TWO SHADES OF GREEN: CAN THE BRITISH ARMY'S WARFIGHTING DIVISION FIGHT AND WIN WITHOUT FOSSIL FUELS IN 2050?

A thesis presented to the Faculty of the U.S. Army
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fulfillment of the requirements for the
degree

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Art of War Scholars

by

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This study explored how abandoning diesel for sustainability could affect warfighting ability and credible deterrence. It was optimistic in nature and attempted to find advantages in alternative power sources. The study found the reduced energy density of electrification or hydrogen compared to diesel forced compromise in platform capabilities across firepower, protection, and mobility. The study argued that future find and strike capability in the deep could mitigate the risks posed by fielding a lighter, faster, electric force in the close. However, the study concluded that an electric warfighting division is unlikely to prevail and win against a conventionally powered adversary. This was because of operational challenges in energy supply, storage, and movement. For example, the study calculated the battery equivalent of a 600,000-liter bulk fuel installation would weigh 6,700 tons, requiring hundreds of support vehicles to move. British and U.S. Army futures teams must focus on developing operational supply, storage, and movement solutions rather than the electrification of individual vehicles at the tactical level. The study also identified a significant finding for 3 (UK) Division and Future Soldier: A lack of realistic sustainment modeling in simulations appeared to exaggerate the impact of deep fires on WARFIGHTER. This correlated with an apparent disconnect between the logistical capacity available to 1st Deep Strike Reconnaissance Brigade under Future Soldier, and its artillery logistics demand. This merits further exploration.

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The opinions and conclusions expressed herein are those of the student author and do not necessarily represent the views of the U.S. Army Command and General Staff College or any other governmental agency. (References to this study should include the foregoing statement.)

ABSTRACT

TWO SHADES OF GREEN: CAN THE BRITISH ARMY'S WARFIGHTING DIVISION FIGHT AND WIN WITHOUT FOSSIL FUELS IN 2050?, by MAJ Christopher Adams, 139 pages.

This study explored how abandoning diesel for sustainability could affect warfighting ability and credible deterrence. It was optimistic in nature and attempted to find advantages in alternative power sources. The study found the reduced energy density of electrification or hydrogen compared to diesel forced compromise in platform capabilities across firepower, protection, and mobility. The study argued that future find and strike capability in the deep could mitigate the risks posed by fielding a lighter, faster, electric force in the close. However, the study concluded that an electric warfighting division is unlikely to prevail and win against a conventionally powered adversary. This was because of operational challenges in energy supply, storage, and movement. For example, the study calculated the battery equivalent of a 600,000-liter bulk fuel installation would weigh 6,700 tons, requiring hundreds of support vehicles to move. British and U.S. Army futures teams must focus on developing operational supply, storage, and movement solutions rather than the electrification of individual vehicles at the tactical level. The study also identified a significant finding for 3 (UK) Division and Future Soldier: A lack of realistic sustainment modeling in simulations appeared to exaggerate the impact of deep fires on WARFIGHTER. This correlated with an apparent disconnect between the logistical capacity available to 1st Deep Strike Reconnaissance Brigade under Future Soldier, and its artillery logistics demand. This merits further exploration.

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ACRONYMS

ADP	Army Doctrine Publication
AMA	Artillery Maneuver Area
CGS	Chief of the General Staff
LSCO	Large Scale Combat Operations
mJ	Millijoules (One thousandth of a joule)
J	Joules (SI unit of energy)
KJ	Kilojoules (1,000 joules)
MJ	Mega Joules (1,000 KJ)
GJ	Gigajoules (1,000 MJ)
TJ	Terajoules (1,000 GJ)
MJ/L	Mega Joules per Liter
MJ/Kg	Mega Joules per Kilogram
MoD	Ministry of Defence
MW	Mega Watts
NATO	North Atlantic Treaty Organization
OSW	Operational Staff Work
PAA	Position Area for Artillery
PEHB	Planning and Execution Handbook
Regt	Regiment
RLC	Royal Logistic Corps
RMA	Revolution in Military Affairs
SOHB	Staff Officers Handbook
UK	United Kingdom

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CHAPTER 1

INTRODUCTION

> I think we may be at that inflection point in how we power our next generation of vehicles
>
> — General Sir Mark Carleton-Smith in his address to Defence and Security Equipment International, 2019

> The decisive factor, however, will be the new types of weapons used and the progress achieved in their use and control. New methods must be discovered that are free of the trammels of military habit and custom of conservative modes of thinking and of all prejudice
>
> — General Hasso von Manteuffel writing for the US Army Historical Division, 1946

Background

A British Army warfighting division will consume 800,000 liters of fuel per day during high-intensity conflict.[1] This equates to the daily output of a medium-sized[2] nuclear reactor in terms of energy supply.[3] While today this is merely an interesting statistic, it becomes troublesome when viewed through the lens of evolving global trends.

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[1] Land Warfare Centre, Doctrine Note 20/01, *Sustainment* (Warminster, UK: Ministry of Defence, February 2020), https://akxonline.defencegateway.mod.uk/sites/vault/BAeBBDoctrine/Doctrine%20Notes/19-12-215%20Sustainment%20Doctrine%20A5%20web.pdf.

[2] "Small Nuclear Power Reactors," World Nuclear Association," last updated May 2022, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

[3] Full quantitative analysis in Chapter 4. Calculated using the energy density of diesel, and the power output of a 440MW reactor over 86,400 seconds in a 24 hour period.

Climate change is a *force majeure* of unparalleled scale, which will affect the energy environment and emerging technologies. Tackling climate change and biodiversity loss is the UK Government's number one international priority.[4] This will affect the operations the Army conducts, not only in terms of the operational environment but the very nature of the capabilities it employs. In 2019, the Chief of the General Staff (CGS), General Sir Mark Carleton-Smith, declared that "Our current equipment program is possibly the last to be dependent on fossil fuel engines" and "I think we may be at that inflection point in how we power our next generation of vehicles."[5] This thesis sought to explore the implications of such change. The introduction began with a brief overview of climate change before describing its effect on energy supply and demand. The introduction then explored how technology and policy were likely to address the challenges posed by climate change. Lastly, it explained how this provides context for current and future defense policy.

Climate Change

Climate change is a global issue reshaping perspectives on human interaction with the environment. Its political importance increases each year as electorates seemingly become more attuned and empathetic toward greener policies. Therefore, public sector organizations are under increasing pressure to lead by example and be environmentally

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[4] Ministry of Defence, *Climate Change and Sustainability Strategic Approach* (Westminster, London: Ministry of Defence, March 2021), 1–15.

[5] Laura Makin-Isherwood, "Army Urged to Phase Out Fossil Fuels in Bid to Attract Future Recruits," *Forces Net*, September 12, 2019, https://www.forces.net/news/army/army-urged-phase-out-fossil-fuels-bid-attract-future-recruits.

conscious when operating and making decisions. This led to the British Government passing a net zero emissions law, binding government policy to bring all greenhouse gas emissions to net zero by 2050.[6] In the *Net Zero Strategy: Build Back Greener*,[7] the government has also published how it will achieve this end. Large parts of the Net Zero Strategy revolve around significant power, fuel supply, and transportation modernization.

Energy

Given the scope of the Net Zero Strategy, the energy environment is inextricably linked to climate change. Currently, the United Kingdom consumes approximately 300-400 Terawatt Hours (TWh) per year.[8] Net Zero includes specific goals such as a commitment to "Support the increased requirement for fuel switching to low carbon alternatives, with an ambition to replace around 50 TWh of fossil fuels per year by 2035."[9] This equates to 12-16% of the UK's energy consumption moving away from fossil fuels every year. Of course, this is dependent on consistent government policy for the next two decades. The primary opposition political party (Labour) would rather have an even more aggressive timeline of achieving the substantial majority of emissions

[6] Department for Business, Energy & Industrial Strategy, and The Rt Hon Chris Skidmore MP, "UK Becomes First Major Economy to Pass Net Zero Emissions Law," Gov.UK, June 27, 2019, https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law.

[7] Department for Business, Energy & Industrial Strategy, *Net Zero Strategy: Build Back Greener* (United Kingdom: HM Government, October 2021).

[8] Ibid.

[9] Ibid.

reductions by the 2030s.[10] Therefore, the more conservative policy is the legally binding Conservative party Net Zero 2050 Strategy. This means that energy supply within the United Kingdom is likely to be transformed in the next 20-30 years.

Technology

Creating environmental laws to reduce greenhouse gas emissions can spark innovation, especially if subsidies are used to reduce the cost of research and development.[11] This innovation is embodied in the slick brand image, and popularity of Tesla Motors, whose share price has increased by 3000% in the last five years.[12] The giants of the automotive world are beginning to adapt too. Numerous automotive manufacturers such as Mercedes,[13] Volkswagen,[14] and Volvo,[15] plan to only produce

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[10] Keir Starmer, "Britain Could Be Taking the Lead in Tackling the Climate Crisis. Where's the Ambition?," *The Guardian*, August 3, 2021, https://www.theguardian.com/commentisfree/2021/aug/03/britain-climate-crisis-where-ambition-cop26-tories-labour-green-recovery-plan.

[11] Adam B. Jaffe, Richard G. Newell, and Robert N. Stavins, "Technological Change and the Environment," (Working Paper 7970, National Bureau of Economic Research, Cambridge, MA, October 2000), https://www.nber.org/papers/w7970.

[12] "Tesla, Inc. Common Stock," NASDAQ, accessed October 31, 2021, https://www.nasdaq.com/market-activity/stocks/tsla.

[13] Mercedes-Benz Group, "Mercedes-Benz Strategy Update: Electric Drive," July 22, 2021, https://www.daimler.com/company/strategy/mercedes-benz-strategy-update-electric-drive.html.

[14] Volkswagen, "NEW AUTO: Volkswagen Group Set to Unleash Value in Battery-Electric Autonomous Mobility World," Volkswagen Group News, July 13, 2021, https://www.volkswagen-newsroom.com:443/en/press-releases/new-auto-volkswagen-group-set-to-unleash-value-in-battery-electric-autonomous-mobility-world-7313.

[15] Volvo Car Corporation, "The Future is Electric," Volvo, accessed November 1, 2021, https://group.volvocars.com:443/company/innovation/electrification.

electric vehicles by 2030. Many more have goals out towards 2040. The energy supply industry is no different. Royal Dutch Shell,[16] and British Petroleum,[17] are already diversifying away from fossil fuels, protecting themselves from a future where demand for their core business degrades. Governments are investing in infrastructure, and publishing strategies, including for hydrogen.[18]

Defence Policy

Achieving Net Zero is the political strategic environment within which the Ministry of Defence (MoD) operates. The MoD accounts for 50% of the UK central Government's emissions.[19] As a part of the public sector, the MoD has unsurprisingly aligned itself with the intent of its higher headquarters, the Government. The MoD therefore has its own Climate Change and Sustainability Strategic Approach,[20] nested within the Government's NZ2050.

> Defence will be stronger if it keeps up with new, adaptable and efficient options. We are already at the forefront of the new and growing green military

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[16] Shell, "Shell Accelerates Drive for Net-Zero Emissions with Customer-First Strategy," February 11, 2021, https://www.shell.com/media/news-and-media-releases/2021/shell-accelerates-drive-for-net-zero-emissions-with-customer-first-strategy.html.

[17] British Petroleum, "From International Oil Company to Integrated Energy Company: Bp Sets out Strategy for Decade of Delivery towards Net Zero Ambition," BP, August 4, 2020, https://www.bp.com/en/global/corporate/news-and-insights/press-releases/from-international-oil-company-to-integrated-energy-company-bp-sets-out-strategy-for-decade-of-delivery-towards-net-zero-ambition.html.

[18] Department for Business, Energy & Industrial Strategy, *UK Hydrogen Strategy* (United Kingdom: HM Government, August 2021).

[19] Ministry of Defence, *Climate Change and Sustainability Strategic Approach*, 6.

[20] Ibid.

agenda, trialling [sic] new types of vehicles, fuels standards, energy storage and much more.[21]

The *Climate Change and Sustainability Strategic Approach* (CCSSA) further declares that "Defence could face significant costs if its designs do not allow for moving away from current power options."[22] CCSSA also links the development of future capabilities to climate change by identifying the requirement for Defence climate assumptions to provide long-term reasonable scenarios and consequences when making capability choices.[23] This is the context behind the former CGS' comments in the opening paragraph about an inflection point in how future vehicles are powered.

Announced as part of the British Army's modernization program, Project Mercury assumes that electrification of the fleet is the best solution to post fossil-fuel energy supply and will explore options to implement the changeover.[24] This aims to explore electrification of the fleet. The inherent assumption in Project Mercury is that electrification is the best solution to post-fossil fuel energy supply.

The key problem is that diesel fuel is energy-dense, easy to transport, and part of a fully integrated supply and distribution system. The technologies it fuels are mature and well understood by the user and maintainers of the army. If an environmentally friendly non-fossil fuel were able to outperform diesel in energy by mass and volume, the

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[21] Ministry of Defence, *Climate Change and Sustainability Strategic Approach*.

[22] Ibid.

[23] Ibid.

[24] Ministry of Defence, "Chief of the General Staff's DSEI Speech in Full," The British Army, September 15, 2021, https://www.army.mod.uk/news-and-events/news/2021/09/cgs-dsei-speech/.

automotive industry and energy companies writ large would be aggressively integrating it into their businesses. Alternatives to fossil fuels are therefore not currently viable in cost or performance.

As there is no direct comparator to diesel fuel's system-wide characteristics, some capability compromises will likely be necessary in a future equipment program. Conversely, there may be tactical or operational advantages in electrification beyond sustainability. History has shown how Revolutions in Military Affairs (RMA's) occur in clusters after seismic shifts in the political, economic and social system. Climate change, and its impact on energy and technology, is likely to cause a similar cluster of RMAs.

Problem Statement

In 2019 CGS suggested that the British Army's current equipment program might be the last to run on fossil fuels. Current technological trends suggest an alternative energy source is unlikely to offer the same energy performance as diesel when new equipment must be developed. This would force change in individual platform design, which will affect the doctrine and organization of the future force.

Purpose of the Study

While this study has been produced as a requirement of the Masters in Military Art and Science (MMAS) program at the U.S. Army Command and General Staff College, its purpose is broader. It is written to help inform the British Army and wider Ministry of Defence. Its spelling and abbreviations follow American 'correctness', but style choices such as passive voice are deliberately aimed at a British reader.

More specifically, this study aimed to explore whether the character of today's conflict is wholly dependent on fossil fuels. This study did not assert that high-intensity warfighting is the most likely future scenario for the British Army. Warfighting is, however, the most challenging in terms of energy supply and demand. Can an oil divested warfighting division prevail and win against a conventional force using fossil fuels? The study sought to define the limits of technological possibility, and then assess whether the British Army can reduce emissions while improving its capability. Ultimately, this study strove for a solution where the British Army can simultaneously divest fossil fuels and become more effective. It provided recommendations for the current British Army, Project Mercury, and potential areas of future research.

Research Questions

The following questions guided the study:

Primary Research Question

How does 3 (UK) Division's fighting power evolve if its land-based warfighting platforms switch from diesel to an alternative power source by 2050?

Secondary Research Questions

1. How does 3 (UK) Division currently fight?
2. Is electrification the best future power source for 3 (UK) Division in warfighting?
3. How would electric land platforms nest in broader future concepts?

Assumptions

The Political Intent to Commit to NZ2050 Will Remain for the Next 20 Years

This assumption was necessary because without it, the impetus for innovation and energy transformation would not exist, and the MoD's desire to become greener will diminish. This assumption was valid because the government has signed NZ2050 into law, and the opposition party (Labour) advocates an even more aggressive timeline to reach the same end-state. Both parties operate in a political environment where the importance of climate related policies is increasing.

Political Strategic Intent Remains to Be Able to Fight an Expeditionary Conflict Anywhere in the World

This assumption was necessary because it underpins whether the UK requires a land warfighting capability in the first place. It was valid because the United Kingdom has historically taken its responsibility as a permanent member of the United Nations Security Council seriously, and perceives a responsibility to help maintain global peace and security. It was an essential assumption because it prevents the study from hiding behind luxuries such as host nation infrastructure, for example national power distribution networks.

The United States Will Follow the UK in Moving Away from Fossil Fuels

This was necessary because a UK Division must be able to fully integrate into a US Corps by 2025, which is not possible if the sustainment chains to supply two different energy systems are vastly different. It was valid because the political strategic drivers that have influenced the MoD to produce CCSSA also impact the US Department of Defense.[25]

Other NATO Members Will Not Follow the UK Quickly

The United Kingdom and United States both spend more in absolute and relative terms on defense than many other NATO allies.[26] With smaller budgets, expensive modernization is unlikely to occur quickly. This was important because it creates a capability divide, where countries that spend more have a force that becomes less interoperable with those that spend less.

China and Russia Will Continue to Field Diesel-Powered Conventional Forces

This assumption was valid because although General Dunford's 4+1 threat concept (Russia, China, North Korea, Iran, and transnational violent extremism)[27] could change significantly by 2050, but these are the state actors most likely to develop future adversarial capabilities. These countries would need to identify a climate or security-based political rationale to divest fossil fuels and modernize towards electrified

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[25] U.S. Department of State, and U.S. Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (Washington, DC: Department of State and Executive Office of the President, November 2021), 5.

[26] Central Intelligence Agency, "Country Comparisons: Military Expenditures," The World Factbook, accessed April 11, 2022, https://www.cia.gov/the-world-factbook/field/military-expenditures/country-comparison.

[27] Fred Dews, "Joint Chiefs Chairman Dunford on the '4+1 Framework' and Meeting Transnational Threats," *Brookings Now* (blog), *Brookings*, February 24, 2017, https://www.brookings.edu/blog/brookings-now/2017/02/24/joint-chiefs-chairman-dunford-transnational-threats/.

platforms. This assumption forced the study to consider whether relative advantage can be found against a conventionally powered force.

Definition of Terms

Fighting power. "This is a concept that describes the operational effectiveness of armed forces, or any element of them. Common across Defence and NATO, the concept guides force development and preparation. It is broken into three components: Conceptual, Moral, and Physical."[28]

Conceptual component. "The conceptual component is the force's knowledge, understanding and application of doctrine – the ideas behind how to operate and fight – kept relevant by its ability to learn and adapt."[29]

Moral component. "The moral component is the force's morale, leadership and ethical conduct: the ability to get people to operate and fight and to do so appropriately."[30]

Physical component. "The physical component consists of manpower, equipment, sustainability, and resources: the means to operate and fight. Training is considered as part of the physical component, although it develops and integrates all three components."[31]

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[28] Land Warfare Development Centre, Army Doctrine Publication (ADP), *Land Operations* (Warminster, UK: Ministry of Defence, March 2017).

[29] Ibid.

[30] Ibid.

[31] Ibid.

3 (UK) Division. "3rd (United Kingdom) Division is the only division at continual operational readiness in the UK. It exists as the United Kingdom's strategic land warfare asset."[32]

Warfighting. The definition from Army Doctrine Publication (ADP) Land Operations encapsulates the environment that this study discussed:

> In warfighting (also referred to as major combat operations), most of the activity is directed against a significant form of armed aggression perpetrated by large-scale military forces belonging to one or more states or to a well-organized and resourced non-state actor. These forces engage in combat operations in a series of battles and engagements at high intensity, varying in frequency and scale of forces involved. The immediate goal is to ensure freedom of action at the expense of their opponents. The rhythm of operations is often high with high logistics consumption. Enemy armed forces may also use irregular forces and CBRN capabilities to support conventional forces' military objectives. Operating in a context where warfighting is the predominant theme may be further exacerbated, perpetuated or exploited by other irregular actors seeking to benefit from instability, whether through insurgency, terrorism, criminality or disorder.[33]

Land-based platforms. Anything that a soldier would drive or operate on land, from a Landrover to a Main Battle Tank (MBT). It does not include helicopters, UAVs, or aircraft.

Energy density by mass. The amount of energy (in Joules) one kilogram of fuel contains, irrespective of volume.

Energy density by volume. The amount of energy (in Joules) one meter cubed of fuel contains, irrespective of mass.

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[32] Ministry of Defence, "3rd (United Kingdom) Division," The British Army, last modified 2021, https://www.army.mod.uk/who-we-are/formations-divisions-brigades/3rd-united-kingdom-division/.

[33] Land Warfare Development Centre, ADP, *Land Operations*.

Transition point. The point at which major equipment programs within the British Army are replaced. This is similar to the transition that saw the "Big five" introduced to the US Army in the twentieth century.

Scope

This study explored how an oil divested British warfighting division would need to evolve to remain a credible fighting organization. It primarily did this through document analysis and did not extend into human subject research for data collection or modeling/simulation for analysis. It also did not consider adversaries in the same level of detail. It aimed to identify the threats and opportunities that alternative fuels bring and proposed a concept for how these can best support the future force.

Limitations

Limitations are imposed on the study and author. These include time available before a defined submission date and the ability to travel for research while also attending study full-time. There are four limitations identified in this study.

Classification

To ensure the thesis was publishable, it had to be unclassified. This limited the type of information that could be quoted or used for evidence in detailed arguments. UK publications primarily use two classification levels; OFFICIAL and OFFICIAL SENSITIVE. There is no unclassified designation below OFFICIAL. This study applied judgment to OFFICIAL material and did not reference or quote OFFICIAL SENSITIVE material. It also did not use U.S. Controlled Unclassified Information (CUI) for the same reasons.

Modeling and Simulation

Using modeling or simulation to evidence findings from the analysis would strengthen the study but was not achievable within the timeframes of an MMAS thesis. This is explained in Chapter 3.

Human Subjects Research

The study did not conduct interviews with subject matter experts across the British Army because it risks introducing external bias into the study. The collective thinking of how the British Army thinks and fights was derived from Operational Staff Work (OSW) and doctrine. This was explained further in Chapter 3.

Chinese and Russian Future Forces

This study did not predict how Russian or Chinese efforts to develop greener forces would compare with UK/US efforts. This is because any sufficiently detailed documentation on Russian/Chinese capabilities was likely to be classified. Without this detail, an objective comparison would be flawed.

Delimitations

Delimitations are reductions in scope chosen by the author. Delimitations help bound the problem and ensure the study balanced depth and breadth. There were seven delimitations identified in this study.

