAL.pdf



Energy Densities of state of the art and emerging battery technologies – Source: Faraday Institution, BEIS Science Update presentation[23]

Once typical conversion and transmission losses are accounted for, energy density by mass and volume for alternative energy storage vectors become somewhat closer in relative terms to those offered by traditional hydrocarbons, but remain sufficiently less dense to provide a compelling case for adoption in the majority of cases. Even accounting for overall power system efficiencies there remains a large gap in energy storage density between the majority of alternative energy vectors and those provided by traditional hydrocarbons.

Advantages	Challenges
• Zero emissions at point of use • Near Silent running and low signature • High energy conversion efficiency at point of use • Rechargeable – potential for reduced through life cost and logistic burden	• Low energy density relative to gasoline and other energy storage vectors • Charging time • Performance diminishes over time • High parasitic mass

Capacitors and high power density storage

Capacitors are devices for the store electric energy consisting of two conductors separated by a non-conductive region. Groups of large, low-inductance, high voltage capacitors are used to supply large pulse of current for applications requiring high pulse power, such as lasers, Directed Energy Weapons, EM armour and railguns.

Advantages	Challenges
• Able to provide high energy density • Near instant power output • Low mass, relative to batteries • High cycle life • Does not typically contain toxic / harmful metals	• Low energy density relative to batteries • High cost relative to batteries

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[23] Faraday Institution presentation to the Department for Business, Energy and Industrial Strategy (BEIS), October 2019

Energy Use and Power Generation

Hybrid Drives

Hybrid Drive systems typically utilise a combination of energy derived from burning gasoline (or a derivative thereof) supplemented by an electric motor, powered by a series of batteries, often recovering energy from regenerative braking to further enhance efficiency. There are varying degrees of Hybrid Drive:

Type	**Start – Stop System**	**Regenerative braking**	**Charge Depleting mode**	**Rechargeable**
Micro Hybrid	🟩	⬛	⬛	⬛
Mild Hybrid	🟩	🟩	⬛	⬛
Full Hybrid	🟩	🟩	🟩	⬛
Plug-In Hybrid	🟩	🟩	🟩	🟩

Advantages	**Challenges**
• Lower emissions than conventional fossil fuel only powertrain systems • Can provide superior performance to conventional engines / powerplants • Option to run silent • Options to run conventional engines / gas turbines at peak efficiency and manage load variation through use of electric power	• Additional system complexity • Retains fossil fuel component • More expensive than standard IC engine powertrain

All electric Drives

Propulsion provided by electric motor, with energy supply via battery storage or Fuel Cell technology.

Advantages	**Challenges**
• Zero emissions at point of use • Can provide superior performance to conventional engines / power plants • Silent running with limited thermal signature • Simple / low maintenance mechanical systems • Area of considerable commercial investment • Very high efficiency compared to IC engines	• Battery energy densities are poor, limiting range and endurance • Additional parasitic mass (less so in the case of fuel cells) • Charging time (batteries) – less of an issue with fuel cells • Requires readily available electricity infrastructure / generation source

Micro deployable reactors

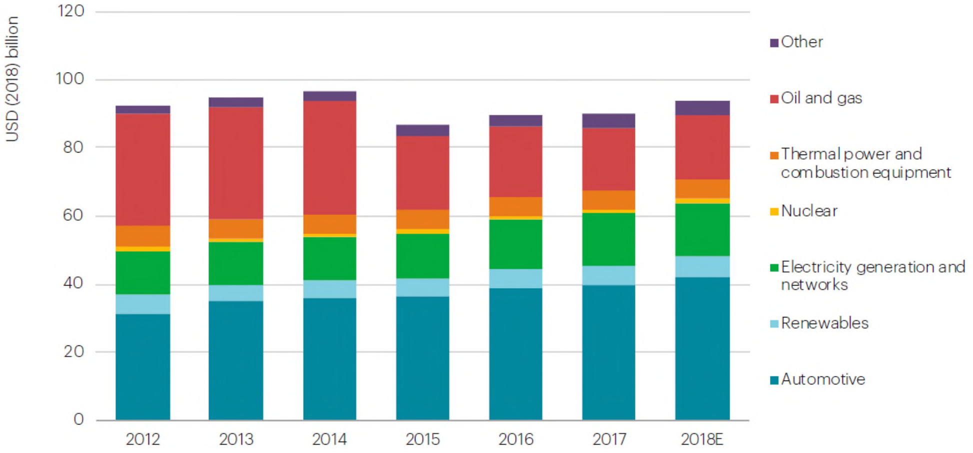
Small scale fission based (Fusion in the future) reactors for local electricity generation.

Advantages	**Challenges**
• Deliver large amounts of low carbon electrical energy • Provide energy source for other storage vectors • May be readily deployable • Ability to produce electricity in remote locations • Load following design • Opportunity to deploy on large naval platforms	• High cost to establish • Public perception of safety • Waste management • Scaling to practical deployable system • Protection in hostile environments

