The Truth Behind Green Alternatives For Future Ship Design

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Synopsis

The most recent IPCC (Intergovernmental Panel on Climate Change) report has outlined the risks and potential impacts across the globe, highlighting that changes we will face under climate change will be both difficult to predict and costly to adapt. As global resource scarcity and the energy crisis collide under a warming climate, it is crucial that we look at solutions for our Defence assets to be future ready, one of the most important being how we generate and store energy for our surface fleets. With current designs, new and improved materials used to power and source energy are being highlighted as successful 'green' alternatives to oil and gas.

This paper examines the production of nuclear, green hydrogen and lithium as alternative energy stores. Discussion is centred around the environmental impacts associated with the mining of the minerals required alongside the present socio-economic challenges faced that, if not addressed, will prevent these emerging systems having a truly sustainable credential. A reduction in carbon emissions is just one aspect of a truly ‘green’ alternative and both the short and long-term impact of these fuels on the environment, economy, and society cannot be ignored.

Keywords: Green fuels; Climate change; Marine systems;

1. Introduction: Background and the issue

It is now widely accepted by researchers that our climate is rapidly changing, both in terms of anthropogenic carbon in our atmosphere and oceans, to resource scarcity and an increase in extreme weather. The natural environment is under threat from a variety of challenges, with climate change being the most uncertain and complex issue (Rising, Tedesco, Piontek and Stainforth, 2022). The IPCC’s 2022 (Portner et al, 2022) report evidences the observed and projected impacts of climate change, with increased weather events resulting in irreversible impacts on some human and natural systems. These impacts have already effected some natural systems and human societies, with increases in disease, loss of species, and extreme weather events causing economic loss, human migration, and subsequent conflict. Climate change will inevitably impact how the Royal Navy (RN) protect, operate, and fight, from melting icecaps causing sea levels to rise and reducing the number of ports available for Navy Ships, new transit routes creating new security risks, and an increased requirement for humanitarian and disaster relief.

It is not only RN ships that will be impacted by these changes, but also commercial shipping. International shipping emissions rose to approximately 700 million metric tons of carbon dioxide ($MtCO_2$) in 2021, accounting for 11% of that year’s total global transportation CO_2 emissions. International shipping emissions have increased by 90% since 1990, due to increasing seaborne trade coupled with an increasing number of ships (Tiseo, 2023). Efforts to decarbonise shipping has increased since 2018 when the adoption of the International Maritime Organisation’s (IMO) Initial Strategy on GHG Reduction took place (IMO 2018), now replaced by the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (IMO 2023). The strategy states indicative checkpoints to reach net-zero GHG emissions, including to strive for a 30% reduction in GHG emissions from international shipping by 2030.

The RN has a heavy reliance on fossil fuels to power its fleet and naval bases and contributes to Defence accounting for 50% of the UK central government’s emissions (Ministry of Defence, 2021). The RN has taken responsibility to drive towards decarbonisation, with a focus on the main issues of powering the fleet and naval bases. The pressure for an efficient transition to green alternatives is also fuelled by fossil fuels rapidly depleting, with oil, natural gas, and coal, being limited in quantity and the scarcity increasing exponentially (Wang and Azam, 2024). This has been furthered by energy market volatailities and geopolitical events, such as COVID-19 and the war in Ukraine, whereby energy prices have been at a record-high. This has taken nations by surprise and identified their severe reliance on imported fossil fuels and the strong interdependence of their domestic electricity process with global gas markets (World Economic Forum, 2022).

The use of alternative fuels is the only route for decarbonising the maritime industry, as well as providing the RN assured security and operability in the future, given that necessary ports will bunker the required alternative fuels.

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 https://doi.org/10.24868/11179

One of the greatest challenges to the RN is resourcing a sustainable source of propulsion. As new power alternatives have been derived, the question remains about how ‘sustainable’ they truly are compared with traditional oil and gas. To be classed as sustainable, alternative power systems must “meet the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987). The alternative source should also present no (or minimal) harm to the environment, be cost-effective, and present no societal challenges. With current designs, new and improved materials used to power and source energy are being highlighted as successful 'green' alternatives to oil and gas, including nuclear, green hydrogen and lithium-ion batteries. With these options evolving, and greenwashing becoming increasingly used by companies, here we will explore the true environmental, economic, and societal impacts associated with the production of these alternatives to seek where improvement is needed for them to become truly sustainable.