Focus on 3 (UK) Division, Not the Entire British Army

As the British Army's warfighting division, 3 (UK) was the most relevant organization to this study. Of course, force design might see a more diverse deployment from across the wider Army, but providing an effective analysis of what this might look like is an opportunity for future research.

Warfighting in LSCO, Not Routine Business in Barracks

This study did not focus on the impact of platform modernization on routine business in barracks. This is because it could confuse the analysis of warfighting, causing the study to be less focused than it otherwise could be. Problems such as adapting infrastructure and energy supply within the UK are already explored in depth by the Future Soldier concept.[34]

Land Platforms

Challenges with energy density and fuel performance mean that electric/hydrogen aircraft are significantly behind land vehicles.[35] As such, this study did not consider a radical modernization of air or aviation to platforms that use alternative fuel sources. This could mean that 3 (UK) Division has logistics requirements for fossil fuels within its rear even if land platforms are electrified.

Multinational Interoperability within 3 (UK) Division

This study did not analyze the challenges associated with multinational elements operating within 3 (UK) Div. For example, a Danish Battlegroup has exercised under a British brigade in recent years, and the UK-led NATO Enhanced Forward Presence

[34] Ministry of Defence, "Future Soldier Guide," The British Army, November 25, 2021, https://www.army.mod.uk/media/14919/adr010310-futuresoldierguide_25nov.pdf.

[35] Sam Howe Verhovek, "By Air: The Gravity Problem," *National Geographic,* October 21, 2021, 66–83.

battlegroup is multi-national by design. Exploring the detailed implications of trying to integrate a conventional fighting force using fossil fuels with a modernized green British division is an area for future research.

Money

Although this study considered cost in its analysis and recommendations, it did not constrain its conceptual exploration solely to what could be affordable in 15 years' time, based on perceptions of today's economic climate.

International Experimentation

Although focused on a British warfighting division, the study did not limit itself to purely British research and experimentation. For example, tests of electric armored vehicles in the US are just as relevant as ones in the UK because the strength of the UK/US alliance means that breakthroughs on one side of the Atlantic will reach the other side rapidly.

Rare Earth Metals

The strategically important locations of rare earth metal deposits, and the industries that refine them, are well documented and directly affect alternative fuel technologies. Today, China is a critical node within the global supply and demand system for metals such as lithium and cobalt. Western technological research is diversifying to neutralize this issue, with emerging research exploring sodium-ion batteries. Sodium-based ideas use a metal from the same elemental group, but extract them from sea water rather than mining. The assumption in this study was that the metals required to build future platforms would be accessible. Thus, it did not consider a scenario where an inability to access rare earth metals prevents capability development.

Significance of the Study

This study aimed to add to the collective knowledge of those working in strategy, concepts, and doctrine roles within the MoD.

Lt Gen Richard Nugee CB CVO CBE, the Defence lead for the Climate Change and Sustainability Review, summed up the importance of adapting to climate change aptly. "If you don't deal with it today, you will not be able to deal with it tomorrow."[36] Capability development takes years, and so the successful design, development, and integration of new technology would need to occur well before 2050.

History has demonstrated how tectonic shifts in technology cause Revolutions in Military Affairs (RMAs). The key ingredient of these RMAs is often the introduction of technology within broader political, societal, and economic evolution. Transitioning to a greener force requires analysis to determine the potential opportunities and threats.

[36] Ministry of Defence, *Climate Change and Sustainability Strategic Approach*.

With a changing world outlined in *Future Operating Environment 2035*,[37] and *Global Strategic Trends*,[38] attempting to anticipate the future strategic and operational environments is crucial to success.

Summary

Climate change and how states respond to it will be a defining characteristic of the 21st Century. The symbiotic relationship between the environment and politics will drive innovation and change in global energy supply, transforming business models and public attitudes to energy supply. Voters will actively consider how environmentally focused a political party's policies are. Voter pressure will drive a reduction in fossil fuel dependency.

The United Kingdom sees itself as the vanguard in adapting to this new strategic environment. It was the first state to bind its environmental policy to reach net-zero by 2050 in law. It has the political consensus,[39] legislated intent, and public appetite to commit to its goals over the next three decades.

The Ministry of Defence accounts for 50% of the British Government's emissions and is compelled to help the government lead by example. The MoD as a *line of effort*

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[37] Ministry of Defence, *Future Operating Environment 2035* (Swindon, Wiltshire: Defence Concepts and Doctrine Centre, Ministry of Defence, 2015), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/646821/20151203-FOE_35_final_v29_web.pdf.

[38] Ministry of Defence, *Global Strategic Trends - The Future Starts Today,* 6th ed. (Swindon, Wiltshire: Defence Concepts and Doctrine Centre, Ministry of Defence, 2018).

[39] A de facto two party system, both of whom are very much committed to reaching net zero by at least 2050, as discussed in the background.

toward the Government's objective is outlined in the MoD's *Climate Change and Sustainability Strategic Approach*. This directly states the need to prepare capability development, force design, and mentality now.

CGS highlighted the implied effects of the MoD's approach: that the current equipment program might be the last to use fossil fuels. With some armored vehicles that have been in service for 60 years and the Challenger 3 Main Battle Tank expected to remain in service until the 2040s, alternatives for their replacements must be explored now.[40]

The fundamental problem is that no alternative fuel exists that offers the same energy performance as diesel. Compromise in capability development is therefore likely to be a necessity for future equipment programs.

While effective anticipation of major societal changes and their consequences is almost non-existent in history, intellectually bracing for the storm of change is important to enable survival. Failing to analyze and prepare for significant change risks obsolescence. Obsolescence quickly leads to irrelevance, which is anathema to the British Government's vision of a "Global Britain." Chapter 2 explored the published research, studies, doctrine, and articles that pertain to this problem.

[40] "FV432 APC," Norfolk Tank Museum," accessed November 1, 2021, http://norfolktankmuseum.co.uk/fv432-apc/.

CHAPTER 2

LITERATURE REVIEW

Introduction

The literature review was divided into three parts. First, Chapter 2 reviewed how 3 (UK) Division currently fights. Doctrine, historical evidence, and simulation data from previous exercises showed how 3 (UK) Division maneuvers in space and time. For example, if a brigade typically only fights 150km over two days prior to an echelon change, it will have different platform requirements to a brigade that typically travelled 400km in two days. The study had to qualify how it fights today to explore how the warfighting division can find relative advantage in the future.

Second, Chapter 2 reviewed the alternative fuels available. When reviewing and comparing fuels, there are two essential criteria: energy density by mass and volume. These require explanation to ensure the reader understands the terms used throughout the remainder of the paper. With an understanding of these, research and literature on different types of fuels can be analyzed in context.

Third, this study explored broader futures concepts currently under development. These mattered because this study's ideas had to nest within them to remain relevant to the Ministry of Defence. As such, the literature review captured what these concepts are.

Throughout all three parts, it proved helpful to evidence ideas with historical vignettes. The study subsequently reviewed the literature surrounding twentieth-century land warfare.

How does 3 (UK) Division currently fight?

A wide variety of sources contribute to an understanding of how 3 (UK) Division currently fights. In Operational Design terms, this represents the current state from which future concepts must evolve. This literature review focused on the doctrine and organization elements of DOTMLPF-P (Doctrine, Organization, Training, Materiel, Leader development, Personnel, Facilities, Policies):

Doctrine

One natural place to begin looking for how 3 (UK) Division fights is the doctrine that it uses. The Army's capstone doctrine that broadly equates to U.S. Army Doctrine Publication (ADP) 1-0 is the 2017 ADP *Land Operations*.[41] This describes the components of fighting power; tactical, operational, and geographic frameworks; and many other concepts. It forms the basis of the British Army's common language to function: both in barracks and on operations. The 2017 version replaced the 2010 version,[42] and contrasting the two documents provides an interesting perspective on how British Army thought has evolved throughout the final years of Afghanistan.

Nested underneath ADP *Land Operations* is the British Army's warfighting doctrine. This comes in four parts. The first is Army Field Manual (AFM): *Warfighting Tactics,* Part 1, *The Fundamentals*.[43] This articulates the role of warfighting within the

[41] Land Warfare Development Centre, ADP *Land Operations*.

[42] Defence Concepts and Doctrine Centre, Army Doctrine Publication, *Land Operations* (Andover: Army Headquarters, 2010).

[43] Land Warfare Centre, Army Field Manual (AFM) - *Warfighting Tactics*, Part 1: *The Fundamentals* (Warminster, UK: Ministry of Defence, July 2018).

conflict continuum. AFM *Warfighting Tactics, The Fundamentals* is rather broad, and its title is the best description of what is contained within. It adds more detail to some of the concepts in ADP *Land Operations* while explaining how others are modified slightly by a warfighting context.

AFM *Warfighting Tactics* has three other parts, which cover different echelons. Part 2 is *Corps and divisional tactics.*[44] *Corps and Divisional Tactics* is designed to be agnostic of Corps and Division design, i.e., it is just as applicable to an infantry division as an armored one. 3 (UK) Division, as an armored Division, needs more finesse and detail to plan and execute effectively. This detail is provided in Divisional Standard Operating Instructions (SOIs). Each integrating cell of 3 (UK) Division has its own SOIs to provide the detail required to plan and execute. The G35 future operations cell currently has a detailed set of SOIs, refined by divisional staff on a successful Warfighter exercise in spring 2021.[45]

Part 3 of the AFM *Warfighting Tactics* series is for brigade level.[46] Nested within Part 2, it provides more detail on how maneuver brigades operate within a divisional context. Even though this study is focused on the divisional level, understanding its subordinate organizations in detail is a necessary for understanding the division as a whole. Staff officers are trained to think *two down* in planning, so Part 4: *Battlegroup*

[44] Land Warfare Centre, Army Field Manual (AFM) - *Warfighting Tactics*, Part 2: *Corps and Divisional Tactics* (Warminster, UK: Ministry of Defence, 2018).

[45] Maj Simon Davies, *3 (UK) Division G35 Standard Operating Instructions,* version 4.2 (Bulford: 3 (UK) Division, 2021).

[46] Land Warfare Centre, Army Field Manual (AFM)- *Warfighting Tactics*, Part 3: *Brigade Tactics* (Warminster, UK: Ministry of Defence, 2018).

Tactics is equally important for the same reasons.[47] As with the division, the brigade also has Standard Operating Instructions. As these are often a product of the brigade Chief-of-Staff, they can change quite frequently. Major James Fern produced a comprehensive version in 2018 for 12 Armored Infantry Brigade.[48]

There are also Army Field Manuals by warfighting function, which provide descriptive approaches integrated at each echelon. AFM *Sustainment,*[49] and AFM *Command* were important guides to understanding 3 (UK) Division's current state.

Two further documents would have been useful for understanding how the division fights: the *Planning and Execution Handbook* (PEHB),[50] and the *Staff Officers Handbook (*SOHB).[51] The PEHB provides detailed common planning and execution processes designed to replace a myriad of SOIs at the Battlegroup level. This ensures a common language and approach among units. The SOHB is colloquially referred to as the Staff Officers' bible; 1.5 Inches thick, it provides detailed reference data, based on

[47] Land Warfare Centre, Army Field Manual (AFM) - *Warfighting Tactics*, Part 4: *Battlegroup Tactics* (Warminster, UK: Ministry of Defence, 2018), https://akxonline.defencegateway.mod.uk/sites/vault/BAeBBDoctrine/Army%20Field%20Manual%20(AFM)%20Warfighting%20Tactics_battlegroup%20web.pdf.

[48] Maj James Fern, *Joint Expeditionary Force Armoured Infantry Brigade Standard Operating Instructions (SOIs) Part A: Planning and Execution* (Bulford: 12 Armoured Infantry Brigade, 2018); Maj James Fern, *Joint Expeditionary Force Armoured Infantry Brigade Standard Operating Instructions (SOIs) Part B: Operate* (Bulford: 12 Armoured Infantry Brigade, December 18).

[49] Land Warfare Centre, Doctrine Note 20/01, *Sustainment*.

[50] Land Warfare Centre, *Planning and Execution Handbook (PEHB)* (Warminster, UK: Ministry of Defence, 2018).

[51] Land Warfare Centre, *The Staff Officers' Handbook 2018 SOHB* (Warminster, UK: Ministry of Defence, 2018).

historical and scientific analysis. It is where every staff officer from company to corps goes to check flow rates of bridges, maximum incline slope for a main battle tank, the amount of water required by a brigade etc. It provides the data underpins military science.

The SOHB is classified as OFFICIAL SENSITIVE and was not directly used for this study. Instead, the open-source 1999 SOHB was used extensively.[52] The study has used the figures and detail from SOHB 1999 for calculations and analysis. The study has only used SOHB 2018 to verify the 1999 values remained relevant. This enabled the study to balance relevance with the classification limitation.

Organization

The United Kingdom's operating force is called the Field Army. Within the Field Army, there are three divisions. 1 (UK) Division is focused on security cooperation activity and low intensity persistent engagement across the world. 6 (UK) Division leads unconventional warfare and has a variety of different specialists to enable this. 3 (UK) Division is the warfighting division. It is the only division trained, equipped, and organized to deploy at scale and support Large Scale Combat Operations, augmented by specialists from 1 and 6 (UK) Divisions.

[52] Land Warfare 1 Branch, Directorate General of Development and Doctrine, *Staff Officers Handbook* (Warminster, UK: Directorate General of Development and Doctrine, 1999), https://vsip.info/staff-officers-hand-book-2-pdf-free.html.

Summary of 3 (UK) Division Literature

Doctrine, Standard Operating Instructions, and Operational Staff Work (OSW) provided the best means to understand how 3 (UK) Division currently fights. The study now transitions into the literature surrounding alternative power sources.

Is electrification the best future power source for 3 (UK) Division in warfighting?

Energy Density

When analyzing a fuel source, there are two critical performance indicators: energy density by mass and energy density by volume. The perfect alternative fuel would exceed diesel in both. Energy is measured in Joules. This is typically expressed in how many millions of joules are present, also known as Mega Joules (MJ).

Fossil fuels can be produced in a variety of ways, each of which produces marginally different energy densities. As fluids contract and expand with temperature, it is important to understand the conditions within which fuels have been measured for their energy density. This study used $45GJ/m^3$ as the energy density of diesel by volume, based upon research at Drexel University, PA.[53] The study used 45.5MJ/Kg as the energy density of diesel by mass, based upon independent research at the Rocky Mountain Institute.[54] These are, therefore, the benchmarks against which other fuels will be evaluated. As an example, 45.5MJ of diesel would weigh one kilo, and occupy $0.0017m^3$

[53] Bradley E. Layton, "A Comparison of Energy Densities of Prevalent Energy Sources in Units of Joules Per Cubic Meter," *International Journal of Green Energy* 5, no. 6 (December 2008): 438–455.

[54] Patrick Molloy, "Run on Less with Hydrogen Fuel Cells," RMI, October 2, 2019, https://rmi.org/run-on-less-with-hydrogen-fuel-cells/.

of space (approximately the size of a large soda bottle, 58 fl oz, or 1.5 quarts), so 45.5MJ of the perfect fuel would weigh *less* than one kilo, and occupy *less* than $0.0017m^3$.

It is important to consider how much energy exists within one kilo of diesel. A comparison to the output of a typical exercise bike offers an effective visualization. A fit individual on an exercise bike will produce a power output of approximately 100 Watts. They would need to keep cycling at this output level for five days without stopping to equal the 45.5MJ contained within one kilo of diesel.[55] The incredible energy density of hydrocarbons is what has powered the twentieth century, and why 90% of the world's transportation today is dependent on oil.[56]

Emergent Technology

Alternative fuels, therefore, need to either match this performance or compromise on the weight or volume required. A plethora of research on alternative fuels is ongoing, with multiple papers reporting incremental progress towards the holy grail of hydrocarbon performance equivalency.

Figure 1 shows how alternative fuels compare to diesel in terms of energy density by mass, and by volume. The literature review focused on those fuels that are not derived from carbon-based fossil fuels. Liquid natural gas and other fossil fuels were therefore not considered as suitable options because they did not meet the intent to divest of fossil

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[55] Christopher Fleming, "Considering Oil Production Variance As An Indicator Of Peak Production," (Senior Service College Fellowship, Civilian Research Project, US Army War College, June 7, 2010).

[56] Aritra Ghosh, "Possibilities and Challenges for the Inclusion of the Electric Vehicle (EV) to Reduce the Carbon Footprint in the Transport Sector: A Review," *Energies* 13, no. 10 (January 2020): 2602.

fuels. Exploring synthetic bio-oil would have led to a study that explored synthetic drop in fuels, and their associated agricultural challenges.[57] This would have prevented a more focused exploration of non-fossil fuel alternatives. Despite this they were nonetheless important reference points.

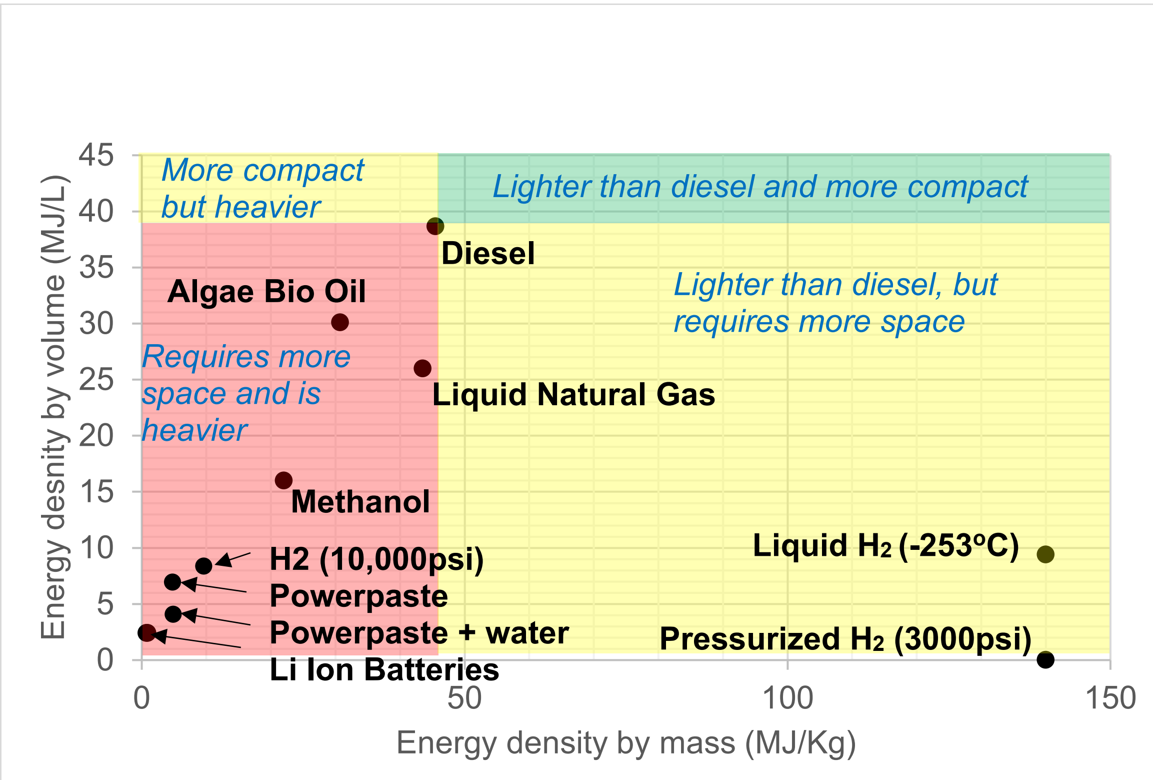

Figure 1. Graph to Show Energy Density by Mass (MJ/Kg) vs. Energy Density by Volume (MJ/L) for Various Fuel Sources

Source: Created by author using data points from Table 1.

[57] Dan Charles, "How A Biofuel Dream Called Jatropha Came Crashing Down," *NPR*, August 21, 2012, https://www.npr.org/sections/thesalt/2012/08/22/159391553/how-a-biofuel-dream-called-jatropha-came-crashing-down.

Table 1 quantifies energy densities by mass and volume, providing the source data for figure 1. The values are color-coded, with dark green highlighting a value that is equal or better than diesel. Light green denotes values that are 50-99% of diesel, orange 20-49%, and red anything below 20%. The perfect fuel would therefore be a non-fossil fuel that was green in both rows.

The energy density of lithium ion batteries is continuously improving, and has tripled since it was first introduced commercially in the 1990's.[58] While some commentary describes how innovation will continually push battery performance ever higher,[59] other papers argue current progress is already close to identified theoretical limits.[60] A detailed 2021 study appears to support this argument, as a plateau in energy density improvement from 2015-2021 is evident in their data.[61] This study consequently used current energy density values and assessed whether they were sufficient for warfighting during the analysis.

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[58] Hannah Richie, "The Price of Batteries Has Declined by 97% in the Last Three Decades," Our World in Data, June 4, 2021, https://ourworldindata.org/battery-price-decline.

[59] Scott K. Johnson, "Eternally Five Years Away? No, Batteries Are Improving under Your Nose," Ars Technica, May 24, 2021, https://arstechnica.com/science/2021/05/eternally-five-years-away-no-batteries-are-improving-under-your-nose/.

[60] George Crabtree, Elizabeth Kócs, and Lynn Trahey, "The Energy-Storage Frontier: Lithium-Ion Batteries and Beyond," *MRS Bulletin* 40, no. 12 (December 2015): 1067–1078.

[61] Micah S. Ziegler and Jessika E. Trancik, "Re-Examining Rates of Lithium-Ion Battery Technology Improvement and Cost Decline," *Energy & Environmental Science* 14, no. 4 (April 2021): 1635–1651.