Appendix 4 - Civil and Defence Investments in Energy and Power

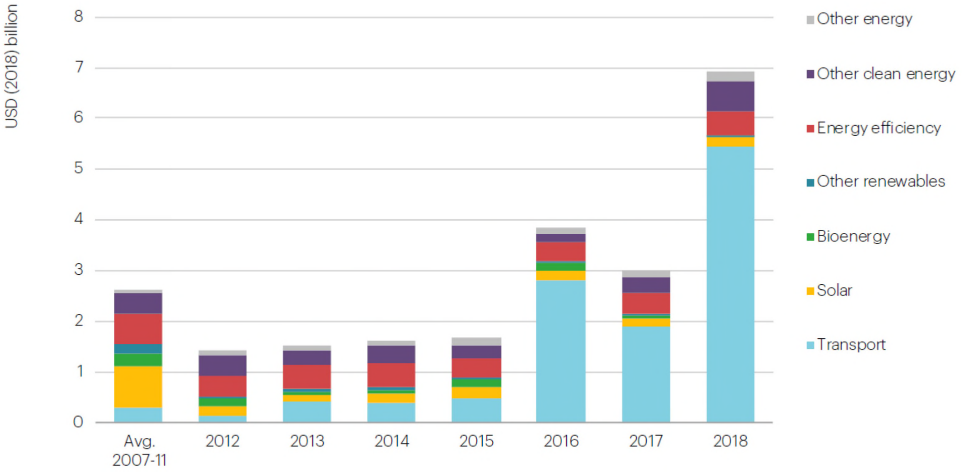
Civil Investment

Global Energy investments were in the order of \$1.8 T in 2018, with low carbon energy and power investment accounting for over 50% of this total.[24] Worldwide State Investment in energy R&D has grown modestly year on year between 2014 and 2018, with corporate investment remaining largely flat (owing to downturn in Oil and Gas Investment). Total energy R&D combining State and Corporate R&D investment was in excess of \$120 billion in 2018. Whilst the overall trend for corporate investment in Energy related technologies is broadly flat owing to the downturn in oil and gas related investments, there are continued upward trends across automotive and renewables.



Corporate spending on Energy R&D,
Source; World Energy Investment 2019, International Energy Agency [24]

The International Energy Agency have identified transport as a major focus area for venture capital investment in energy technology companies.



Global Venture Capital Investment in energy technology companies
Source; World Energy Investment 2019, International Energy Agency [24]

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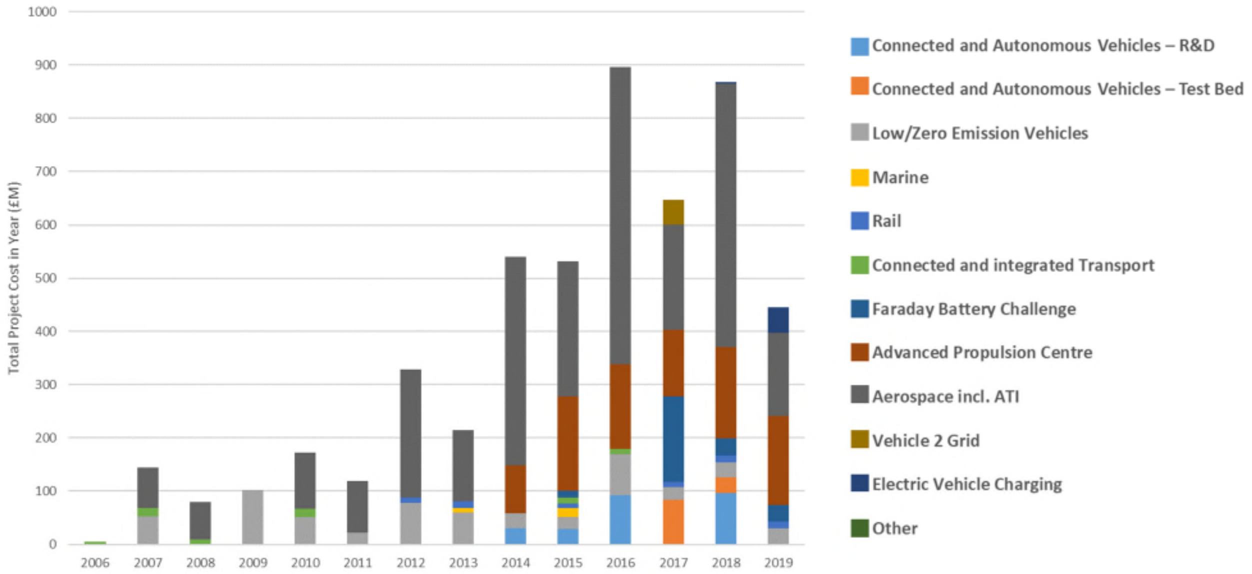
[24] World Energy Investment 2019, https://www.iea.org/reports/world-energy-investment-2019



Innovate UK – Transport related project investments 2006-2019
Source: Innovate UK

Defence Investment

Global Defence spending is estimated to have been $1.8T in 2018. Annual defence spending on energy consumption is thought to be around 2% of this total, or $36Bn per annum (2018). Of defence spending on energy consumption, 70% ($25.2 Bn) of this is estimated to be directed towards operational energy consumption, with the remaining $10.8 Bn accounting for base and infrastructure energy consumption spending.[25] Global Defence R&D expenditure, specifically targeted to Energy and Power technologies is estimated to be in the order of $4.5Bn per annum, with over 80% of this total coming from the US Department for Defence.[25]

In the UK, the latest published ONS figures indicate that defence specific R&D accounts for approximately £2bn, 5% of the UK's total R&D spending (£37.1 billion or 1.7% of GDP)[26]. The Defence Technology Framework (DTF) [27] recognises "Power, energy storage, conversion and transmission" as one of seven technology families. The DTF recognises the weight of investment from the commercial sector and acknowledges that whilst defence will benefit from this investment, a number of commercial solutions will need modification to meet the needs of defence.

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[25] Project NAVITAS, Energising Defence International Market Study, 23rd April 2020, A Frost & Sullivan report for the UK Defence Solutions Centre
[26] https://www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2018
[27] Defence Technology Framework, Defence Science and Technology, September 2019, https://www.gov.uk/government/publications/defence-technology-framework