2. Introduction to alternative systems

Various systems have been proposed around the world that provide what is quoted to be ‘environmentally friendly’ and ‘sustainable’ sources of power. Here we introduce nuclear, green hydrogen and lithium-ion as contenders for marine propulsion, alongside their general advantages and limitations.

2.1. Nuclear power

The Nimitz Class, of the US Navy, are a class of ten nuclear-powered aircraft carriers, which use two A4W pressurised water reactors. These reactors conduct nuclear fissions that heat the water to produce steam which is then passed through four turbines shared by the two reactors. Power is then transmitted through a gearbox which produces power to four propeller shafts and can produce a maximum power of 190 megawatts (MW) (Gibbons, 2001). Choosing nuclear power, over coal or oil, has many operational advantages, such as allowing ships to operate for over 20 years without refuelling. Nuclear power has been present in UK submarines since 1954 allowing increased speed and operational radius as a submarine can remain submerged on patrol for months (Friedman 2024). All fuel is contained within the nuclear reactor, meaning no supply space is sacrificed for fuel, exhaust stacks or combustion air intakes. The many benefits of nuclear marine propulsion are to be admired, however, the high operating costs and wariness of insurers providing cover for ships sailing into commercial ports without more understanding of the risks, limit the use of it in civil ships, hence why nearly all nuclear-powered vessels are military (Trakimavicius, 2021).

Research into the feasibility of nuclear-powered container ships has identified risks that need to be overcome for it to be viable. The risks include how a reactor will be fitted onboard and the potential for radiation exposure to installers. Questions have also arisen over the safeguards required when the vessel is in motion, the ownership of the vessel, and if tighter security is required when at sea (Saul, 2021).

2.2. Hydrogen Fuel

Hydrogen (H_2) is widely accepted as critical to the decarbonisation of transport and industry, with ~100 million tonnes per annum (Mtpa) being produced globally (IEA, 2023). However, the majority of H_2 is currently produced from fossil-based feedstocks. Therefore, the development of low-emission production methods whilst also increasing the volume of H_2 produced is required to achieve significant CO_2 abatement via emerging H_2-related applications.

Blue H_2 refers to production methods whereby the carbon generated from steam reforming is captured and stored underground through industrial carbon capture and storage (CSS) and is commonly referred to as carbon neutral (World Economic Forum, 2021). This paper will focus on green H_2 which is most commonly formed through water electrolysis, powered by renewable electricity. The water electrolysis method has been associated with higher costs (Yu, Wang and Vredenburg 2021), however, it is recognised as the most viable option for producing H_2 in a low-emissions manner to reach net-zero targets by 2050 (IRENA, 2022).

With increasing interest in H_2 as a replacement to fossil fuels, more research has been conducted into the environmental impact of H_2 leakages into the atmosphere. Sand et al (2023) conducted a multi-model assessment of the 100-year time-horizon Global Warming Potential (GWP100) of H_2. The results estimated a H_2 GWP100 of 11.6, which is significantly higher than CO_2 which has a GWP of 1. Although H_2 is not directly a GHG, it reacts with and increases the abundance of GHGs such as methane, stratospheric water vapour, ozone, and aerosols.

H_2 propulsion systems can be implemented via a fuel cell plant that creates electricity to power a propulsion electric motor or an Internal Combustion Engine (ICE), this can be used as either an electrical generator or as a main engine (Beard et al, 2023). Utilising fuel cells and combining them with batteries can remove the need for generators as the power plant can be altered to include both hotel load and propulsion requirements. If all H_2 and electrical power is produced via renewable electricity, then a fuel cell-based system has the potential to operate emission-free. However, H_2 is categorised as a low flashpoint fuel, with a flashpoint of -253^{O}C, meaning vapours that can ignite are formed in almost any condition and has a flammable range of 4-75 vol% in air (Lewis and Elbe, 1987).

With H_2 having a lower volumetric energy density compared to diesel, ships would need to store larger quantities of hydrogen to obtain the same level of endurance as diesel-powered ships. This results in larger or multiple storage tanks being required onboard which may increase the overall size of a ship, or eat into valuable space on curent designs (H2 IQ, 2024). Moreover, the requirement for larger storage facilities and specialised equipment for the handling of H_2 will lead to the construction of new infrastructure at ports, such as safety systems, bunkering facilities and fueling stations.