Table 1. Comparison of Energy Densities (Descending Order of Energy Density by Mass

Ser	Fuel:	Energy density by mass (MJ/Kg)	Energy density by volume (MJ/L)
1	H2 (10,000psi) without tank	140	8.28
2	H2 (Atmospheric)	143	0.0127
3	Liquid H2 (-253)	140	9.4
4	H2 (3000psi)	140	0.00972
5	Diesel	45.5	38.675
6	LNG	43.5	26
7	Algae Bio Oil	30.7	30.1
8	Methanol	22	16
9	Magnesium Hydride Powerpaste (without water)	5.8	6.8
10	Magnesium Hydride Powerpaste (including water)*	3.44	4.296
11	Nickel Cobalt Aluminium (NCA) Lithium-Ion battery	0.9	2.4
12	Nickel Manganese Cobalt (NMC) Lithium-Ion battery	0.72	2.4
13	H2 (10,000psi) inc tank	0.27	0.252

Source: Created by author using sources as annotated:
H_2 (10,000psi); H_2 (10,000psi) with tank - Johnson et al., "Advancements and Opportunities for On-Board 700 Bar Compressed Hydrogen Tanks in the Progression Towards the Commercialization of Fuel Cell Vehicles"
Liquid H_2; H_2 (3,000psi); LNG; methanol - Moghbelli et al., "A Comparative Review of Fuel Cell Vehicles (FCVs) and Hybrid Electric Vehicles (HEVs) Part I"
diesel - Molloy, "Run on Less with Hydrogen Fuel Cells"
algae bio-oil - Supriyanto et al., "The Recent Progress of Natural Sources and Manufacturing Process of Biodiesel"
powerpaste - Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, "Powerpaste for Off-Grid Power Supply"
NCA battery; NMC battery - Stampatori, Raimondi, and Noussan, "Li-Ion Batteries,"; Clean Energy Institute, "Lithium-Ion Battery"
NOTE: *Published values do not include the water required for the chemical reaction. One kilo of powerpaste would need 0.68Kg of water. One liter of powerpaste would require 0.58 liters of water. The "without water" figures have therefore been divided to account for this.

Finally, the automotive industry offers an interesting perspective on hydrogen versus electricity. With finite research and development funds, companies are deciding to invest in one technology or the other. A review of different automotive manufacturers' future plans implies that the vast majority are choosing to develop battery technology, not hydrogen fuel cells.[62] It is unclear whether these decisions are based on long-term potential or manufacturing cost in the short term. Either way, it provides a useful indicator for this study.

Deployable Nuclear Power

The US military is exploring the feasibility of small deployable nuclear reactors to provide 1-5MW of power.[63] The employment of these reactors beyond the continental United States is, however, a contentious issue.[64] There is significant literature surrounding the development of small nuclear reactors in the near future, such as Rolls-Royce's Small Modular Reactor (SMR) concept.[65] There is also a wide variety of UK[66]

[62] Based on comparative analysis of leading automotive manufacturer websites.

[63] Aaron Mehta, "Portable Nuclear Reactor Project Moves Forward at Pentagon," *Defense News*, March 23, 2021, https://www.defensenews.com/smr/energy-and-environment/2021/03/23/portable-nuclear-reactor-project-moves-forward-at-pentagon/.

[64] David Kramer, "Pentagon's Battlefield Nuclear Reactor Plans Come under Fire," Physics Today, June 28, 2021, https://physicstoday.scitation.org/do/10.1063/PT.6.2.20210628a/abs/.

[65] Rolls-Royce, *Nuclear Small Modular Reactors - Once in a Lifetime Opportunity for the UK* (London, UK: Rolls-Royce, PLC, 2017), https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/nuclear/smr-brochure-july-2017.pdf.

[66] Member States, Convention on the Physical Protection of Nuclear Material (CPPNM) and Its Amendment (International Atomic Energy Agency Information

and international law[67] surrounding the use of nuclear materials and associated responsibilities, such as security and protection.

Summary of Alternative Power Source Literature

There are numerous alternatives to fossil-fuels, but none can match the performance of diesel or gasoline in energy density by mass *and* by volume. If current alternative technologies are used to replace fossil fuels, they are likely to force compromise and change in equipment capability. The study now turns to literature on future concepts, and historical examples.

How would electric land platforms nest in broader future concepts?

Official UK concepts are nested within descriptive strategic predictions, most notably *Global Strategic Trends – The Future Starts Today*,[68] and the *Future Operating Environment 2035*.[69] The British Army is closely following the development of Multi Domain Operations[70] in the US Army, with a view to forming its own concept that

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Circular, Vienna Austria, October 26, 1979), https://www.iaea.org/publications/documents/conventions/convention-physical-protection-nuclear-material-and-its-amendment.

[67] Andy Erickson, "Build Small Nuclear Reactors for Battlefield Power," *Defense One,* September 20, 2018, https://www.defenseone.com/ideas/2018/09/build-small-nuclear-reactors-battlefield-power/151434/.

[68] Ministry of Defence, *Global Strategic Trends*.

[69] Ministry of Defence, *Future Operating Environment 2035*.

[70] U.S. Army Training and Doctrine Command (TRADOC), TRADOC Pamphlet 525-3-1, *The U.S. Army in Multi-Domain Operations 2028* (Fort Eustis, VA: U.S .Army Training and Doctrine Command, December 2018), https://api.army.mil/e2/c/downloads/2021/02/26/b45372c1/20181206-tp525-3-1-the-us-army-in-mdo-2028-final.pdf.

maximizes interoperability. This is currently described in Joint Concept Note (JCN) 1/20 *Multi Domain Integration*.[71] This nests within the broader JCN 1/17 *Future Force Concept*.[72]

At an Army level, the "Future Soldier Guide" was released 25 November 2021, which explains how the British Army will be structured in 2030.[73] There are also older concepts that were introduced in the 2010's but have since been abandoned, such as STRIKE.[74] Broader literature from serving members of the British Army provide a detailed commentary on the rise and fall of STRIKE, which, as a medium weight rapid capability, offers useful lessons for this study.[75] In particular, one insightful article links STRIKE to battlecruisers to critique the concept.[76]

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71 "Joint Concept Note 1/20, Multi-Domain Integration" (n.d.): 90.

72 Ministry of Defence, Joint Concept Note 1/17, *Future Force Concept* (Swindon, Wiltshire: Defence Concepts and Doctrine Centre, Ministry of Defence, July 2017), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/643061/concepts_uk_future_force_concept_jcn_1_17.pdf.

73 Ministry of Defence, "Future Soldier Guide."

74 Jack Watling and Justin Bronk, "Strike From Concept to Force," (Occasional Paper, Royal United Services Institute for Defence and Security Studies, Royal United Services Institute for Defence and Security Studies, London, UK, June 2019), https://static.rusi.org/201906_op_strike_web.pdf.

75 Nicholas Drummond, "Strike Brigades - More than Just a Medium Weight Capability," Wavell Room, January 7, 2020, http://staging.wavellroom.com/2020/01/07/strike-brigades-more-than-just-a-medium-weight-capability/.

76 Lt Col Martin A Smith, "The STRIKE Brigade: The Army's Battlecruiser for the 21st Century?," *The British Army Review*, no. 178 (Summer 2020): 32–37.

US concepts are also important. *Global Trends 2040*[77] provides a useful comparison to the UK's *Global Strategic Trends*. *Multi Domain Operations 2028*[78] is also influential, as is subsequent commentary by GEN Wesley[79] and BG Wass de Czege.[80]

Finally, literature from journals, think tanks and historians offer useful insight. These range from expeditionary maneuver warfare concepts[81] to specific articles on how future tanks could be powered by electricity.[82] Several articles predict how the US Army of the future will be electric.[83] This existing literature, while varied, usually fails to grasp the scale of the problem: From flawed ideas that 'dumping fossil fuels' would completely

[77] National Intelligence Council, *Global Trends 2040: A More Contested World* (Washington, DC: National Intelligence Council, March 2021), https://www.dni.gov/index.php/gt2040-home/gt2040-media-and-downloads.

[78] TRADOC, TRADOC Pamphlet 525-3-1.

[79] LTG Eric Wesley, "The Future Force in Multi-Domain Operations," video of leader professional development session, Fort Eustis, VA, 22 January 2020, https://www.youtube.com/watch?v=RItpEV0enYU.

[80] Huba Wass de Czege, *Commentary on "The US Army in Multi-Domain Operations 2028,"* (Carlisle, PA: U.S. Army War College Press, April 2020), 66.

[81] James Jones, "Expeditionary Maneuver Warfare Concept," *Inside the Navy* 14, no. 49 (December 2001): 11–15, http://www.jstor.org/stable/24828780.

[82] Kyle Mizokami, "Future Tanks Could Be Powered by Electricity," *Popular Mechanics*, September 16, 2019, https://www.popularmechanics.com/military/weapons/a28985236/future-tanks-powered-electricity/.

[83] Caleb Larson, "A Risky Bet? The U.S. Army of the Future Will Be Electric," *19FortyFive*, April 26, 2021, https://www.19fortyfive.com/2021/04/a-risky-bet-the-u-s-army-of-the-future-will-be-electric/.

remove the need for sustainment trains,[84] to suggestions that nuclear powered tanks are the answer. There are, however, useful articles to offer depth and breadth to the study. Progress in materials science that affects armor is available[85] which allows for more realistic calculations in platform design compromises. The Royal United Services Institute (RUSI) have also produced comprehensive analysis on the impact of sub-threshold competition on strategic energy supply.[86] This highlights the vulnerability of civilian electrical infrastructure to cyber-attacks, which was relevant to analysis in Chapter 4.

Historical Examples for Illustrative Case Studies

A divestment of fossil fuels is not the first major transition in operational energy.[87] Armies faced significant change when adopting the internal combustion engine in the twentieth century.[88] These were of limited relevance for this study because previous transitions have been towards a power source that offered relative performance

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[84] Bridie Schmidt, "An Electric Tank? Army Sees Multiple Advantages in Dumping Fossil Fuels," *The Driven*, September 10, 2019, https://thedriven.io/2019/09/10/an-electric-tank-army-sees-multiple-advantages-in-dumping-fossil-fuels/.

[85] Connie Lee, "Army to Continue Metal Matrix Composite Research for Lighter Vehicles," *Inside the Army* 29, no. 33 (2017): 3–3.

[86] Daniel K. Jonsson, "Preparing for Greyzone Threats to the Energy Sector" (Occasional Paper, Royal United Services Institute for Defence and Security Studies, London, UK, November 2020), https://static.rusi.org/185_jonsson_web_0.pdf.

[87] Charles A. Berg, "Process Innovation and Changes in Industrial Energy Use," *Science* 199, no. 4329 (February 1978): 608–614.

[88] Robert J. Icks, "How Armies Are Mechanizing: A Summary of Automotive Equipment, Trends and Policies," *Army Ordnance* 14, no. 84 (1934): 330–338.

improvement. Based on the previous section of the literature review, divesting fossil fuels is likely to be a transition to a fuel that either does not perform as well, or has different characteristics. Subsequently, naval transitions from sail to coal and coal to gasoline have limited utility because they reduced compromise.[89]

The United Kingdom has not conducted warfighting at scale since Iraq in 1991 and 2003. 1991, in particular, provides an excellent example of a British division conducting operational maneuver with equipment largely still in service today. Numerous articles in the *British Army Review* (BAR) provide detailed first-hand accounts of this operation. Most notably, General Sir Rupert Smith's contributions in the BAR special edition on the First Gulf War.[90] Written eight years later, the 1999 version of the *Staff Officers' Handbook* (SOHB) provides open-source detailed information that is highly relevant to modern analysis.[91] SOHB 1999 was explained in more detail earlier in the literature review, but its link to the 1991 Gulf War is worth highlighting here.

Summary

There is a plethora of documentation that describes how 3 (UK) Division is designed to fight, and how it conducted itself on recent exercises. These sources enable the study to create an understanding of how 3 (UK) Division fights in space and time. There is a clear hierarchy of documents from strategic reviews such as Global Britain,

[89] "Petroleum Fuel Better Than Coaling Stations," *Scientific American* 80, no. 25 (June 1899): 404.

[90] General Sir Rupert Smith, "The Division," *British Army Review Special Report - The Gulf War* 1 (Winter 2020): 28–45.

[91] Land Warfare 1 Branch, *Staff Officers Handbook*.

down to battlegroup tactics and below, allowing a divisional concept to remain nested in broader strategic direction. There are open-source documents that describe the future strategic and operational environments that provide an effective foundation for analyzing a warfighting division within the future character of conflict.

Operational Staff Work (OSW) provides highly detailed examples of how divisional staffs (and their subordinate brigades and battlegroups) have employed capability. One can build a picture of how the division actually fights through dates, timings, and grid references in OSW. This OSW provides an insight into how 3 (UK) Division currently train and expect to fight.

Robust peer reviewed scientific research on alternative fuels and their applications is extensive. Very little of it is focused on military applications, however. Chapter 4 of this study, the analytic Chapter, must therefore derive the military implications of this research.

Broader future concepts exist, but only in detail until approximately 2030. Beyond this, descriptive strategic guides such as the *Future Operating Environment 2035* and *Global Strategic Trends* are somewhat speculative. These provide the context with which any conclusions in Chapter 5 must align.

Ultimately, the available literature represents sufficient means to use document analysis as a way of answering this study's research questions. The methodology used to analyze this literature is described in Chapter 3.

CHAPTER 3

RESEARCH METHODOLOGY

> Lessons often comprise an agreed historical perspective, the current received wisdom, the addition of some recent experiences, predictions about technological development, and an extrapolation about a possible future.
>
> — MG (Ret) Jonathan Bailey,
> "Military History and the Pathology of Lessons Learned"

> Military leaders often distort and contort new evidence to sustain their views of the future as they wish it to be.
>
> — MG (Ret) Jonathan Bailey,
> "Military History and the Pathology of Lessons Learned"

Introduction

The research methodology comprises four parts. Firstly, an explanation of the research method employed for data collection and analysis. Secondly, an overview of the types of sources used for data collection, along with criteria for relevance and credibility. Thirdly, how the method will be applied to research questions during data analysis. Finally it discussed ethical considerations and how the study has mitigated any identified risks.

Method

This study used a Grounded Theory approach to develop a concept that answers the primary research question. A grounded theory seeks to build a new theory or concept from qualitative data, which provides the grounding or basis. It does not begin with a hypothesis to prove or disprove. One approach to developing a grounded theory is to use three phases of analysis referred to as open, axial and selective coding.[92]

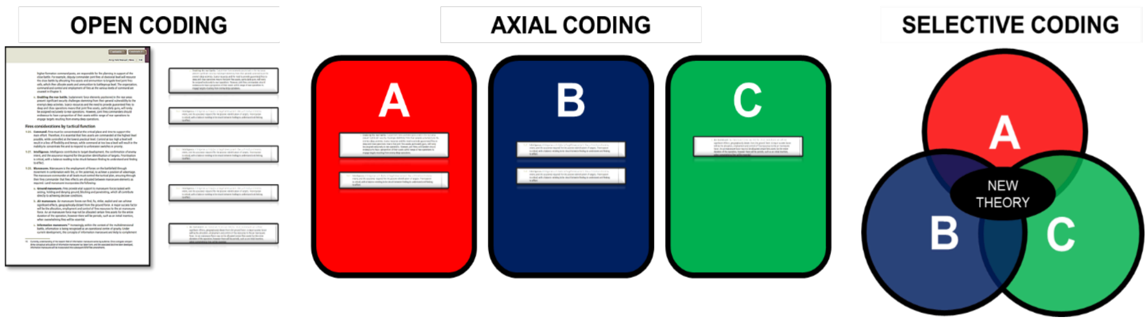

Figure 2. Visualization of the Three Stages of Coding in Grounded Theory

Source: Created by author.

Open coding is the identification of potentially relevant information or data from whatever source is being researched. An example from this study was the operational range of a Challenger 2 Main Battle Tank (MBT). Document analysis of the Staff Officer's Handbook (SOHB) yielded this information, which was then allocated a code. There were a large number of these codes, which remain fragments of information without any form of grouping or categorization.

Axial coding takes these numerous fragments and groups them into categories. This study double categorized data for the first secondary research question. Where appropriate, it also categorized the same open code for each secondary research question. Categories can be bespoke, or an existing framework that is likely familiar to readers.

[92] Delve, "Grounded Theory Explained in Simple Terms," October 20, 2021, video, 3:01, https://www.youtube.com/watch?v=tirZ7ktPW64&t=1s.

This study used the eight components of the US Army definition of 'Combat Power' from ADP3-0 as its categories for axial coding, when exploring how 3 (UK) Division currently fights. The elements of combat power were chosen as the categories because they form an interlocking and comprehensive overview of how a formation fights. The operational range of a Challenger 2 MBT was grouped in the 'Movement and maneuver' category. There were inevitably links between categories beginning to appear, or dilemmas about which category a specific piece on information best sits within. These would necessitate new categories being formed. With all of the information categorized, the links between them were analyzed.

Selective coding is the integrative process that identifies links between categories, and uses them to develop a holistic perspective of the information as a whole. A core concept is derived from this holistic perspective, grounded in the data. The coding used for this study is attached in Appendix A.

Data Collection

Sources

The study relied primary on document analysis. These include published doctrine and concepts, detailed equipment manuals, and staff work from previous exercises. It also used peer reviewed scientific research papers and broader literature/commentary from journals. It did not use interviews for reasons outlined in the ethical considerations section below. All of the references explained in Chapter 2 form sources used for the study.

Criteria for Assessing Relevance

As this is a qualitative grounded theory, relevance is inherently subjective. In researching how 3 (UK) Division currently fights, its tactics and processes on the beaches of Normandy in 1944 have little in common with the Division's form and function today. The rapid advances in technology, and the significant transformation outlined in "Future Soldier" also challenge the relevance of more recent conflicts such as Operation Desert Storm in 1991.

As this study looked at warfighting, relevant data about how 3 (UK) Division fights is limited to when it switched its focus from force generating for Afghanistan to becoming a warfighting headquarters in approximately 2015-2017. Therefore, this study only considered documents and articles describing how 3 (UK) Division fights were from 2017 and beyond.

In analyzing alternative power sources, there is a significant amount of research for the civilian transport industry and energy sector. For example, literature discussing hydrogen to power heavy-goods vehicles is much more relevant than information on large-scale industrial facilities to generate hydrogen within the UK. While both are clearly linked, the former more readily translates to a deployable warfighting capability. Literature that provides key quantitative data for subsequent analysis is also relevant. An article on powering remote African villages is relevant, if it includes a peer reviewed figure for the energy density of a Lithium-Ion battery in 2021.

Finally, official future concepts such as JCN 1/20 *Multi-Domain Integration*[93] are relevant because any conclusions from this study must nest within the future they describe. Broader publications and ideas are also relevant as they can offer alternative perspectives and counterarguments to analyze.

Criteria for Assessing Credibility

Evidence of peer review in published material is the primary means of ensuring the credibility of sources, especially for the analysis of alternative fuels. The credibility of each item used in coding is within Appendix A. Official documents such as doctrine and concepts will be deemed credible, with more recent documents taking precedence over earlier ones if there is a contradiction. Documents and articles that do not evidence claims or assertions with sound logic or numerical reasoning do not have enough credibility to be included in the study.

Data Analysis

Below is a visualization of how this study analyzed each of the three secondary research questions. Each secondary research question directly informs the questions that come afterwards. These should flow towards a comprehensive understanding of the problem by the end of Chapter 4. This enables a final synthesis of ideas during Chapter 5 to develop the final grounded theory.

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93 Ministry of Defence, Joint Concept Note 1/20, *Multi-Domain Integration* (Swindon, Wiltshire: Defence Concepts and Doctrine Centre, Ministry of Defence, November 2020), 20.

Explanation of Method Visualizations

Each of the three figures is structured to show some example source documents at the top. The documents shown in each visualization are not an exhaustive list, but merely representative of the type of document that will be analyzed. Next, the open codes extracted from source documents are represented by snippets of cut-out text underneath the example sources. These then flow downwards into the axial coding categories in a green rectangle. Selective coding resulting from these categories is shown as an abstraction that varies for each secondary research question.

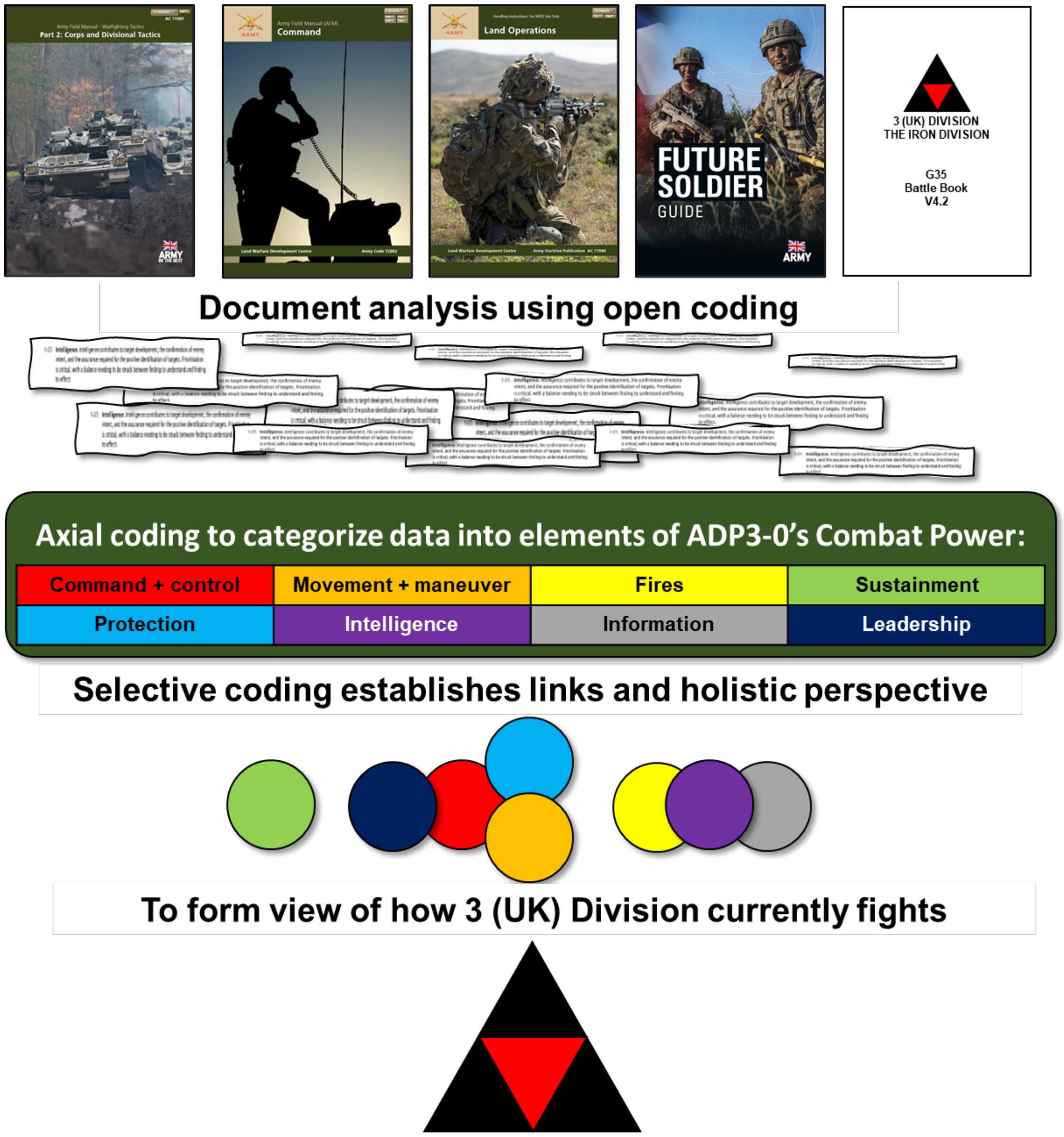

Figure 3. Visualization of Methodology for First Secondary Research Question

Source: Created by author. NOTE: Documents shown are representative and not the only ones to be analyzed.

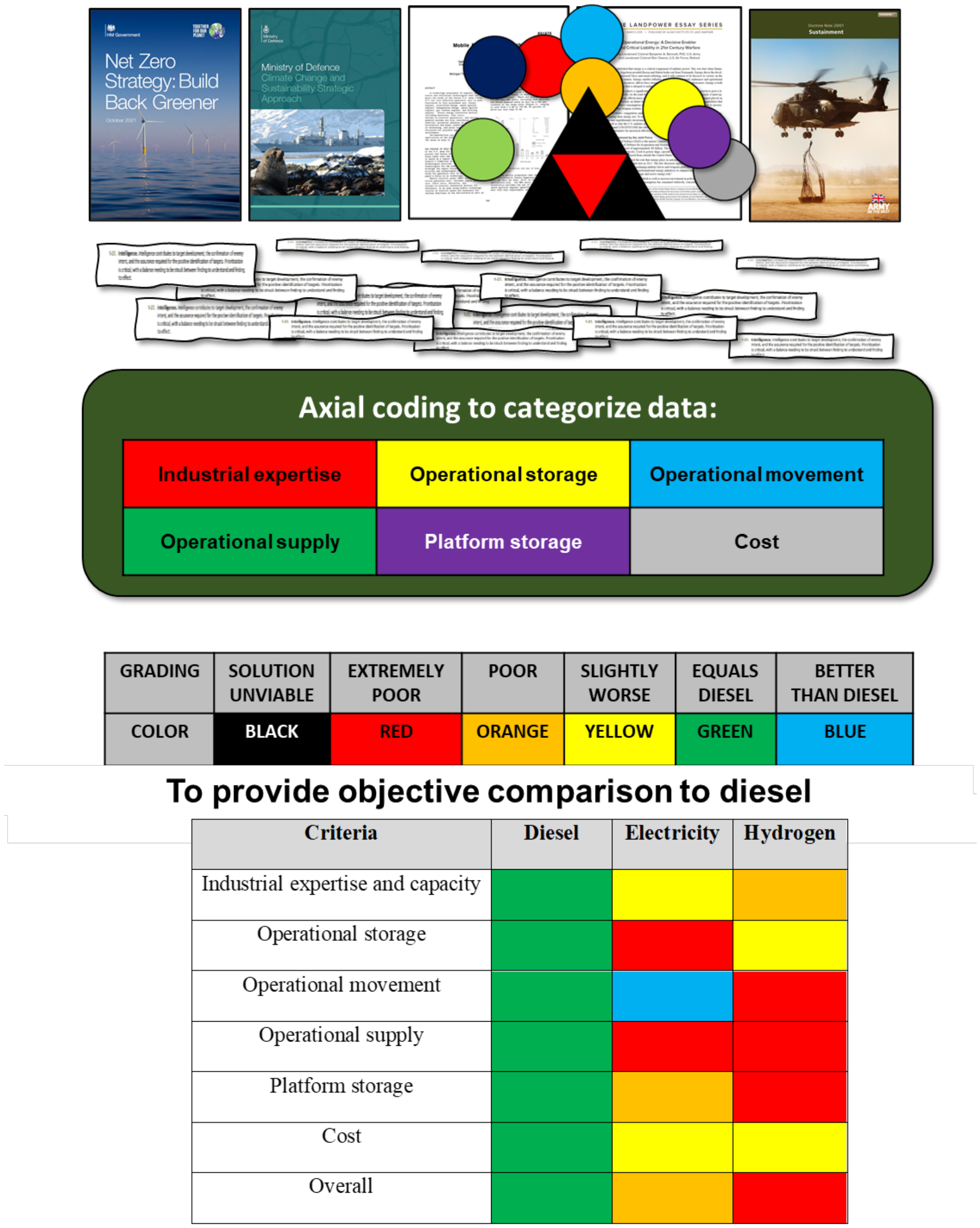

Figure 4. Visualization of Methodology for Second Secondary Research Question

Source: Created by author. NOTE: Documents shown are representative and not the only ones to be analyzed.

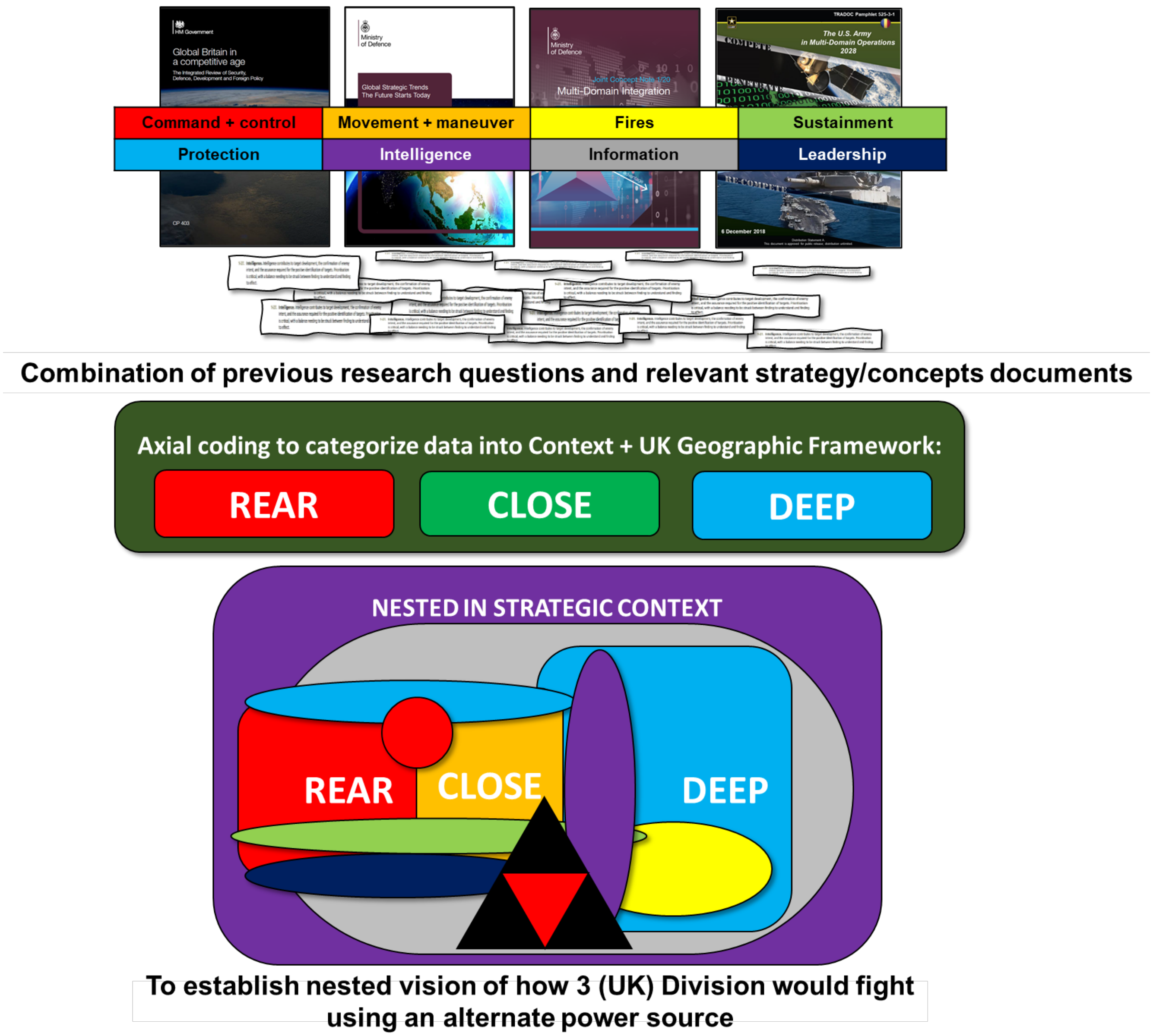

Figure 5. Visualization of Methodology for Third Secondary Research Question

Source: Created by author. NOTE: Documents shown are representative and not the only ones to be analyzed.

Ethics Considerations

The principal ethical concern in this study was bias. Firstly, the author's personal bias based on experience of the organization in the primary research question. Secondly, external bias during data collection. Both were examined in detail below.

The author's personal experience of 3 (UK) Division and the wider British Army could have created personal bias. This experience has created personal opinions based on detailed insight of 3 (UK) Division. But as distinguished journalist Andrew Marr noted when leaving the British Broadcasting Corporation, "If you don't have some opinions you aren't thinking."[94] These opinions were therefore useful to help focus research. The intent however was to build a strong thesis based on evidence rather than conjecture. The study has declared if opinion is used to connect evidence or synthesize information.

The author also completed a Masters in Physics, and therefore has a tendency to think using a positivist epistemological perspective. In simple English this means that truth is absolute, and full understanding it is aspirational. For Chapter 4 it means the style and tone revolved around trying to disprove theories, and only accepting that which remained. This was relevant because it shaped the assessment of sources and the style of analysis throughout the study.

Failing to understand the motives, interests and context of sources could have introduced bias to the study. The Integrated Review (IR)[95] has compelled every part of

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[94] BBC, "Andrew Marr to Leave BBC for LBC to 'Get My Own Voice Back,'" *BBC News*, November 19, 2021, https://www.bbc.com/news/entertainment-arts-59348808.

[95] Cabinet Office, *Global Britain in a Competitive Age: The Integrated Review of Security, Defence, Development and Foreign Policy* (United Kingdom: HM Government,

the force to justify its size, role, and cost as it modernizes. Regimental history and job security shape individual interests, and influence perceptions. Within 3 (UK) Division, the author spent two years as a battalion S3, and a year as group (brigade minus) S3. From this experience, 3 (UK) Division is a busy organization. A request for interviews with SMEs would most likely only be resourced with the minimum number of people, if at all. It would have been difficult to obtain a wide variety of objective interviews without command influence to pressure interviewees to support the study. It was therefore not feasible within the scope of this study to include human subject research, because the risk of introducing bias could be adequately mitigated or measured.

Summary

To answer the primary research question, this study answered the three secondary research questions sequentially, in order. Analysis began with understanding how 3 (UK) Division fights. Document analysis produced open codes. These were categorized according to the eight elements of ADP 3-0's definition of combat power. Selective coding was used to establish links between these categories, which formed a holistic perspective of how 3 (UK) Division fights, and answered the first secondary research question.

A similar process generated codes from climate change policies, scientific research, and doctrine categorized them. This was synthesized with the view of how 3

March 2021), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/969402/The_Integrated_Review_of_Security__Defence__Development_and_Foreign_Policy.pdf.

(UK) Division fights to provide an evidenced opinion on whether electrification is the most suitable alternative power solution.

Finally, broader strategic publications and futures concepts were open coded. The information gleaned will then be axially coded into ADP3-0's eight elements of combat power, just like the research question exploring how 3 (UK) Division fights currently. This was then synthesized with the previous research questions to generate a nested concept for how 3 (UK) Division might fight without fossil fuels in the future.

CHAPTER 4

ANALYSIS

> The engine of a tank is no less a weapon than its gun.
>
> —General Heinz Guderian

> Moving on a single route with 100m between vehicles at 20kih[96] the Division occupies some 400km of road, takes 24 hours to pass a point, and needs some 150 square kilometres of mixed countryside to hide in when at rest.
>
> —General Sir Rupert Smith, describing the British Armored Division he commanded in 1991

Introduction

The analysis Chapter worked through each secondary research question in turn. The final synthesis of ideas to produce a grounded theory is the centerpiece of the conclusion in Chapter 5.

Chapter 4 first analyzes how 3 (UK) Division fights, using the method explained in the methodology and the sources identified in the literature review. It axially coded information into the eight elements of combat power (Fires, Movement and maneuver, Command and control, Protection, Sustainment, Intelligence, Information, and Leadership). Some of these axial codes proved of limited use to answer the primary research question. As such, the length of analysis in each category varied significantly. Command and control, protection, and leadership are not included in the pages below, because they proved of limited relevance through the remainder of Chapter 4. The

[96] Kih is kilometers in the hour. It stresses an average speed over time, rather than maintaining a consistent speed irrespective of driving conditions. This is allegedly based on a soldier who believed 20kph meant they were not allowed to slow down for tight corners, hence the nuance in term.

remainder of the elements of combat power are included, and have been positioned in priority order.

With 3 (UK) Division's style of fighting understood, the study moved to the next research question: It assessed whether electrification was the best alternative power source. It compared diesel, hydrogen and lithium-ion batteries across metrics outlined in the research methodology. It combined numerical reasoning with military judgement to affirm that electrification is challenging but preferrable to hydrogen.

Finally, the Chapter assessed future concepts, such as Multi-Domain Operations,[97] to understand how the future context for an electrified division. This analysis proved shorter than anticipated because future concepts did not appear to have the longevity to remain relevant in 2050. The analysis consequently focused more on the future operating environment of the 2040's as described in strategic documents such as Global Trends 2040,[98] and Global Strategic Trends.[99]

How does 3 (UK) Division currently fight?

The analysis in this Chapter is assumes the reader is familiar with the division as an abstract echelon that sits above a brigade or regiment, but underneath a Corps. This assumption allowed the study to focus its analysis on 3 (UK) Division specifically.

[97] TRADOC, TRADOC Pamphlet 525-3-1.

[98] National Intelligence Council, *Global Trends 2040.*

[99] Ministry of Defence, *Global Strategic Trends*.

The Division is also undergoing a period of significant modernization outlined in "Future Soldier" (25 November 2021). This study used the Future Soldier structure rather than the 3 (UK) Division of 2021/22 to maximize relevance.

3 (UK) Division in Context

3 (UK) Division is the only warfighting division in the British Army. Its destruction in LSCO would have a dramatic impact on all three components of fighting power: moral, physical and conceptual. The British Army's small size compared to potential adversaries is nothing new. Since WW2, basic assumptions about fighting outnumbered characterized the Cold War, and became reality in Korea. Force preservation is therefore deeply engrained within the British Army's approach to fighting.

Force preservation underpins what ADP *Land Operations* terms the *Manoeuvrist Approach* which is "an indirect approach which emphasizes effects on the will of the enemy."[100] The *manoeuvrist approach* is therefore focused on destroying the moral component of fighting power, with as few casualties as possible.

This context is important because it underpinned the detail throughout this secondary research question.

Fires

One of the most effective ways to achieve the force preservation described above is to destroy enemy forces in the deep battlespace and present an anti-climactic close fight for maneuver brigades. This is not just the preserve of the Royal Artillery but

[100] Land Warfare Development Centre, ADP, *Land Operations*, 79.

includes air and maritime component capabilities too. Assets the Fires function leverages are also likely to be multinational. With UK participation in the US Warfighter exercises, procedural and technical interoperability with US forces is paramount.[101] As such, the Division's fires function revolves around a Divisional Joint Air Ground Integration Center (JAGIC).[102] AFM *Fires* para 3-48 to 3-54 describe in detail how fires are integrated across plans, future operations, and current operations.[103]

The JAGIC "co-locates personnel with delegated decision-making authorities from the land and air components with the best situational awareness to support the maneuver commander's concept of operations."[104] The best place to assess the success or failure of this model is the 3 (UK) Division MCTP After Action Review from Warfighter 21.4, which is beyond the classification of this study. It must be noted that lessons identified from simulations are only useful if the limitations of the simulation are well understood. The limitations of the simulation are more pertinent to movement and maneuver, and are explored in greater depth in that section.

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[101] Major Orlando Howard, "Warfighter 21-4 to Support Multinational Interoperability," U.S. Army, March 30, 2021, https://www.army.mil/article/244807/warfighter_21_4_to_support_multinational_interoperability.

[102] Headquarters, Department of the Army (HQDA), Army Techniques Publication (ATP) 3-91.1, *The Joint Air Ground Integration Center* (Washington, DC: Army Publishing Directorate, April 2019), https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN16449_ATP%203-91x1%20FINAL%20WEB.pdf.

[103] Land Warfare Centre, Army Field Manual (AFM) - *Fires* (Warminster, UK: Ministry of Defence, 2019).

[104] HQDA, ATP 3-91.1, 7.

Using fires to prosecute a deep battle, and thereby shape the close fight is consequently the principle aim of fires within 3 (UK) Division. The inherent tension between resourcing the deep or close with fires can be seen in online journals, especially when authored by staff officers serving in maneuver brigades that desire more support for the close.[105] This is exacerbated by what RUSI describes as the British Army's "critical shortage of artillery."[106] General Sir Rupert Smith, who commanded the 1st British Armored Division into Iraq in 1991 provides a compelling argument for prioritizing the deep over the close.[107] Writing in 2008, he simply compares the resources available and the resources required to achieve an effect with indirect fires. He synthesizes these to argue that in supporting the close fight, the Division can only hope to resource three targets, and thereby at most one friendly brigade.

This matches the Future Soldier modernization program which explicitly emphasizes that the Army will "double the proportion of the deployable force that contributes to deep effects."[108] This includes doubling the number of deep fires regiments

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[105] Steve B, "The British Way of War - Balancing Fire and Manoeuvre for Warfighting," Wavell Room, May 9, 2018, https://wavellroom.com/2018/05/09/the-british-way-of-war-balancing-fire-and-manoeuvre-for-warfighting/.

[106] Jack Watling, "The Future of Fires: Maximising the UK's Tactical and Operational Firepower," (Occasional Paper, Royal United Services Institute for Defence and Security Studies, London, United Kingdom, November 2019), 6, https://rusi.org/explore-our-research/publications/occasional-papers/future-fires-maximising-uks-tactical-and-operational-firepower.

[107] Smith, "The Division," 37.

[108] Ministry of Defence, "Future Soldier Guide," 14.

in the Royal Artillery and integrating them into the 1st Deep Recce Strike Brigade Combat Team.[109]

Artillery logistics uses a significant amount of a modern division's vehicles. 3 (UK) Division is no exception. The unclassified 1999 *Staff Officers' Handbook* (SOHB 1999) provides useful data for calculating the demand of artillery logistics. Although the figures come from a time before precision fires, Dr Jack Watling of RUSI argues that conventional munitions still play a significant role in future conflict because they are an order of magnitude cheaper, and significantly easier for an industrial base to produce.[110]

SOHB 1999 lists the typical ammunition demand for one 155mm self-propelled artillery regiment as 910 pallets,[111] each containing 17 rounds.[112] That is 15,470 155mm rounds per regiment per day. There are two AS90 Regiments in Future Soldier,[113] with a daily consumption of 30,940 155mm rounds, or 1,820 pallets. There are also two deep fires regiments using MLRS, each of which will consume 540 Rocket Pod Containers (RPCs) per day.[114] Each RPC contains six rockets.[115] 1st Deep Strike Recce Brigade's artillery logistics demand is therefore in the region of 1,080 Rocket Pod Containers and

[109] Ministry of Defence, "Future Soldier Guide," 58.

[110] Watling, "The Future of Fires, " 32.

[111] Land Warfare 1 Branch, *Staff Officers Handbook*, 287.

[112] Ibid., 284.

[113] Ministry of Defence, "Future Soldier Guide," 58.

[114] Land Warfare 1 Branch, *Staff Officers Handbook*, 287.

[115] Ibid., 285.

1,820 pallets of 155mm ammunition every day. This is larger than the estimate of 760 pallets of ammunition for a Division outlined in Doctrine Note 20/01 *Sustainment*, but this is likely because DN20/01 is based on a single deep fires Regiment, and a greater proportion of precision fires. The size of a NATO ammunition pallet is also unchanged.[116] This study therefore used the detailed calculations inferred from SOHB 1999, because they are clearly derived from a primary source and reflect ammunition consumption in an era of conventional munitions. These figures were used to calculate wheeled vehicle demand when considering sustainment.

The doubling of deep fires regiments and organizational integration with recce elements highlights how convinced the British Army is that shaping the deep is something that is necessary, and worth the financial cost in spite of competing priorities.

Summarizing fires, two key themes have been identified. First, the importance of divisional fires to apply lethal effect in the deep is fundamental to how 3 (UK) Division fights. Second, conventional munitions in warfighting remain relevant, and the artillery logistics to support 3 (UK) Division's deep fight are significant. Combining these into one output, the energy demand of 3 (UK) Division's artillery logistics is critical to how it fights. Artillery logistics is subsequently explored in more detail in the sustainment section of this research question.

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[116] Headquarters, Department of the Army (HQDA), Department of the Army Pamphlet (DA PAM) 746-1, *Pallets and Storage Aids for Army Use* (Washington, DC: Army Publishing Directorate, August 29, 2018), 13, https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN3394_DAPam746_1_FINAL.pdf.

Movement and Maneuver

The study had to analyze how 3 (UK) Division moves in time and space before the sustainment implications of artillery logistics could be considered. The distances that the division can move in a day determine the distances and throughput requirements for artillery ammunition. This, along with the movement of maneuver brigades is provided the basis for vehicular movement, and thus energy demand.

This study needed to develop a detailed sense of how 3 (UK) Division operates in space and time to understand energy supply and demand. There were several different ways to try and model this: simulations, history, and doctrine. This study analyzed all three.

First is to use modern simulation data from recent Command Post Exercises (CPX's) such as Warfighter 21/4. This has the advantage of being recent, with contemporary doctrine. MG Maria Gervais, who commanded the Synthetic Training Environment Cross Functional Team in 2018 accurately describes how the WARSIM software used for Warfighter exercises does not model sustainment accurately.[117]

This correlates with the author's experience on Warfighter 21/4, where any vehicle within 100km of a sustainment vehicle would automatically be resupplied. Automatic simulated resupply prevented targeting of sustainment, negated throughput issues on routes, and allowed an excessive amount of artillery ammunition to move 100km across the battlefield in seconds instantly. This 'teleporting' ammunition could

[117] MG Maria R. Gervais, "The Synthetic Training Environment Revolutionizes Sustainment Training," U.S. Army, August 23, 2018, https://www.army.mil/article/210105/the_synthetic_training_environment_revolutionizes_sustainment_training.

then be expended in the simulator without any regard for thermal management of the guns.[118] The WARSIM software also does not model the complexity of terrain, especially rice paddies, irrigation ditches, and steep gradients.

The result is a simulation system that generates a disconnect between terrain, sustainment and maneuver which has most likely built a degree of hubris into what US and UK divisional planners believe is possible, especially with regard to operational reach and endurance of fires.

It is for this reason that the study took data from CPX simulations, but also used real world empirical maneuver that was bounded by the realities of sustainment and to a lesser extent, terrain. The best example for this is Operation Desert Storm in Iraq, 1991, for four reasons. First, the majority of the platforms used are still in service today, albeit upgraded. Second, numerous detailed sources are readily available. Third, relatively unconstrained terrain compared to Eastern European CPXs sees 1 (BR) Armored Division maximizing its operational reach, at the limit of real divisional level sustainment. Finally, the brigade's maneuver elements consisted of two armored brigades task organized with combat support elements,[119] which is the same as the Future Soldier concept for 3 (UK) Division.[120] This section thus begins with 1 (BR) Armored Division

[118] Lieutenant Colonel Matt Wilks, "Firepower! Lessons from 1 (BR) Armoured Division's Deep Battle," *British Army Review Special Report - The Gulf War* 1 (Winter 2020): 52-63.

[119] Col Matt Baker OBE, "Operation DESERT SABRE - 1st British Armoured Division," *British Army Review Special Report - The Gulf War* 1 (Winter 2020), 16, https://www.army.mod.uk/umbraco/Surface/Download/Get/17217.

[120] Ministry of Defence, "Future Soldier Guide," 53.

in Iraq 1991, moves into contemporary CPX simulations, and finally analyzes doctrine. It identifies consistent themes across all three to determine a generalized rate of advance.

1 (BR) Armored Division Movement and Maneuver in Iraq, 1991

Preliminary movements and staging are more relevant to the sustainment analysis later in the study. The fighting in the decisive phase saw 1 (BR) Armored Division advance 300km in less than 100 hours.[121] This provides a useful yardstick, but it is insufficient in itself for detailed analysis because the division's platforms almost certainly did not travel in a straight line at just under 75km per day. The problem is akin to the 'coastline paradox' whereby increasingly detailed analysis (such as counting every small bay from New York to Miami versus approximating with a straight line) generates increasingly large numbers.[122] In a similar vein, plotting the route taken by one of the vehicles that ended up 300km from the Line of Departure will yield a value well in excess of 300km. 75km per day is hence a conservative estimate.

CPX Simulations

CPX simulations offer an alternative insight into movement across space and time. The author was SO2 Engineers within 3 (UK) Division G35 Future Operations cell on Exercise Warfighter 21/4 and previous preparation training (Ex Cerberus). As such, he was heavily involved in the movement and maneuver planning and execution. From

[121] Baker, "Operation DESERT SABRE," 24.

[122] Sophie Weiner, "Why It's Impossible to Accurately Measure a Coastline," *Popular Mechanics*, March 3, 2018, https://www.popularmechanics.com/science/environment/a19068718/why-its-impossible-to-accurately-measure-a-coastline/.

memory and personal notes, the following open codes are relevant.On Cerberus, 3 (UK) Division conducted two rapid movements of 80-100km to seize key terrain suitable for a divisional defense. Both movements involved at least two maneuver brigades, and were completed within 24 hours. On Warfighter, 3 (UK) Division executed a movement to contact with two brigades forward, and a brigade in echelon behind each. They advanced 60km eastward from assembly areas near the Polish border to the river Neman within the first 24 hours, before conducting a deliberate divisional obstacle crossing between Alytus and Merkine. From these numbers one can establish that 3 (UK) Division needs to move brigades up to 100km within 24 hours, with the ability to conduct offensive, enabling or defensive action at the end of such a movement. This provides a baseline value which an alternative power source must be capable of supporting.

Doctrine

The division occupies a 15km frontage in the attack, and can defend an area 30km wide by 60km in depth.[123] The 1999 SOHB concurs with these figures, while adding the division can delay across a 60km frontage.[124]

SOHB also has rates of advance for a division and a brigade against various force ratios, terrain and types of defenses. They also include modifying factors for night and surprise. For example, an armored division with a 3:1 advantage against a prepared defense in unrestricted terrain would expect to advance at 8 kilometers per hour in the day. Assuming no operational surprise and eight hours of darkness, this equates to 160km

[123] Smith, "The Division," 32.

[124] Land Warfare 1 Branch, *Staff Officers Handbook*, 214.

in 24 hours. As such, the rates of advance in SOHB 1999 are generally faster than data from CPX's or desert storm.

These frontages are from doctrine and experience that is over 20 years old, but the equipment and underlying sustainment remains the same. The current frontages and rates of advance exist within the current Staff Officers Handbook, and as such are OFFICIAL SENSITIVE, meaning they were not used in this study.

Summarizing movement and maneuver, evidence from history, CPX's and doctrine shows that 3 (UK) Division can and must be able to advance over 100km in 24 hours, while in contact. 100km seems like a significant distance to fight to those staff officers familiar with planning in the constrained terrain of eastern Europe or the caucuses, but Desert Storm provides an example where such distances are relevant. Considering larger distances in less restrictive terrain is of more relevance to this study than more condensed operations in complex terrain because of the demands placed on sustainment are more challenging from a fuel perspective. General Sir Rupert Smith establishes the operational reach of maneuver brigades based upon the loop times of sustainment vehicles, assuming they only travel at night to increase survivability.[125] Such calculations appear easier if force elements are closer together.

Sustainment

The fires section above has identified a demand for wheeled vehicles to move substantial amounts of artillery ammunition. Movement and maneuver has shown that 3 (UK) Division could expect to advance 100km in a day. Both are important to this study

[125] Smith, "The Division," 44.

because they form the basis of daily vehicular energy demand. Examining the sustainment capacity of the division is the natural corollary to these sections. It begins with useful statistics from Operation Iraqi Freedom in 2003, before using SOHB 1999 and "Future Soldier" to understand vehicle demand.

1st Marine Expeditionary Force Sustainment in Iraq, 2003

In Iraq 2003, the US Navy explored how to 'unleash' US combat forces from the tether of fuel. They discovered that over 90% of the Marine Expeditionary Force's fuel consumption came from wheeled vehicles, with only a small fraction being used by the heavier armored platforms.[126] There is also a significant risk to force associated with transportation of fuel, especially in a complex operating environment with a range of adversaries:

> Taking a close look at its supply chain, one Pentagon study found that through 2009 more than three thousand troops and civilian contractors had been killed or wounded protecting convoys; 80 percent of those were transporting truck fuel. The United States would probably have lost more had the Taliban not earned so much money by letting fuel pass at a price, rather than attacking it.[127]

Sustainment efforts to transport fuel during operations in a comparatively recent example of warfighting have consumed the vast majority of the force's fuel, and sustained a large number of casualties in transporting fuel. This is important because if

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[126] Naval Research Advisory Committee Future Fuels Study Panel, "Breaking The Tether Of Fuel," *Military Review* (January-February 2007): 96, https://www.armyupress.army.mil/Portals/7/military-review/Archives/English/MilitaryReview_20070228_art013.pdf.

[127] COL (Ret) Greg Douquet, "Unleash Us from the Tether of Fuel," (Atlantic Council, Washington, DC, January 11, 2017), https://www.atlanticcouncil.org/content-series/defense-industrialist/unleash-us-from-the-tether-of-fuel/.

wheeled electric vehicles can recharge through host-nation infrastructure, or via some form of cabling, then the force's transportation demands drastically reduce. There is no reason to believe that 3 (UK) Division would fare any better than I MEF in such circumstances, because it also has to sustain significant numbers of vehicles at reach. As such, movement of fuel to prolong the division's endurance is as important as artillery logistics. These two sustainment demands are the focus of sustainment analysis from this point onwards.

Divisional Sustainment in British Doctrine

> Finally, at intense rates with all of the Division in contact some 3000 tons are required each day. If we add on the Corps Artillery, who we might expect to be firing in support in these circumstances and a figure for the spares, main assembly and Engineer stores that might be required, then some 4,500 tons is required every day. Bear in mind this is all palletized at approx. 1 ton per pallet and you start to see the significance of your fork lift plant and the problems of breaking bulk.[128]

This focused on two of the most demanding sustainment requirements for a warfighting division; artillery logistics and fuel supply. It does so to understand the wheeled vehicle demand from an energy supply perspective. If there is plenty of redundancy, there is opportunity for slow refueling or recharging using an alternative power source. If there is no redundancy, then two options emerge. First, any alternative power for wheeled vehicles must be rapidly interchangeable or recharged. Second, increasing the number of wheeled vehicles to create enough redundancy for slower recharging. These conclusions can only be identified through a deep analysis of fires, movement, and sustainment.

[128] General Sir Rupert Smith, writing about the scale of a British Division in 2008.

As explained in the literature review, this study used the 1999 *Staff Officers Handbook* for detailed figures. Readers with access to SOHB 2018 are encouraged to cross-check figures to confirm this study's relevance. The study first calculated the available wheeled vehicular lift in 3 (UK) Division, before comparing this to the demand for artillery logistics.

Artillery Logistics

1 Regt and 4 Regt RLC provide logistic support to the two maneuver brigades within 3 (UK) Division. Their transport capacity is used between the Brigade Support Group and the troops in the close battle. This leaves just 10 Queen's Own Gurkha Logistic Regiment (QOGLR) and 27 Regiment RLC to provide support to divisional activity.

Table 2. Overview of Royal Logistic Corps Units within 3 (UK) Division

Royal Logistic Corps Unit	Supports	Subunits
1 Regt RLC	20 BCT	2 x Close Sp, 1 x General Sp
3 Regt RLC (To be disbanded)	N/A	2 x Close Sp, 1 x General Sp
4 Regt RLC	12 BCT	2 x Close Sp, 1 x General Sp
10 QOGLR	3 (UK) Div	2 x General Sp
27 Regt RLC	3 (UK) Div	1 x Gen Sp, 1 x Fuel/GS, 1 x Tank transport

Source: Table created by author using data from Ministry of Defence. "Future Soldier Guide," The British Army, November 25, 2021, https://www.army.mod.uk/media/14919/adr010310-futuresoldierguide_25nov.pdf; Ministry of Defence. "Regular RLC Units." The British Army. accessed February 25, 2022, https://www.army.mod.uk/who-we-are/corps-regiments-and-units/royal-logistic-corps/rlc-regular-units/.

Between 10 QOGLR and 27 Regt RLC, there are just three squadrons available. SOHB 1999 describes the composition of Close Support and General Support logistics regiments.[129] Crucially, a second line General Support regiment supporting 1 (UK) Armored Division in 1999 had six squadrons, four of which were for artillery logistics.[130] These numbers matter because 3 (UK) Division today only has three squadrons available between two regiments, compared to six squadrons in a single regiment. The lift capacity of a British division has thus shrunk considerably in the last 23 years. In the following paragraphs, the study calculated the lift capacity of 3 (UK) Division today, and compared the result to the division's artillery demand in pallets and RPCs.

[129] Land Warfare 1 Branch, *Staff Officers Handbook*, 118.

[130] Ibid., 119.

This study assumed the best-case scenario for artillery logistics; that every transport vehicle within the three support squadrons in 10 QOGLR and 27 Regt RLC were available to transport 1,820 pallets and 1080 Rocket Pod Containers.

There were 36 DROPS platforms in a GS squadron in 1999.[131] This study assumed that a squadron in 2022 has the same number of DROPS. The DROPS platform has since been replaced with the Enhanced Pallet Loading System, which carries the same number of pallets.[132] The study referred to EPLS from this point. Each EPLS can carry 10 standard NATO pallets, allowing the squadron to lift 360 pallets at once.[133] Alternatively, an EPLS can carry four MLRS Rocket Pod Containers.

With three squadrons there are 108 EPLS platforms available to support artillery logistics. Using SOHB 1999 structures for ammunition transport organic to AS90 and MLRS units, they respectively hold 18 and 38 EPLS each.[134] 3 (UK) Division's artillery units thus hold 112 EPLS organically for artillery logistics. There are 220 EPLS across 3 (UK) Division for artillery logistics assuming 100% vehicle availability and that nothing else is transported, such as water, food, defensive stores.

Analysis indicates 1,820 pallets of 155mm ammunition require 182 EPLS loads; 1080 Rocket Pod Containers requires 270 EPLS loads. Carrying all of the division's daily

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[131] Land Warfare 1 Branch, *Staff Officers Handbook*, 119.

[132] Ministry of Defence, "Logistic Workhorse Rolls out Fleet Fit for the Future," The British Army, accessed February 25, 2022, https://www.army.mod.uk/news-and-events/news/2021/04/epls-fleet-upgrade/.

[133] Land Warfare 1 Branch, *Staff Officers Handbook*, 281.

[134] Ibid., 74.

155mm and MLRS consumption at the same time would therefore require 452 EPLS platforms.

Over two round trips are therefore required to sustain artillery logistics, using 100% of the available vehicles. Simplifying to two loops per 24 hours at General Sir Rupert Smith's figure of 20 kilometers in the hour,[135] a maximum reach of 120km is calculated. This assumes a higher headquarters has pushed ammunition forward to the division's rear, that loading and unloading is instant, and that ammunition only needs to move from one point to another. This simple model would look like this:

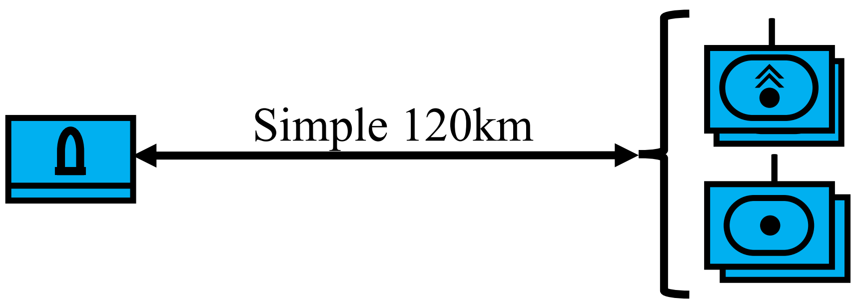

Figure 6. Simple Modeling of Divisional Artillery Logistics

Source: Created by author.

Reality is however likely to be significantly worse. The required ammunition doesn't simply move from one point to another, but has to be distributed among numerous Artillery Maneuver Areas (akin to an American Positional Area Artillery (PAA)). Distribution among a network rather than point to point will significantly reduce

[135] Smith, "The Division," 31.

the operational range that logistics units can support the artillery across. Loading, unloading and breaking apart pallets of ammunition also consumes time.

Assuming that each battery has its own AMA/PAA, and that it takes 30 mins to load and unload at each end (for each loop), this study can develop a more accurate assessment of artillery logistic reach, and hence the demand from an energy supply perspective.

With the shorter ranges of conventional artillery, it is assumed that the two AS90 units will be operating in different parts of the battlespace. MLRS logistics for both deep fires units could however be co-located to create efficiency through economies of scale. A more realistic distribution solution is depicted in Figure 7.

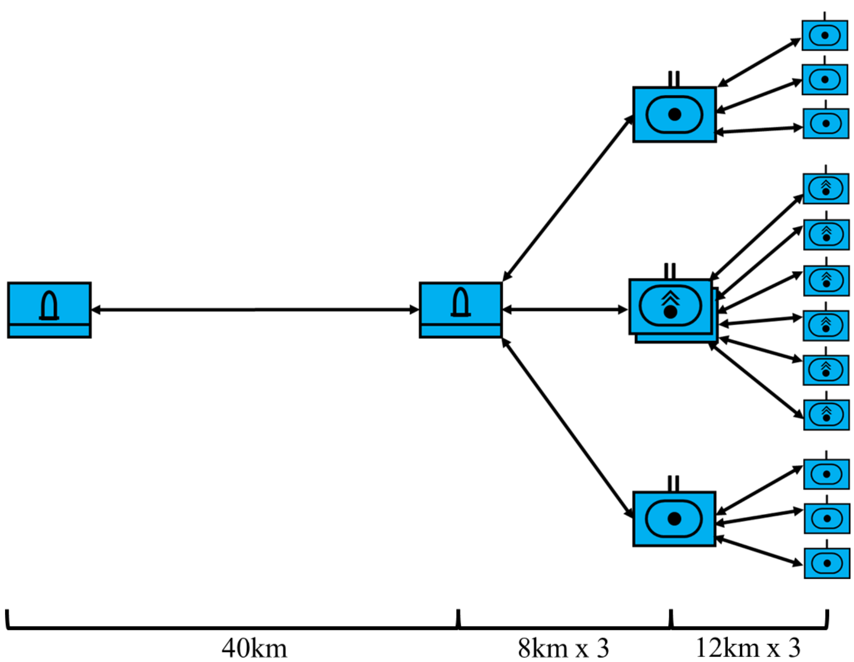

Figure 7. Distributed Modeling of Divisional Artillery Logistics

Source: Created by author.

This demonstrates that using all of the available lift can only sustain artillery logistics, even in a simplified model, up to approximately 60km.

Even if artillery is firing from the Forward Line of Own Troops (FLOT) at the start of an operation, after a day of 3 (UK) Division's maneuver it could be 100km behind the FLOT. Even with new MLRS ammunition ranging 150km,[136] deep fires assets would only be able to reach 50km beyond the FLOT. If fires assets move forward to the new FLOT their ability to influence the deep will decrease, as there are not enough EPLS to sustain them further away from the Divisional Support Area (DSA).

While bleak, this is also highly relevant to the study because it highlights the importance of using contractors to move materiel and fuel, as in Desert Storm.[137] Such contractors are unlikely to be using an alternative fuel system that is technically interoperable with whatever 3 (UK) Division is using, presenting significant problems for sustainment in the divisional rear.

This is important to the study for two reasons. First, it demonstrates that there is no redundancy in wheeled vehicles for divisional logistics. Transition to an alternative power source would therefore require a rapid refuel/recharge ability, or an increase in vehicles to enable a recharging rotation. Second, there is a significant dissonance between how 3 (UK) Division fights in the deep on simulations such as Warfighter compared to what it is actually able to sustain. While not an intended finding of this study, it is

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[136] Ministry of Defence, "Upgrades to Multiple Launch Rocket Systems Strengthen Deep Fires Capability," The British Army, accessed January 22, 2022, https://www.army.mod.uk/news-and-events/news/2021/03/mlrs-upgrade-agreement/.

[137] Baker, "Operation DESERT SABRE - 1st British Armoured Division," 72.

relevant to 3 (UK) Division's operational effectiveness under Future Soldier, and is addressed as a recommendation in Chapter 5.

Fuel Logistics

The introduction began with the statistic that a warfighting division would consume approximately 800,000 liters of fuel per day.[138] Fuel must be considered on a macro and micro scale. Macro fuel considerations are the bulk storage, transportation and consumption of fuel by the division as a whole. Micro fuel considerations stem from the relationship between fuel and individual platforms, such as a main battle tank.

The limitations of recent simulations prevent thorough stress testing of fuel supply in much the same way as they do for artillery logistics. There is only one semi-dedicated squadron to conduct fuel supply for the warfighting division. Within SOHB 1999 the ancestors of 10 QOGLR and 27 Regt RLC (10 and 27 Transport Regiments RLC) each have a fuel squadron with 50 "22.5m^3 TTF."[139] This study assumes that TTF stands for "Truck Transporter Fuel" as there are no other alternative fuel carrying vehicles listed. The modern equivalent vehicle is the Close Support Tanker (CST), which can carry 20,000 liters of fuel or water.[140] 50 CSTs enables 27 Regt RLC's fuel squadron to transport up to one million liters of fuel in one lift. With 800,000 liters per day the demand signal of a warfighting division, this implies that fuel supply has sufficient lift to

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[138] Ministry of Defence, Joint Concept Note 1/20, *Sustainment*.

[139] Land Warfare 1 Branch, *Staff Officers Handbook*, 124.

[140] Ministry of Defence, "152 Regiment RLC," The British Army, accessed March 1, 2022, https://www.army.mod.uk/who-we-are/corps-regiments-and-units/royal-logistic-corps/rlc-reserve-units/152-regiment-rlc/.

meet the demands of today's 3 (UK) Division. Within this supply network, a typical Bulk Fuel Installation (BFI) contains approximately 600,000 liters. This is less than a day's consumption for the division, and pales in comparison to the 7,000,000 liters of fuel 1 (British) Armored Division held in its rear areas prior to Operation Desert Storm in 1991.[141]

Summarizing sustainment, artillery logistics constrains the operational reach of the division because it cannot follow the maneuver brigades during an advance and continue to shape the deep due to a lack of lift for its ammunition. Fuel supply is less of a constraint with the current force, but the scale of fuel required is significant. The size of logistic units to support the division must increase even if fossil-fuels continue to be used, because there is a dissonance between how 3 (UK) Division thinks it fights in the deep, and how it can actually be resourced. This is likely the result of simulations such as that used on Warfighter failing to model sustainment. With so little redundancy, any alternative power source must either refuel/recharge as quickly as existing vehicles. If this is not possible, an increase in the number of vehicles is required to enable vehicles to rotate through charging.

The study now stops considering the materiel, movement and logistics of the division, and instead focusses on how it functions in terms of intelligence and information. These sections are most relevant during the final synthesis of ideas in Chapter 5. This is because 3 (UK) Division's ability to find and strike in the deep is used to mitigate compromises that emerge from adopting an alternative power source.

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[141] Baker, "Operation DESERT SABRE - 1st British Armoured Division," 21.

Intelligence

At a national level, the United States and the United Kingdom have similar capabilities. Examples include the National Security Agency c.f. Government Communications Headquarters, and the Central Intelligence Agency c.f. the Secret Intelligence Service. Unified Action[142] in the US military, and Integrated Action[143] in the UK seek to leverage these non-military organizations to achieve military end states.

The difference lies in access to these capabilities because a smaller army benefits from fewer layers of management such as Corps and Combatant Commands. With only one warfighting division in the British Army, integrated action partners are much more concentrated, and employed at a lower level. This is reflected in doctrine, with the specialists[144] described at a Corps level in the US Army's FM3-94[145] held at divisional and brigade level in The British AFM Warfighting doctrine.[146]

This is important to the study because 3 (UK) Division can leverage national assets more directly, and thereby quickly, than its larger peers and adversaries. This affects 3 (UK) Division's ability to find enemy targets in its deep battlespace. If 3 (UK)

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142 Headquarters, Department of the Army (HQDA), Army Doctrine Publication (ADP) 3-0, *Operations* (Washington, DC: Army Publishing Directorate, July 2019).

143 Land Warfare Development Centre, ADP, *Land Operations*.

144 Specialists in the literal sense, rather than the U.S. Army rank.

145 Headquarters, Department of the Army (HQDA), Field Manual (FM) 3-94, *Armies, Corps, and Division Operations* (Washington, DC: Army Publishing Directorate, July 2021), 121.

146 Land Warfare Centre, AFM - *Warfighting Tactics,* Part 2: *Corps and Divisional Tactics*, 31.

Division can find and strike enemy targets in the deep with ease, its maneuver platforms might be able to operate with less armor, and thereby weight. This would reduce energy demand, and could make an alternative power source feasible. Effective and timely integration of national assets is therefore relevant to this study.

An alternative means of collecting intelligence is Ground Mounted Reconnaissance (GMR). Space or aerial Information, Surveillance and Reconnaissance (ISR) can be affected by weather, and cannot provide the finesse and detail of GMR. For example, a satellite is unlikely to produce the same detailed wet gap crossing analysis as an engineer reconnaissance sergeant on the ground. GMR subsequently has a role, and is unlikely to be obsolete in 2050.[147]

GMR is important to this study because it revolves around stealthy vehicles travelling large distances beyond the FLOT. If GMR platforms use an alternative power source, their sustainment is a challenging problem for this study.

Summary of Secondary Research Question One

3 (UK) Division relies on deep fires to destroy enemy assets in its deep battlespace. Its maneuver brigades could advance up to 100km in a day. It lacks the logistical lift to move these distances, and continue to use deep fires in the deep. This means there is a dissonance between how 3 (UK) Division fights in simulations, and how it would mathematically fight in reality. As such, an increase in divisional logistic support is necessary for 3 (UK) Division's real operational effectiveness to match its

[147] Alex Humphreys, "Preserving Formation Reconnaissance," Wavell Room, December 22, 2021, https://wavellroom.com/2021/12/22/realising-platform-agnostic-recce-excellence-preserving-our-formation-reconnaissance-capability/.

performance in simulations. The study next considered whether electrification was the best alternative power source for the 3 (UK) Division described in the pages above.

Is electrification the best alternative power source for 3 (UK) Division in warfighting?

The word 'best' requires some clarification in order to answer this secondary research question. Best is relative to alternatives, not necessarily good in absolute terms. There are several metrics to consider beyond just energy density by mass and volume.

While the previous research question was a macro view of how 3 (UK) Division fights, this research question focused on micro use cases for alternative power sources. It used sustainment and maneuver vehicles as its primary energy demand problems, based on the analysis from the previous research question.

Despite these platforms having vastly different usages, their energy supply is remarkably similar. For today's 3 (UK) Division it involves petroleum either shipped into theater, or refined in the Joint Security Area (JSA).[148] Fuel is then stored, either in host nation infrastructure or in Bulk Fuel Installations. Some of these BFIs can be vast. 3rd Army's BFIs during Operation Desert Shield were each over three million gallons in size.[149] 1 (BR) Armored Division had 7 million liters of fuel in the divisional rear area.[150] From these BFIs, fuel must be transported as outlined in the previous research question. It then needs to be stored on each individual platform prior to consumption.

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[148] Baker, "Operation DESERT SABRE - 1st British Armoured Division," 68.

[149] Ministry of Defence, "Robert Scales Gulf War Papers, 22nd Support Command, Box 3, ARCENT/3rd Army Logistics Brief," (PowerPoint, Iraq, February 11, 1991).

[150] Baker, "Operation DESERT SABRE - 1st British Armoured Division," 21.

Alternative hydrocarbons, such as Liquid Natural Gas (LNG), are assessed as not meeting the intent to divest from fossil fuels for sustainability because they are still fossil-fuels, with the same emissions problem. Likewise, the development of Algae bio-oils was not be considered because synthetic fuel production is at a low Technology Readiness Level (TRL),[151] and is decades away from being commercially viable,[152] and still generates the same emissions when consumed.[153]

Instead, the study focused on two alternative power sources: electricity and hydrogen. It also considered nuclear power from an operational energy storage perspective. In doing so, the study applied the following metrics:

[151] Eric Wesoff, "Hard Lessons from the Great Algae Biofuel Bubble," *GreenTechMedia,* April 19, 2017, https://www.greentechmedia.com/articles/read/lessons-from-the-great-algae-biofuel-bubble.

[152] Joe Carroll, "Exxon at Least 25 Years Away from Making Fuel From Algae," *Bloomberg*, March 8, 2013, https://www.bloomberg.com/news/articles/2013-03-08/exxon-at-least-25-years-away-from-making-fuel-from-algae.

[153] As the end product is the same hydrocarbon chains that constitute oil, which still undergo combustion in the same way.

Table 3. Evaluation Criteria for Alternative Fuels

Criteria	Diesel	Electricity	Hydrogen
Industrial expertise and capacity			
Operational storage			
Operational movement			
Operational supply			
Platform storage			
Cost			
Overall			

Source: Created by author.

Table 4. Grading System for Alternative Fuel Criteria

Grading	Solution unviable	Extremely poor	Poor	Slightly worse	Equal to diesel	Better than diesel
Color	Black	Red	Orange	Amber	Green	Blue

Source: Created by author.

Every criteria/metric listed in table 3 is allocated a color using the grading system in table 4. As well as explaining what the six criteria are, table 3 also doubles as a 'bottom line up front' for the following 14 pages of analysis.

Hydrogen

Industrial Expertise and Capacity of Hydrogen

Hydrogen production already exists within the United Kingdom, largely within chemical factories and refineries. There is also a national strategy to increase hydrogen infrastructure throughout the twenty first century drastically.[154] This is however a political document, which pledges relatively minimal investment in the tens of millions of pounds.[155] As such, it is likely that commercial venture is more likely to drive development of hydrogen structure. ASSESSED: ORANGE.

Operational Storage of Hydrogen

As a gas, hydrogen's energy density by mass is almost three times higher than diesel. While 1Kg of hydrogen would contain 140MJ of energy, it would also have a volume of 11,200 liters at room temperature[156] Significant compression is therefore essential to create a viable power source, with 10,000psi tank being the current industry

[154] Department for Business, Energy & Industrial Strategy, *UK Hydrogen Strategy*, 8.

[155] Ibid., 55.

[156] 1 mole (22.4 liters) of hydrogen atoms has a mass of 1 gram. 1 mole of H2 molecules has a mass of 2 grams. 1Kg is therefore 500 moles of H2, which is 500 * 22.4 = 11,200 liters.

standard.[157] This can only be achieved by storing compressed hydrogen in a reinforced (and heavy) container, significantly degrading energy density performance.[158]

The alternative to pressurization is to condense hydrogen into a liquid, where its energy density by volume is better. Liquid hydrogen requires cooling to -253 degrees Celsius. Cooling equipment that can achieve such a temperature is likely to be heavy, bulky, and will also degrade energy density performance.[159]

A high efficiency hydrogen fuel cell is approximately 34% efficient[160] (compared to 25% for a diesel internal combustion engine and 96% for an electric motor). Using the same 600,000 liter (23.2TJ) Bulk Fuel Installation as the electrical analysis, 17.1TJ of energy stored as hydrogen is required. Without considering the container, at 10,000psi this would require 122 tons of hydrogen, occupying 2,000,000 liters. The bulk fuel installation would therefore need to be three times the size of a current diesel one, before the materials to provide pressurized containers are considered. ASSESSED: YELLOW.

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[157] Kenneth Johnson, Michael J. Veenstra, David Gotthold, Kevin Simmons, Kyle Alvine, Bert Hobein, Daniel Houston, et al., "Advancements and Opportunities for On-Board 700 Bar Compressed Hydrogen Tanks in the Progression Towards the Commercialization of Fuel Cell Vehicles," *SAE International Journal of Alternative Powertrains* 6, no. 2 (2017), http://www.jstor.org/stable/26169163.

[158] Ibid.

[159] Timothy Coffey, Dennis R. Hardy, Gottfried E. Besenbruch, Kenneth R. Schultz, Lloyd C. Brown, and Jill P. Dahlburg, *Hydrogen as a Fuel for DOD,* Defense Horizons Number 36 (Washington, DC: Center for Technology and National Security Policy, National Defense University, November 2003), 12.

[160] Andrew Reddaway, "Hydrogen: Help or Hype?," (Discussion Paper, Alternative Technology Association, Melbourne, Australia, June 2019), 16–19.

Operational Movement of Hydrogen

Compression or cooling of hydrogen during transport adds mass beyond that of the fuel. The only credible figures identified in the literature review offer 0.27MJ/Kg and 0.252MJ/L for a relatively small pressurized 10,000psi container. This study tripled these numbers to account for the fact that a large military vehicle has more space for containers, and there is an associated economy. Simply, the energy density of pressurized or liquid hydrogen in containers is lower than that of lithium-ion batteries. It therefore cannot be more efficient for operational movement than electrical solutions, even before cabling options are considered.

Similarly, a quick comparison of the energy densities for diesel and hydrogen shows they differ by an order of magnitude. Transporting compressed hydrogen by sustainment vehicles of the same size is therefore going to transport less than ten percent of the energy transported today. Vehicles can't feasibly become much larger because they need to fit on railheads and move under bridges. ASSESSED: RED.

Operational Supply of Hydrogen

Unlike electrical power, there is unlikely to be a national hydrogen grid that can be exploited in a future conflict. Hydrogen must therefore be generated in theater, or transported from behind the Joint Security Area (JSA). Hydrogen is converted into electricity before driving a motor, and is therefore less efficient from a supply perspective.[161] ASSESSED: RED.

[161] Reddaway, "Hydrogen: Help or Hype?," 17.

Platform Storage for Hydrogen

If a 25% efficient diesel Challenger Main Battle Tank needs 61.6GJ in fuel, a 34% efficient hydrogen MBT would require 45.3GJ of energy. The tank and hydrogen required to contain this energy would weigh 56 tons, and occupy 59 meters cubed. Hydrogen's relative inefficiency to electricity makes it even less viable as a solution for armored platforms such as MBTs. ASSESSED: RED.

Cost of Hydrogen

The future cost of hydrogen production depends largely on commercial adoption and innovation. The UK Hydrogen Strategy predicts that hydrogen will support up to a third of the UK's energy demand in 2050.[162] Assuming this happens, hydrogen supply should drop substantially in price from economies of scale. To transport, store operationally etc., the MoD would still need to identify requirements and procure its own infrastructure. Hydrogen is therefore broadly comparable in cost to electricity solutions. ASSESSED: YELLOW.

Electricity

Industrial Expertise and Capacity for Electric Solutions

Electric vehicles have a high TRL, and are in-use around the world today. Although these are primarily smaller vehicles at present, there are larger trucks being developed for transport/haulage companies.[163] Western companies such as Tesla

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[162] Department for Business, Energy & Industrial Strategy, *UK Hydrogen Strategy*, 38.

[163] "Tesla Semi," Tesla, accessed March 1, 2022, https://www.tesla.com/semi.

represent world-leading expertise in electric automotive technology. The industrial capacity of the United Kingdom is also developing, with the Government investing $130 million in an electric car battery plant that should be operational by 2028.[164] Lithium is required to make these batteries at present, and is in demand globally. The political economic challenges of ensuring a supply of lithium are much larger than the military. As such, the British Government will need a strategy to secure access to Lithium for much of its Net Zero 2050 strategy.[165] ASSESSED: AMBER.

Operational Storage of Electricity

A typical British Army Bulk Fuel Installation (BFI) holds 600,000 liters of fuel.[166] 1 (BR) Armored Division moved 7 million liters of fuel into its rear area before the beginning of Operation Desert Storm. Nicolaus Otto's internal combustion engine in 1876 was just 17% efficient, whereas a typical road car in 2013 was 30% efficient.[167] The remaining 70% is lost as primarily as heat and sound.

This study assumed that the internal combustion engines powering warfighting platforms today are 25% efficient given their age. Formula One racing represents the best

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[164] Jasper Jolly, "Britishvolt Gets £100m Boost to Build UK's First Large-Scale 'Gigafactory'," *The Guardian*, January 21, 2022, https://www.theguardian.com/environment/2022/jan/21/britishvolt-electric-car-battery-uk-gigafactory-blyth-jobs.

[165] Department for Business, Energy & Industrial Strategy. *Net Zero Strategy*.

[166] Ministry of Defence, "152 Regiment RLC."

[167] Mercedes-Benz, "INSIGHT: Five Examples Why F1 Is Accelerating the Future," AMG Petronas Formula One Team, accessed March 1, 2022, https://www.mercedesamgf1.com/en/news/2018/10/insight-five-examples-why-f1-is-accelerating-the-future/.

battery/electrical technology available today. Their electric motors are 96% efficient.[168] This study assumed that such an efficiency is commercially viable on a broader scale by 2050. These numbers clearly provide a best-case scenario in relative efficiencies, which is useful because even with favorable estimates there is still a significant challenge to find relative advantage on the battlefield.

Diesel has an energy density by volume of 38.675 megajoules per liter (MJ/L),[169] whereas a Nickel Cobalt Aluminum (NCA) Lithium-Ion battery has just 2.4MJ/L.[170] This means the 600,000-liter BFI contains 23,205,000MJ, or 23.2 terajoules (TJ). If an electric motor is 96% efficient compared to 25% for an internal combustion engine, then only 6.04TJ are required to 'refuel' the same amount of energy actually converted by the platform into movement. If there's only 2.4 MJ in a liter of lithium-ion batteries however, this will require 2.5 million litres of batteries by volume. To put this into perspective, if the battery were 2m high, it would be a 35x35 meter square. With an energy density by volume of 0.9MJ/Kg, this battery would weigh 6,700 tons. As a comparison, this single battery would weigh over twice as much as the Saturn V rocket that put Neil Armstrong onto the Moon.[171]

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168 Mercedes-Benz, "INSIGHT: Five Examples Why F1 Is Accelerating the Future."

169 Molloy, "Run on Less with Hydrogen Fuel Cells."

170 "Lithium-Ion Battery," Clean Energy Institute, University of Washington, accessed November 1, 2021, https://www.cei.washington.edu/education/science-of-solar/battery-technology/.

171 National Aeronautics and Space Administration, "Saturn V," Rocket Park, last updated September 16, 2011, https://www.nasa.gov/centers/johnson/rocketpark/saturn_v.html.

Transporting the equivalent weight of two Saturn V rockets would require 400 EPLS. Sustainment analysis in the previous research question demonstrates that this would consume the entire division's vehicular lift capacity. Re-positioning such a battery would consequently require an operational pause for all of the division's sustainment effort. Ironically, these same vehicles would likely need to recharge from the battery to enable its movement. Storage by battery is therefore not feasible.

Battery technology is however continually improving. The sheer weight of batteries required means that the technology would need to improve by 1000% to require just 40 EPLS to move. From 1989[172] to 2020,[173] performance increased by 750%. Recent research suggests that a similar increase in performance over the next thirty years is unlikely. This is because the rate of improvement in lithium technology is already plateauing,[174] and theoretical limits make a 1000% increase highly unlikely.[175]

If energy cannot be stored easily on the battlefield, the only alternative is a responsive and dynamic generation of energy to meet demand, in much the same way as a national electrical grid would. Dynamic generation of electricity is explored below as part of operational energy supply. ASSESSED: RED.

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[172] James J. Zucchetto, John H. Johnson, Phillip S. Myers, and Thomas Jahns, "Mobile Electric Power Technologies for the Army of the Future," *SAE Transactions* 98 (1989): 1834–1846.

[173] Daniele Stampatori, Pier Paolo Raimondi, and Michel Noussan, "Li-Ion Batteries: A Review of a Key Technology for Transport Decarbonization," *Energies* 13, no. 10 (May 2020): 2638.

[174] Ziegler and Trancik, "Re-Examining Rates of Lithium-Ion Battery Technology Improvement and Cost Decline."

[175] Crabtree, Kócs, and Trahey, "The Energy-Storage Frontier."

Operational Movement of Electricity

Electricity must move from wherever it is generated to where it is consumed. If operational storage of electricity is unworkable, then movement from generation to consumption is important. Electrical energy can primarily be transported in two ways; conventional sustainment using vehicles, or via high voltage cabling.

High voltage electrical cabling is used extensively in urban areas to provide power distribution. This includes underwater, subterranean and surface laid cable as well as aerial solutions using pylons.[176] This technology could replicate the methods Coalition forces used to rapidly build a 62-mile-long oil pipeline in Saudi Arabia in 1991.[177] The typical large electric pylons one would see dissecting the countryside typically operate at 400,000 volts (400kV). They operate at a high voltage to minimize heat loss, which is proportional to the current squared.[178] However, operating at higher voltages typically comes with greater financial cost.[179]

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[176] Borealis, *Bringing Energy All Around* (Vienna, Austria, Borealis AG, June 2020), https://www.borealisgroup.com/storage/Polyolefins/Energy/FINAL_WC_ BROCH-049-GB-2018-03-BB_Bringing-energy-all-around_SCREEN.pdf.

[177] Baker, "Operation DESERT SABRE - 1st British Armoured Division," 21.

[178] EMFs info, "Terminology – An Introduction," accessed March 3, 2022, https://www.emfs.info/what/terminology/.

[179] Inner City Fund (ICF) Consulting, *Overview of the Potential for Undergrounding the Electricity Networks in Europe* (London, United Kingdom: ICF Consulting Ltd., February 28, 2003), https://ec.europa.eu/energy/sites/ener/files/ documents/2003_02_underground_cables_icf.pdf.

The typical 400kV power line can transmit 700MW of power.[180] Using the energy density of diesel, divisional daily fuel consumption, and relative efficiency of electric motors, one can calculate the average power demand of the division in Watts. This is 175MW. A standard 400kV cable rated to 700MW is therefore sufficient to power a Corps sized electrified force.

Conventional sustainment using vehicles will be less efficient than transporting diesel in Close Support Tankers (CSTs) purely because of energy density by mass. It is however still possible, and will directly benefit from technological development in civilian transport and logistics. The future CST might look a lot like the Tesla Semi of the 2020's.[181] Transporting electrical energy by CST will require a significant increase in the number of vehicles dedicated to energy transport.

Operational movement of electrical energy is assessed as better than diesel because there are two options, both of which are viable. High voltage cabling has the throughput to meet the division's needs, and can interface directly with a national grid. ASSESSED: BLUE.

<u>Operational Supply of Electricity</u>

One choice for operational energy supply is solar power. Using the volume of diesel, its energy density and the relative efficiency of electric motors, one can calculate the energy requirement for the division in Joules. This is 8.04 TeraJoules (TJ). This,

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[180] Borealis, *Bringing Energy All Around*.

[181] "Tesla Semi," Tesla.

combined with the intensity of sunlight can create a best case surface area for the solar panels required to power the division.

Assuming the sun is directly overhead as in the tropics, each square centimeter receives 137 millijoules every second.[182] With 10,000 square centimeters in a meter squared this equates to 1.37 kilojoules per meter squared, each second. There are 3,600 seconds in an hour, meaning a meter squared receives 4.9 MJ per hour. To gain 8.04TJ from solar power over 20 hours would require a solar panel the size of fifteen American football fields.[183]

15 football fields of solar panels would require a vast amount of strategic lift to transport into theatre. It would likely be a fixed installation for the duration of a conflict. It would also be easy to spot, and vulnerable to long range fires such as ballistic or hypersonic missiles. Ultimately it would be a critical vulnerability, and a soft target.

Nuclear power is another choice for operational energy supply which is frequently touted as a solution.[184] The Pentagon has recently started awarding contracts to develop a 1-5MW small nuclear reactor.[185] The 8.04TJ of energy required by the division each day averages at a 93MW continuous demand. Nuclear reactors typically operate at 85% of

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[182] National Aeronautics and Space Administration, "Calculating the Energy from Sunlight over a 12-Hour Period," Glenn Research Center, accessed March 1, 2022, https://www.grc.nasa.gov/www/k-12/Numbers/Math/Mathematical_Thinking/sun12.htm.

[183] 8.04TJ / 20 = 0.402TJ per hour. 1m2 recieves 4.9MJ per hour. 82,000m2 therefore required. American football pitch is 5321m2. 82,000/5321 = 15.4 American football pitches

[184] Erickson, "Build Small Nuclear Reactors for Battlefield Power."

[185] Mehta, "Portable Nuclear Reactor Project Moves Forward at Pentagon."

their maximum capacity for safety reasons.[186] 3 (UK) Division would therefore require 22 small nuclear reactors to supply its steady state energy demand.

These could be dispersed throughout the battlespace, but would require significant resources to protect. It is also likely to present a variety of nuclear proliferation issues with respect to international law, offers an information opportunity to an adversary, and generates the risk of nuclear material being lost to non-state actors during the conflict. This study therefore assumes that the political appetite to deploy dozens of small nuclear reactors across a battlespace dominated by fires is non-existent.

Using some form of ship to shore electrical supply is not viable because the Royal Navy's fleet is not nuclear. The largest power plants in service are the two MT30 gas turbines powering each of the Queen Elizabeth Aircraft Carriers,[187] which only produce approximately 40MW each.[188]

The simplest solution to operational energy supply is to use host nation infrastructure. This is insufficient because it simply doesn't exist in austere environments, and is likely vulnerable to adversary cyber-attacks, especially if it is identified as a Critical Requirement for the British Army. Using diesel generators to produce electricity

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[186] "Frequently Asked Questions (FAQs)," U.S. Energy Information Administration, accessed December 20, 2021, https://www.eia.gov/tools/faqs/faq.php.

[187] Rolls-Royce, *Powering the Queen Elizabeth Class Aircraft Carriers* (London, UK: Rolls-Royce, PLC, 2014_, 6.

[188] Rolls-Royce, "MT30 Marine Gas Turbine," accessed March 7, 2022, https://www.rolls-royce.com/products-and-services/defence/naval/gas-turbines/mt30-marine-gas-turbine.aspx.

is potentially viable in an emergency, but defeats the purpose of electrifying in the first place (as well as being even less efficient).

Summarizing energy supply, solar is not a feasible solution. The risk of a nuclear reactor going missing, or exploding is less politically palatable than simply continuing to use fossil-fuels. Nuclear is not the answer. Host Nation Infrastructure is vulnerable to cyber-attack and forces 3 (UK) Division to seize and protect predictable points geographically. This hands initiative to an adversary. ASSESSED: RED.

Platform Storage of Electricity

Using similar calculations to operational energy supply, the solar panel required to sustain one electric Main Battle Tank (MBT) would be 12.6m x 12.6m solar panel, and would take at least 20 hours to recharge. By contrast, the 1,592 liter fuel tank in a Challenger 2 MBT takes approximately seven minutes to fill from a Close Support Tanker (CST).[189]

Refueling by diesel is significantly faster than recharging electric batteries. In warfighting, where a brigade command post is likely to move several times per day, remaining static using large solar panels is not a viable solution. Even a Tesla 'supercharger' would take 18 hours to charge an electric Challenger 2 MBT.[190]

[189] Based on informal conversation with a Lt Col from the Royal Armored Corps with extensive knowledge of operating in Challenger 2 MBTs.

[190] "Supercharger," Tesla, accessed March 10, 2022, https://www.tesla.com/supercharger.

Converting the 1,592-liter diesel fuel tank into energy and accounting for the relative efficiency of electric motors, the battery required to power an electric Challenger 2 MBT would be the size of a small car and weigh 22 tons.

The Perkins CV12-6A V12 diesel engine[191] and transmission weigh approximately 3 tons.[192] The combined diesel power train including fuel therefore weighs approximately 5 tons. A MBT could therefore remain the same weight and size as today, but would only hold less than a quarter of the energy. This would see operational ranges reduced from 550km on road and 250km off road,[193] to just over 60km. Such a change would require a recharge to achieve the 100km in a day movement the maneuver brigades in the division are currently capable of. The only other alternative is to reduce protection or firepower to extend operational range.

This is one of the most important deductions in this study: It is not likely to be possible to produce a lithium-based electric 75-ton tank that can travel 500km with the same firepower and protection as a modern MBT.

For lighter vehicles, compromises are not as stark. As explained in operational movement, the Technology Readiness Level (TRL) of electrified transport vehicles is significantly higher than for armored vehicles.[194] ASSESSED: ORANGE.

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[191] Ministry of Defence, “Combat Vehicles,” The British Army, accessed January 20, 2022, https://www.army.mod.uk/equipment/combat-vehicles/.

[192] Based on an informal conversation between the author and an armored crew member

[193] Ministry of Defence, “Combat Vehicles.”

[194] “Tesla Semi,” Tesla.

Cost of Electrification

The main cost of lithium-ion batteries at present is lithium. Demand for electric vehicles globally is rapidly increasing, which supply is struggling to keep up with. The cost of lithium carbonate has already increased by 74% since the beginning of January 2022.[195] It's therefore difficult to gauge how expensive lithium is likely to be in 10-15 years' time. Despite this, the cost of lithium-ion batteries has reduced by 97% since the 1990's.[196]

75% of the world's lithium is in Chile, Argentina and Bolivia, with limited infrastructure to extract it. There is therefore potential for the lithium mining industry to radically change over the next 20 years, and address the huge increase in demand.[197] It is therefore difficult to predict future costs of lithium with any certainty. There is discussion of sodium ion batteries providing a cheaper alternative to lithium ion, but the TRL of these solutions is too low to provide a quantifiable energy density for this study.[198]

In a similar vein, the price of oil fluctuates wildly as supply and demand both react to what happens in the world. In April 2020, the price of barrel of oil was briefly

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[195] "Lithium," Trading Economics, accessed March 4, 2022, https://tradingeconomics.com/commodity/lithium.

[196] Ziegler and Trancik, "Re-Examining Rates of Lithium-Ion Battery Technology Improvement and Cost Decline."

[197] "The Lithium Triangle: Where Chile, Argentina, and Bolivia Meet," Harvard International Review, January 15, 2020, https://hir.harvard.edu/lithium-triangle/.

[198] "Scientists Develop Stable Sodium Battery Technology," National Science Foundation, January 6, 2022, https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=304167.

negative, as a side-effect of the coronavirus pandemic.[199] This study assumes that refining oil into diesel will remain a more cost-effective solution than developing batteries, because the infrastructure will still exist even if electric vehicles render internal combustion engines obsolete. This is because refining of oil will still be in demand to develop plastics, lubricants etc, and altering the fractional distillation in a refinery to change the proportions of each byproduct is commonplace today to finesse supply.[200] ASSESSED: AMBER.

Summary of Alternative Power Sources

Neither electrification nor hydrogen can match current diesel-based capabilities in terms of supplying energy to meet the demands of a warfighting division. Electricity appears to be the most suitable alternative power source for a warfighting division, although with significant changes to force and platform design. These will be explored in the final research question.

How would electric land platforms nest in broader future concepts?

> The word domain, as used in MDO, does not describe the realm or context of air, land, sea, space, cyber and information operations. While no nation's armed forces have ever fought by domains, this pamphlet gives the impression that the future armed forces might.[201]

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[199] Insider, "Crude Oil Price Today," Markets Insider, accessed March 4, 2022, https://markets.businessinsider.com/commodities/oil-price.

[200] Crown Oil Ltd., "Fractional Distillation of Crude Oil Guide," Crown Oil, accessed March 4, 2022, https://www.crownoil.co.uk/guides/crude-oil-fractional-distillation/.

[201] Wass de Czege, *Commentary on 'The US Army in Multi-Domain Operations 2028",* 17.

Context

Describing the operational environment in 2050 is difficult, given how much can happen in 20-30 years. The 1992 predictions of force design in 2020 would have failed to consider the war on terror, the advent of smartphones, and the proliferation of the internet. Indeed the 1990 'Options for change' Defence review sought to capitalize on the 'peace dividend' of the Cold War ending.[202] Anticipating where conflict is likely to happen, and against whom are therefore highly speculative.

The doctrine used by a force is broadly designed around the capabilities it possesses. Equally, capabilities are developed to enhance military capability based on an understanding, from doctrine, of how that force will fight. There is therefore always a symbiotic relationship between capability and doctrine.

The US Multi-Domain Operations (MDO) 2028 concept, and the related UK Multi-Domain Integration (MDI) are both likely to have been replaced by 2050, given how frequently capstone doctrine is changed.[203] Multi-domain themed doctrine will drive capability development through the 2020's and into the 2030's. These new capabilities will subsequently provide grounding for new doctrinal ideas in the future.

BG (Ret) Huba Wass de Czege's critique of MDO2028 is a logical and historically minded paper that outlines several reasons why MDO2028 is insufficient as a

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[202] Claire Mills, Louisa Brooke-Holland, and Nigel Walker, "A Brief Guide to Previous British Defence Reviews," (Briefing Paper Number 07313, House of Commons Library, London, UK, February 26, 2020), 39.

[203] Luke O'Brien, "The Doctrine of Military Change: How the US Army Evolves," *War on the Rocks*, July 25, 2016, https://warontherocks.com/2016/07/the-doctrine-of-military-change-how-the-us-army-evolves/.

capstone doctrine.[204] It argues that MDO2028 will require a similarly existential refinement to the Active Defense concept of 1976, which ultimately saw it evolve into Air Land Battle in 1982. Wass de Czege also argues that no nation's forces have ever fought by domains.[205] This study therefore concurred with Wass de Czege, meaning it is likely that MDO2028 will be thoroughly obsolete by the 2040's. The British Multi-Domain Integration is an off-shoot of MDO2028, and is unlikely to survive without the interoperability rationale of matching the American concept. Strategy documents such as the Ministry of Defence's Global Strategic Trends (GST) provide a more useful depiction of the future operating environment because they are broader and more abstracted. GST describes increasing urbanization,[206] rising costs of military modernization,[207] and proliferation of diverse types of energy infrastructure.[208]

A key theme in both British and American strategic documentation is a world in which people, devices, and environments are drastically more connected than today. The US National Intelligence Council's Global Trends 2040 talks of a 'hyperconnected world',[209] while GST describes a complex interconnected world.[210]

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[204] Wass de Czege, *Commentary on 'The US Army in Multi-Domain Operations 2028",* 10.

[205] Ibid., 17.

[206] Ministry of Defence, *Global Strategic Trends* 135.

[207] Ibid., 90.

[208] Ibid., 37.

[209] National Intelligence Council, *Global Trends 2040*, 55.

[210] Ministry of Defence, *Global Strategic Trends*, 147.

Discussion of multiple domains and convergence therefore seems short sighted, because in a hyperconnected world working across 'domains' would be so engrained into people's thinking that it would be a part of society's future culture. This study therefore believed that warfighting in 2050 will not take place across 'multiple domains', but rather in a fused singular inseparable digital and physical environment.

A corollary of such an environment is its vulnerability. Host nation power infrastructure can be highly vulnerable to cyber-attack, effectively dislocating energy supply from the force. Attacks on power infrastructure are already happening, with Russia attacking Ukrainian infrastructure from 2014 onwards.[211]

A future 3 (UK) Division must therefore be prepared to operate in this hyperconnected world, but cognizant that its interconnected nature comes with risk. From an operational energy perspective, there are subsequently two scenarios the Division must be capable of operating within.

A 'most-likely' scenario for warfighting sees 3 (UK) Division operating in an inseparable digital and physical environment, among significant numbers of civilians. A 'most-dangerous' scenario for warfighting sees 3 (UK) Division operating in an austere environment, devoid of host-nation infrastructure, against conventionally powered armored forces.

Summary

The analysis Chapter has identified how 3 (UK) Division fights in space and time. It relies heavily on deep fires to shape the close fight, and years of simulations have

[211] Jonsson, "Preparing for Greyzone Threats to the Energy Sector," 12.

masked a disconnect between artillery demand and logistical capacity. The Chapter has also examined alternative power sources and concluded that lithium-ion batteries are a preferable option to hydrogen, albeit with significant issues in operational energy supply and storage. Finally, it has argued that MDO2028 has limited relevance, and that Global Strategic Trends and Global Trends 2040 are of more use. The study cohered these findings in the conclusion, before offering recommendations.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Introduction

Very few people are inclined to read over 90 pages of introduction, literature review, methodology, and analysis. As such, this Chapter is designed to function as a standalone summary. It combines the analysis from the three research questions in Chapter 4 into one single argument. It uses close, deep, and rear to structure its thinking while zooming out from tactical to operational. It then closes with recommendations.

The Chapter begins by exploring the compromises that electrification would force in maneuver vehicles. It argues that operational reach is essential for maneuver, and that electrified vehicles can only achieve this if they are lighter than today's diesel vehicles. It concludes that weight-loss efforts must prioritize firepower and mobility over protection.

The Chapter then discusses the implications of this in the deep battlespace. It argues that 3 (UK) Division's ability to leverage national assets such as space-based capabilities quickly, enables it to find and strike in the deep, mitigating the risks posed by maneuver vehicles with less protection.

The Chapter then focuses on the rear, and the challenges of operational energy supply, storage and movement. The Chapter explains why various options in each of these areas are unworkable. It ultimately does not succeed in proposing a viable operational energy solution for electrified vehicles.

This means that while electrification at a tactical level could work with compromises, operational level electrification would be vulnerable to targeting.

Therefore, the study concludes that 3 (UK) Division's ability to win depends on fossil-fuels.

Finally, the study moves into recommendations. These are grouped into three categories: recommendations for the today's British Army, recommendations for Project MERCURY, and recommendations for future research.

The Close Fight

From the First World War onwards, militaries have grown accustomed to unprecedented firepower, protection, and mobility. Current materiel solutions such as Main Battle Tanks and aviation owe their very existence to the performance of fuels that allow range, survivability, and lethality to coexist without relative compromise.

Electrified Heavy Armor

Chapter 4 calculated that electrifying a 75-ton Challenger MBT that can travel 500km without refueling would require a 22-ton lithium-ion battery that would take at least a day to recharge. This will rightly lead some readers to query whether electrification and 'tanks' are mutually exclusive. Abandoning heavy armor would be much simpler for electrification. But such a force can only win if enemy armor can be defeated either by light forces in the close, or fires in the deep. This study must conclude whether heavy armor is worth the effort of electrification to answer its title and primary research question. In simple terms, will the 'tank' of the twentieth century be obsolete by 2050?

There will always be a close fight, and concepts that argue long-range fires can achieve all of the lethality a force needs[212] fundamentally misunderstand the nature of war. Clausewitz's friction concept[213] aptly describes how neutralization in the deep cannot be guaranteed, which is a reality that sometimes materializes in simulations.[214] Capability to defeat enemy armor must therefore exist in the close. MCPD1: *Warfighting* describes how fog, friction, and uncertainty produce complexity as part of the nature of war.[215] The best divisional fires teams will not prevent the chaos of meeting engagements because they are human and their information is imperfect. One of this study's assumptions was that likely adversaries would continue to field conventionally powered armor. The nature of war consequently means that troops in the close fight must be able to destroy whatever materiel solution an adversary uses for land maneuver. That is most likely to still be an MBT in 2050.

It is necessary to abstract the uses of contemporary armor further to understand how to compromise across mobility, firepower, and protection. Maneuver warfare is ultimately about trying to gain superiority. A key element in generating superiority at a

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[212] Simon Middleton, "Rise of the Rocket Launcher: The End of the Armoured Division, " Wavell Room, February 23, 2022, https://wavellroom.com/2022/02/23/rise-of-the-rocket-launcher.

[213] Carl Von Clausewitz, *On War*, ed. and trans. Michael Howard and Peter Paret (Princeton, NJ: Princeton University Press, 1989), 119.

[214] Steve B., "The British Way of War."

[215] U.S. Marine Corps (USMC), Marine Corps Doctrine Publication (MCDP) 1, *Warfighting* (Washington, DC: Department of the Navy, Headquarters U.S. Marine Corps, 2018), 21.

decisive point is surprise, which features as a principle of war in both the US Army[216] and the British Army.[217] Clausewitz argues that surprise lies at the root of all operations and is generated by secrecy and speed.[218] Therefore, a quiet electric tank with minimal thermal signature that can move rapidly is well suited to generating surprise.

Summarizing these ideas, 3 (UK) Division requires a capability that can react to inevitable friction by traveling quickly and defeating conventional enemy armor. It must also be fast enough to enable the generation of surprise at an operational level. Mobility and firepower must subsequently be prioritized over protection.

Prioritizing Mobility and Firepower over Protection

Fast, light, and lethal electric armor with limited survivability offers several thought-provoking corollaries. How fast, light, and lethal depends on the scale of compromise in platform design. This study explores this compromise to try and identify realistic parameters for future electric armor, quantifying range and survivability.

This study assumes a linear relationship between weight and range (halving the weight would double the range if everything else remained the same). With the space and mass available, an electrified 75-ton Challenger 3 MBT would only be able to travel 50km before running out of power. To achieve the 100km in a day that 3 (UK) Division planners would expect, an electric MBT would need to be approximately 40-50 tons, with

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[216] HQDA, ADP 3-0.

[217] Land Warfare Development Centre, ADP, *Land Operations*.

[218] Clausewitz, *On War*, 198.

less protection. Combining the density of steel armor,[219] dimensions of a Challenger 2,[220] and penetration experiments of 30mm ammunition[221] to determine armor thickness, at least 14 tons of hardened steel is needed to protect against just 30mm on all four sides and above. Combining these, the study approximated that a 50-ton platform that can cover 200km and survive up to 30mm direct fire is possible by 2050.

Second, an electric 50-ton MBT would provide higher tactical mobility than contemporary MBTs. Reduced ground bearing pressure limits sinkage in soft ground. Reduced weight allows for a broader range of existing gap crossings to be exploited. It also allows close support bridging to become longer, allowing more crossing options than current bridging. 50-ton platforms also open up opportunities to adopt similar bridging to the Russian TMM systems,[222] where wheeled launchers can rapidly lay a modular bridge as far as required. Increased tactical mobility also supports protection by reducing the terrains' ability to canalize the force.

The amount of protection required varies depending on operation. If an electric MBT could survive heavy machine gun and Infantry Fighting Vehicle calibers, the

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[219] Emre Palta, Matthew Gutowski, and Hongbing Fang, "A Numerical Study of Steel and Hybrid Armor Plates under Ballistic Impacts," *International Journal of Solids and Structures* 136–137 (April 2018): 279–294.

[220] Ministry of Defence, "Combat Vehicles."

[221] U.S. Army Audit Agency, Northeastern District, Memorandum, Subject: Armor Penetration Requirements for Medium Caliber Weapon Systems (Philadelphia, PA, July 10, 1975), https://www.archives.gov/files/declassification/iscap/pdf/2013-027-doc9.pdf.

[222] "TMM-6," WeaponSystems.net, accessed March 18, 2022, https://weaponsystems.net/system/308-TMM-6.

primary direct fire threats are anti-tank missiles and other tanks. Recent fighting in Ukraine has shown that even modern Russian heavy armor today can be defeated by light anti-tank weapons such as Javelin.[223] Prepared anti-tank matrices are likely to be an enduring threat in 2050 too, particularly in an urban environment.

Module armor to maximize protection at the expense of range should be a part of any materiel solution for electric armor. This study focused on high-intensity warfighting, and hence further explored the implications of the compromises in protection outline above. The conclusion next moved to explore how the deep can mitigate compromises in protection.

Shaping the Deep

Finding Targets

It is naïve to assume that ISR will ever be sufficient to provide the commander with a perfect understanding of the battlefield. That said, an analysis of current open-source technologies provides an impressive indication of what classified technologies may be able to achieve in 2050. Consider the threat of adversary conventionally powered armored forces facing friendly 50-ton electric tanks. Finding that enemy armor before it can overmatch lighter opponents is critical. One of 3 (UK) Division's advantages compared to an American division was its relative ease of access to national capabilities.

One national space-based capability that is highly likely to exist in 2050 is LiDAR mapping of the earth's surface. Aerial LiDAR techniques can already identify 70-

[223] "Russia Says It Is Changing Its War Aims in Ukraine," *The Economist*, March 28, 2022, https://www.economist.com/europe/2022/03/28/russia-says-it-is-changing-its-war-aims-in-ukraine.

year-old tank pits within heavy woodland.[224] NASA has been experimenting with space-based LiDAR since the 1970's.[225] With automotive and machine learning technology developing at ever-increasing speeds, the analysis of LiDAR scanning can become rapid and automated.[226] Therefore, it is highly likely that in 2050 space-based capabilities will be able to survey the operational deep and autonomously identify individual tanks as targets in real-time.

This is clearly dependent on communications not being degraded. Ground Mounted Reconnaissance (GMR) still has a role to play in degraded environments, or where detailed technical understanding of the terrain is essential. Applying similar calculations to the close fight conclusions, mounted GMR would struggle to maintain a recce gap if armored and electrified. Consequently, future electric GMR would most likely need to be light and wheeled to remain viable.

Striking Targets

A future electric warfighting division fielding armor with less protection is going to be even more reliant on striking targets in the deep than today's division. In simulations, divisional fires achieve this with great effect. Future Soldier's increased focus on the deep is therefore a step in the right direction, but it must be supported by

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[224] "Finding Russian Tanks in Polish Forests," Rapidlasso GmbH, October 12, 2013, https://rapidlasso.com/2013/10/12/finding-russian-tanks-in-polish-forests/.

[225] Xiaoli Sun, "Space-Based Lidar Systems," (Conference Paper, 2nd Conference of Laser and Electro-Optics (CLEO), San Jose, CA, May 6, 2012), https://ntrs.nasa.gov/citations/20120012916.

[226] National Intelligence Council, *Global Trends 2040,* 59.

increased logistics and evidenced by more accurate simulations. Chapter 4 showed that artillery logistics shortcomings mean the division can no longer shape the deep effectively once targets are more than 210km from bulk ammunition storage in the rear.

This is exacerbated by the lack of a Close Support Logistics Regiment (CSLR) to support 1st Deep Strike Recce Brigade, because this 210km figure assumes all of the divisional lift is allocated to artillery, and GMLRS-ER[227] is in service. This is not replicated in simulations such as Warfighter because sustainment is essentially not modelled. 3 Regiment RLC should not be disbanded, but allocated to 1st Deep Strike Recce Brigade. Artillery logistics is not the only challenge in the divisional rear area however. Energy supply, storage and movement in the rear present sizeable challenges in their own right.

Sustaining in the Rear

Movement

Electrifying the warfighting fleet does not remove the requirement to sustain the force with water, rations, medical supplies and ammunition. Transportation of these by vehicles on the ground will therefore remain a necessity.

Fuel transportation could however be replaced by cabling. Taking inspiration from the 62-mile-long pipeline established to support 1 (BR) Armored Division in DESERT Storm,[228] power can be transported almost instantaneously via surface laid or

[227] Ministry of Defence, “Upgrades to Multiple Launch Rocket Systems Strengthen Deep Fires Capability.”

[228] Baker, “Operation DESERT SABRE - 1st British Armoured Division,” 21.

even buried cables. One 400kV cable's throughput is enough to power the division. 90% of the Marine Expeditionary Force's fuel consumption in Iraq 2003 came from wheeled vehicles.[229] Reducing the number of fuel transport vehicles by relying on cables could therefore have a noticeable impact on overall demand. This does however create its own vulnerabilities.

A surface laid cable would radiate in the electromagnetic spectrum (EMS)[230] and it is almost certain a peer adversary would readily detect them with an Electronic Warfare (EW) capability. Unless dug in they would also be vulnerable to fires. While these challenges are not insurmountable, vehicles transporting batteries are a necessary alternative.

The use of contractor support is also complicated by electrifying the warfighting division, as technical interoperability is significantly degraded. This is an area for future research.

Storage

The electrical equivalent of a 600,000-liter Bulk Fuel Installation (BFI) would be the same size as 32 40-foot ISO containers, and weigh 6,700 tons. This weight would take over 400 EPLS or SV 15T to transport. This would likely consume the lift capacity of the two logistics regiments supporting divisional level activity. Such an electrical

[229] Naval Research Advisory Committee Future Fuels Study Panel, "Breaking The Tether Of Fuel," 96.

[230] "Electric and Magnetic Fields from Power Lines," U.S. Environmental Protection Agency, last updated November 27, 2018, https://www.epa.gov/radtown/electric-and-magnetic-fields-power-lines.

storage installation would likely have to be pre-positioned or require an operational pause to move. As such, they would likely also be limited in number. As storage is so challenging, the ability to generate electricity dynamically to meet demand is more important.

Supply

Nuclear power is not the answer. A division would need at least two dozen of the 5MW reactors being developed for the US military. In the case of Joint Forcible Entry (JFE), this would involve forcibly proliferating nuclear material into another state. Each reactor would require significant protection to ensure it wasn't captured by irregular forces or criminals. Finally, despite shielding a nuclear reactor can still be detected from space, allowing an adversary to see every support area within the division's rear.[231]

Ship to shore is not the answer either. The Queen Elizabeth carriers each have two 40MW engines. Even if a carrier were able to deploy 100% of this energy ashore, it would not meet the steady state requirements for the division. It also doesn't work in landlocked austere environments such as Afghanistan.

Solar panels are not the answer. Even with 100% efficiency and 20 hours of sunlight per day, the division would require 15 American football fields worth of panels. This is likely to be beyond the capacity of strategic lift to project into a theater, and beyond operational capacity to transport and build. It would also be impossible to conceal and easy to target.

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[231] "ESA Satellite Technology Enhances Nuclear Monitoring," The European Space Agency, March 28, 2022, https://www.esa.int/Applications/Telecommunications_Integrated_Applications/ESA_satellite_technology_enhances_nuclear_monitoring.

The only remaining solution is to use Host Nation Infrastructure (HNI). It would prevent the British Army from being able to sustain an expeditionary conflict in austere locations. An electrified British warfighting division reliant on HNI would have been unable to land in San Carlos Bay in 1982 to recapture the Falklands. HNI is also vulnerable to cyber-attack, especially in the interconnected world described by Global Strategic Trends.[232] Connecting to the existing power system is likely also only possible in certain places such as transformer stations. These would become decisive points that an adversary would protect or deny, and would anchor 3 (UK) Division plans. This would make it difficult for the division to seize the initiative. Without a secure energy supply, the remainder of the electrification concept is not viable. If the warfighting division is the British Army's Center of Gravity, this is its Critical Vulnerability.

Recommendations

From this conclusion, there are several recommendations for the future force.

Recommendations for the Current British Army

Simulations used on command post exercises must accurately model sustainment. One unintended but important finding relates to the use of simulations for experimentation. WARSIM does not accurately model sustainment, particularly for artillery logistics. If Future Soldier's decision to "privilege the deep fight over the close"[233] is based upon 3 (UK) Division's performance on simulations such as

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[232] Ministry of Defence, *Global Strategic Trends*, 147.

[233] Ministry of Defence, "Future Soldier Guide."

WARFIGHTER, there will be disconnect in the division's organization and equipment. This study recommends 3 (UK) Division conduct a detailed quantitative comparative analysis of its Class I, III, IV and V consumption versus logistic capacity in warfighting.

1st Deep Strike Recce Brigade must have a dedicated Close Support Logistics Regiment (3 RLC must be retained). This recommendation is a direct corollary of the one above. This study calculated that 1st Deep Strike Recce Brigade would require a daily demand of 1,080 Rocket Pod Containers and 1,820 pallets of 155mm ammunition in warfighting. This appears to be beyond what 10 QOGLR and 27 RLC can supply, given the requirement to transport food, water, rations, other ammunition types etc. as well. There is no logistics unit listed to support 1st Deep Strike Recce Brigade. This report recommends that the British Army consider retaining 3 Regt RLC to support the brigade's deep fires logistics.

Recommendations for Project Mercury

Focus on operational energy supply, storage, and movement. Recent experimentation to explore electrification has focused on individual vehicles.[234] The challenges of electrifying an armored vehicle are intuitive to most readers. The less obvious, and more significant, challenges lie at the operational level. There does not appear to be a viable means of supplying electricity without a critical reliance on Host Nation Infrastructure or 20 small nuclear reactors. A battery that would store less than one day's charge would weigh 6,700 tons and require 400 EPLS operating at their weight

[234] Ministry of Defence, and Jeremy Quin MP, "Armoured Vehicles to Test Electric Technology," Gov.UK, August 20, 2020, https://www.gov.uk/government/news/armoured-vehicles-to-test-electric-technology.

limits to move. This study recommends that Project Mercury prioritizes operational challenges over the tactical considerations of individual platforms.

Areas for Future Research

Operational energy supply for electrified warfighting. The critical vulnerability for an electric warfighting division is its energy supply. This study has highlighted the problem of operating in an austere or energy-denied environment, but has been unable to provide a concrete solution. This is an area that merits further research to understand the problem, especially vulnerability of host-nation infrastructure to cyber threat and whether a nuclear submarine can feasibly provide ship to shore energy supply.

Electric aviation: plot hole, or unmanned, lighter and easier in 2050? This study has focused on ground maneuver at the expense of attack aviation to minimize length. Either aviation remains conventional and uses a separate sustainment chain (which is an evasion of the problem), or it has to reduce in weight by transitioning to smaller drones. Both merit further analysis, which this study has been unable to include.

Are partner/contractor interoperability and radical modernization incompatible? For example, could a Danish conventionally powered armored battlegroup integrate into an electric British Brigade? This study hoped to analyze these implications but lacked the capacity to do so. Similarly, if contractors cannot refuel their vehicles through the force, how much support are they able to provide? Each journey that could have been one way has to become a loop, essentially halving their ability to project.

Summary

This study has examined 3 (UK) Division in warfighting because this presents the most demanding requirement in terms of speed, mass and sustainment. It has found that potent as 3 (UK) Division is, its success in recent simulations appears unrealistic logistically. This is especially true for artillery logistics. As such, this report recommends that Future Soldier retains 3 Regt RLC within the division to support 1st Deep Strike Recce Brigade's deep fires units.

This study has also compared hydrogen and electrification, arguing in support of the latter. Nevertheless, lithium-ion chemistry in the early 2020's is nowhere near sufficient to create the levels of firepower, protection and mobility enjoyed by users of fossil fuels. This forces a rethink in tank design. It would force Ground Mounted Reconnaissance to become lighter and less survivable if they are to maintain a recce gap. It creates an increased reliance on space-based capabilities to find, and long-range precision fires to strike adversary armor.

In the rear storage of electrical energy is exceedingly difficult, which creates a dependence on dynamic energy supply to meet demand. Supply from host nation infrastructure cannot be relied on in an energy-denied environment. Solar and land based nuclear options are unfeasible. For expeditionary operations in austere environments, nuclear submarines may provide the only viable energy supply solution.

Ultimately, the character of today's conflict is founded upon fossil fuels. The internal combustion engine has unlocked possibilities in the twentieth century such as powered flight and motorization that continue to shape the fundamental assumptions of how to fight. These fundamental assumptions provide the instinct, planning data, and tactics used by commanders and their staff. Abandoning fossil fuels, and relying on a different solution for operational energy supply, storage, and movement would invalidate many of these fundamental assumptions. Electrification is therefore likely to demand a reassessment of these fundamental assumptions, and could significantly evolve the character of conflict as a result.

APPENDIX A

OPEN AND AXIAL CODING TABLES

OPEN CODING

Ser	Item	Source	Source quality
1	Historical importance of engine as a weapon	Guderian	
2	Typical speed on a route is 20kph	Rupert Smith in BAR Gulf War Special	
3	British Army structure in 2025	Future Soldier	
4	Manoeuvrist approach	ADP Land Ops	
5	UK/US interoperability is important	Warfighter press releases	
6	3 (UK) Division JAGIC	ATP 3-91.1	
7	3 (UK) Division success on WFX21/4	Author experience	
8	Tension between arty resource of close and deep	Steve Broadhurst, British Way of War, Wavell Room	
9	British Army "Critical shortage of artillery"	Jack Watling, RUSI	
10	Deep more important for fires than close	Rupert Smith in BAR Gulf War Special	
11	British Army will double proportion of deep fires units	Future Soldier	
12	Creation of 1st Deep Strike Recce BCT	Future Soldier	
13	Conventional munitions still relevant	Jack Watling, RUSI	
14	Ukraine, PGM stocks running low	Jack Watling, RUSI	
15	Conventional munitions an order of magnitude cheaper than PGM	Jack Watling, RUSI	
16	One AS90 unit needs 910 pallets of 155mm per day	SOHB 1999	
17	One MLRS unit needs 540 RPC per day	SOHB 1999	
18	Two AS90 units in 1st DSR BCT	Future Soldier	
19	Two MLRS units in 1st DSR BCT	Future Soldier	
20	Divisional ammunition consumption is 760 pallets	DN 20/01 Sustainment	
21	NATO ammunition pallet unchanged since before 1999	DA Pam 746-1	
22	WARSIM does not model sustainment accurately	MG Maria Gervais	
23	WFX21/4 100km teleporting sustainment	Author experience	
24	WFX 21/4 WCOPFOR exploited lack of sustainment modeling	Author experience	
25	WARSIM does not model thermal management	Informal conversation with FA57 Fd Grade	
26	CERBERUS and WARFIGHTER are only fully staffed Divisional exercises	3 (UK) Div OSW	
27	CERBERUS and WARFIGHTER terrain was the baltics	3 (UK) Div OSW	
28	1 (BR) Armoured Div had two maneuver brigades	COL Baker, BAR Gulf War Special	
29	3 (UK) Division will have two armored BCTs	Future Soldier	
30	1 (BR) Armoured Div advanced 300km in less than 100 hours	3 (UK) Div OSW	
31	CERBERUS two 24hr movements of 80-100km by two mvr brigades	3 (UK) Div OSW	
32	WFX21/4 2up maneuver to contact	3 (UK) Div OSW	
33	WFX21/4 All 3 (UK) Div maneuver brigades conducted 60km advance in 24 hours	3 (UK) Div OSW	

34	Divsional frontage in attack is 15km	Rupert Smith in BAR Gulf War Special	
35	Division in defense is 30km width, 60km depth	Rupert Smith in BAR Gulf War Special	
36	Divisional rates of advance	SOHB 1999	
37	Rupert Smith's logistics calculations assume only moving at night	Rupert Smith in BAR Gulf War Special	
38	90% of 1 MEF fuel consumption in Iraq 2003 was wheeled vehicles	Naval Research Advisory Committee	
39	In 2009, 3,000 personnel KIA/WIA protecting convoys, 80% of which were fuel	COL (Ret) Douquet, Unleash us from the tether of fuel	
40	3,000 tons of consumables required each day by a division in HIC	Rupert Smith in BAR Gulf War Special	
41	RLC units, and who they support	British Army Website	
42	A GSR supporting 1 (BR) Armd Div had six sqns, for of which were for fuel	SOHB 1999	
43	36 DROPS in a GS Sqn in 1999	SOHB 1999	
44	EPLS can carry same number of pallets/RPCs as DROPS	British Army Website	
45	Organic artillery unit lift for artillery ammunition	SOHB 1999	
46	MLRS-ER will range to 150km	British Army Website	
47	Warfighting division would consume 800,000 liters of fuel per day	DN20/01 Sustainment	
48	Truck Transporter Fuel holds 22.5m3 of fuel	SOHB 1999	
49	Modern CST holds 20,000 liters of fuel	152 Regt RLC website	
50	1 (BR) Armd Div had 7 million liters of fuel in its rear for Iraq 1991	COL Baker, BAR Gulf War Special	
51	Typical Bulk Fuel Installation is 600,000 liters	152 Regt RLC website	
52	Unified Action	ADP 3-0	
53	Integrated Action	ADP Land Ops	
54	Location of specialists in US Army	FM3-94	
55	Location of specialists in British Army	AFM Wafighting, Corps and Div	
56	Ground Mounted Recce still required in 2050	Alex Humphreys, Preserving Fmn Recce, Wavell Room	
57	VII Corps BFIs in Iraq 1991 were 3.4 million gallons each	Robert Scales Collection, USAHEC	
58	Algae Fuel doesn't meet intent	Greentech media	
59	TRL of electric trucks	Tesla	
60	HMG investing in electric car battery infra	Net Zero Strategy	
61	1876 ICE was 17% efficient	Mercedes AMG F1	
62	2018 ICE 30% efficient	Mercedes AMG F1	
63	2018 electric motor 96% efficient	Mercedes AMG F1	
64	Tracked vehicles entered service from 1962 to 1998	Army website	
65	H2 10,000 psi ED	Johnson et al	
66	Liquid H2 ED	Moghbelli et al	
67	H2 3,000psi ED	Moghbelli et al	
68	Diesel ED	Molloy	
69	LNG ED	Moghbelli et al	
70	Algae bio-oil ED	Supriyanto et al	
71	Methanol ED	Moghbelli et al	
72	Powerpaste ED	Fraunhofer institute	
73	NCA battery ED	Stampatori et al	

74	NMC battery ED	Stampatori et al	Green
75	H2 10,000 psi with tank ED	Johnson et al	Green
76	Battery price reduced by 97% in 30 years	Our world in data	Yellow
77	Relative effieincy of hydrogen compared to batteries	Molloy	Green
78	Weight of Saturn V rocket	NASA	Green
79	Limits on Li Ion tech evolution	Zielger et al	Green
80	Electric cable data	Borealis AG	Green
81	Use of pipelines in 1991	COL Baker, BAR Gulf War Special	Green
82	Intensity of sunlight	NASA	Green
83	Pentagon developing 1-5MW nuclear reactors	DoD	Green
84	Reactors operate at 85%	US Energy Information Administration (EIA)	Green
85	UK Aircraft carriers non-nuclear	Rolls-Royce plc	Green
86	MT30 Gas Turbine peak power	Rolls-Royce plc	Green
87	Time to refuel a CR2 MBT	British O5 at CGSC	Red
88	Supercharger power rating	Tesla	Green
89	Current CR2 MBT engine	Army website	Green
90	Weight of CR2 engine and gearbox	Armored crew member	Red
91	Lithium prices	Tradingeconomics.com	Green
92	Lithium natural resources	Harvard Int'l review	Green
93	Sodium tecnology	USG	Green
94	Oil prices	markets.businessinsider.com	Yellow
95	Hydrogen for military	Coffey et al	Green
96	Hydrogen efficiency	Reddaway	Green
97	Multi-Domain concept	MDO2028	Green
98	Multi-Domain doctrine	Draft 2022 FM3-0	Green
99	UK Multi-domain	Multi-Domain Integration	Green
100	Issues with MDO2028	Wass de Czege	Green
101	British view of future OE	Global strategic trends	Green
102	American view of future OE	Global Trends 2040	Green
103	Vulnerability of HNI	Jonsson, RUSI	Green

One person's opinion	Red
Multiple sources, not peer reviewed	Yellow
Formally published/peer reviewed	Green

AXIAL CODING

		SRQ1: How 3 (UK) Division fights		SRQ2: Power source		SRQ3: Future concepts
Serial	Item	Primary category	Secondary category	Primary category	Secondary Category	Primary category
1	Historical importance of engine as a weapon	Movt and mvr		Operational movement	Platform movt	Close
2	Typical speed on a route is 20kph	Sustainment	Movt and mvr	Operational movement	Platform movt	Rear
3	British Army structure in 2025	C2	Movt and mvr	Operational movement	Platform movt	Deep
4	Manoeuvrist approach	C2	Leadership	Operational movement	Platform movt	Close
5	UK/US interoperability is important	C2	Leadership	Operational supply	Platform movt	Rear
6	3 (UK) Division JAGIC	Fires	C2			Deep
7	3 (UK) Division success on WFX21/4	Fires	Leadership			Deep
8	Tension between arty resource of close and deep	Fires	Movt and mvr	Operational supply		Deep
9	British Army "Critical shortage of artillery"	Fires				Deep
10	Deep more important for fires than close	Fires	Movt and mvr			Deep
11	British Army will double proportion of deep fires units	Fires				Deep
12	Creation of 1st Deep Strike Recce BCT	Fires	Intelligence			Deep
13	Conventional munitions still relevant	Fires	Sustainment			Deep
14	Ukraine, PGM stocks running low	Fires	Sustainment			Deep
15	Conventional munitions an order of magnitude cheaper than PGM	Fires	Leadership			Deep
16	One AS90 unit needs 910 pallets of 155mm per day	Sustainment	Fires	Operational movement		Deep
17	One MLRS unit needs 540 RPC per day	Sustainment	Fires	Operational movement		Deep
18	Two AS90 units in 1st DSR BCT	Fires	Sustainment			Deep
19	Two MLRS units in 1st DSR BCT	Fires	Sustainment			Deep
20	Divisional ammunition consumption is 760 pallets	Sustainment	Fires	Operational movement		Deep
21	NATO ammunition pallet unchanged since before 1999	Sustainment	Movt and mvr	Operational movement		Rear
22	WARSIM does not model sustainment accurately	Sustainment	Fires	Operational movement	Operational supply	Rear
23	WFX21/4 100km teleporting sustainment	Sustainment	Fires	Operational movement	Operational storage	Rear
24	WFX 21/4 WCOPFOR exploited lack of sustainment modeling	Sustainment	Fires	Operational movement	Operational storage	Rear
25	WARSIM does not model thermal management	Fires	Sustainment			Deep
26	CERBERUS and WARFIGHTER are only fully staffed Divisional exercises	Leadership	C2	Operational movement		Deep
27	CERBERUS and WARFIGHTER terrain was the baltics	Movt and mvr	Sustainment	Operational movement	Platform movt	Close
28	1 (BR) Armoured Div had two maneuver brigades	Movt and mvr	C2	Operational movement	Platform movt	Close
29	3 (UK) Division will have two armored BCTs	Movt and mvr	C2	Operational movement	Platform movt	Close
30	1 (BR) Armoured Div advanced 300km in less than 100 hours	Movt and mvr	Sustainment	Operational movement	Operational supply	Close
31	CERBERUS two 24hr movements of 80-100km by two mvr brigades	Movt and mvr	Sustainment	Operational movement	Operational supply	Close
32	WFX21/4 2up maneuver to contact	Movt and mvr	Sustainment	Operational movement	Platform movt	Close

33	WFX21/4 All 3 (UK) Div maneuver brigades conducted 60km advance in 24 hours	Movt and mvr	Sustainment	Operational movement	Platform movt	Close
34	Divsional frontage in attack is 15km	Movt and mvr	Sustainment	Operational movement	Platform movt	Close
35	Division in defense is 30km width, 60km depth	Movt and mvr	Sustainment	Operational movement	Platform movt	Close
36	Divisional rates of advance	Movt and mvr	Sustainment	Operational movement	Platform movt	Close
37	Rupert Smith's logistics calculations assume only moving at night	Sustainment	Movt and mvr	Operational movement	Platform movt	Rear
38	90% of 1 MEF fuel consumption in Iraq 2003 was wheeled vehicles	Sustainment	Movt and mvr	Operational movement	Platform movt	Rear
39	In 2009, 3,000 personnel KIA/WIA protecting convoys, 80% of which were fuel	Protection	Sustainment	Operational movement	Platform movt	Rear
40	3,000 tons of consumables required each day by a division in HIC	Sustainment	Movt and mvr	Operational movement		Rear
41	RLC units, and who they support	Sustainment	C2	Operational movement		Rear
42	A GSR supporting 1 (BR) Armd Div had six sqns, for of which were for fuel	Sustainment	C2	Operational movement		Rear
43	36 DROPS in a GS Sqn in 1999	Sustainment	Movement and maneuver	Operational movement		Rear
44	EPLS can carry same number of pallets/RPCs as DROPS	Sustainment		Operational movement		Rear
45	Organic artillery unit lift for artillery ammunition	Sustainment	Fires	Operational movement		Rear
46	MLRS-ER will range to 150km	Fires	Movt and mvr			Deep
47	Warfighting division would consume 800,000 liters of fuel per day	Sustainment	Movt and mvr	Operational storage		Rear
48	Truck Transporter Fuel holds 22.5m3 of fuel	Sustainment	Movt and mvr	Operational movement		Rear
49	Modern CST holds 20,000 liters of fuel	Sustainment	Movt and mvr	Operational movement		Rear
50	1 (BR) Armd Div had 7 million liters of fuel in its rear for Iraq 1991	Sustainment	Movt and mvr	Operational storage		Rear
51	Typical Bulk Fuel Installation is 600,000 liters	Sustainment	Movt and mvr	Operational storage		Rear
52	Unified Action	C2	Fires	Operational supply		Deep
53	Integrated Action	C2	Fires	Operational supply		Deep
54	Location of specialists in US Army	C2	Leadership			Close
55	Location of specialists in British Army	C2	Leadership			Close
56	Ground Mounted Recce still required in 2050	Intelligence	Movt and mvr	Operational movement	Platform movt	Deep
57	VII Corps BFIs in Iraq 1991 were 3.4 million gallons each	Sustainment	Movt and mvr	Operational storage		Rear
59	TRL of electric trucks	Sustainment	Movt and mvr	Operational movement	Platform movt	Rear
60	HMG investing in electric car battery infra	Sustainment		Industrial expertise and capacity	Operational storage	
61	1876 ICE was 17% efficient	Sustainment	Movt and mvr	Platform movement		
62	2018 ICE 30% efficient	Sustainment	Movt and mvr	Platform movement		
63	2018 electric motor 96% efficient	Sustainment	Movt and mvr	Platform movement		
64	Tracked vehicles entered service from 1962 to 1998	Sustainment	Movt and mvr	Platform movement		
78	Weight of Saturn V rocket	Sustainment	Movt and mvr	Operational storage	Platform movt	Rear
79	Limits on Li Ion tech evolution	Sustainment	Movt and mvr	Operational storage	Platform movt	
80	Electric cable data	Sustainment	Movt and mvr	Operational movement		Rear
81	Use of pipelines in 1991	Sustainment	Movt and mvr	Operational movement		Rear
97	Multi-Domain concept	Fires	Information	Operational supply		Deep

98	Multi-Domain doctrine	Fires	Information	Operational supply		Deep
99	UK Multi-domain	Fires	Information	Operational supply		Deep
100	Issues with MDO2028	Fires	Information	Operational supply		Deep
101	British view of future OE	Protection	Sustainment	Operational supply		Rear
102	American view of future OE	Protection	Sustainment	Operational supply		Rear
103	Vulnerability of HNI	Protection	Sustainment	Operational supply		Rear

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