Precious metals such as platinum and iridium are typically required as catalysts in fuel cells and some types of water electrolyser, which means that the initial cost of these technologies can be high, it is currently twice as expensive as blue H_2 (Beard et al, 2023). This high cost has deterred some from investing in H_2 fuel cell technology. Such costs need to be reduced to make H_2 fuel cells a feasible fuel source for all.

Moreover, an environmental aspect to consider is that the use of H_2 in a marine ICE can lead to the thermal formation of nitrogen oxides (NOx). Careful control of combustion conditions can reduce emissions; however, this may lead to reduced power performance and output. Aftertreatment for the removal of NOx is a possibility for ships, but it will increase the complexity and cost of appliances (Laursen et al, 2023).

2.3. Lithium-Ion

Battery power has become a popular option for the transportation sector, with the maritime industry incorporating batteries onboard ships to reduce GHG emissions. lithium-ion batteries can be used as backup power to support the operating profile of a ship, such as maintaining Dynamic Positioning (DP) systems. Ships can run in zero emissions mode when batteries are used as the only source of electricity and can be used for “peak shaving” when taking over from onboard generators to deliver the peak load of electricity (Bureau Veritas, 2021).

A key challenge however is the safety issue known as “thermal runaway”, when a battery is either damaged or subject to high temperatures it can emit heat, flames, and gas, which can harm crew members and damage vessels (Bureau Veritas, 2021). Specific rules and standards are complied with when testing batteries for damage, and safety measures, such as a Battery Management System (BMS) can be applied, to ensure a battery is in an optimal working condition.

A major disadvantage is that lithium-ion batteries suffer from ageing, which is dependent on the number of charge-discharge cycles that the battery has undertaken. Furthermore, the viability of a fully battery-powered vessel depends on its operating profile and the reliability of shoreside charging infrastructure from fossil-free sources (Ship & Boat International, 2023).

3. Production activities and impacts of alternative systems

Here we will investigate the impacts involved in the production of these energy sources, namely the extraction and manufacture of the materials used to assess whether they are the final and sustainable solution they are advertised to be or whether they are just a temporary fix.

*Note due to the different country specifications and uncertainty around it, deep sea mining has not been included within this review.

3.1. Nuclear

The lifecycle resource use of nuclear power generation is commonly assessed using the concept of total material requirement (TMR), which expresses the total mass of primary materials extracted (European Environment Agency, 2016). The first stage of nuclear power production is the mining of the primary nuclear fuel, uranium, which is distributed in the earth’s crust as uranium ore. The three major techniques for uranium mining are underground mining, open-pit mining and in-situ leaching (ISL).

The open-pit method involves drilling the earth’s surface, which is then blasted and excavated. To extract the uranium ore, a large quantity of overburden, including mine waste, is extracted. The underground method involves drilling the earth’s surface to develop vertical tunnels to access the uranium deposit (Doka, 2011).

The in-situ leaching method involves injecting a lixiviant, usually sulfuric acid, into the boreholes. The acid interacts with the ores and leaches out a mixture of uranium that is then collected, the uranium is extracted and then purified. This process can result in water contamination when the lixiviant mixes with underground water, which can lead to the sulfuric acid being present in downstream ecosystems (Srivastava, Pathak and Perween 2020).

Milling is then conducted to convert the uranium into a usable form, which consists of crushing the uranium into a fine sand and the use of a lixiviant to separate and purify the uranium into a form known as “yellow cake”. Tailings is the term given to the radioactive rock and sand byproducts of this process, with finer dust residue being mixed with water and the slurry placed into tailing ponds.

Tailings are the primary environmental challenge associated with uranium extraction. Uranium tailings contain miniscule particles that are transported by the wind and can contaminate soil and water (Dewar, Harvey and Vakil, 2013). Leaks from tailing ponds result in contamination of underground water with heavy metals, which can lead to the pollution of rivers and lakes. Rain added to tailings can introduce sulfuric acid to aquatic ecosystems and direct wildlife exposure to tailings can be fatal. In 2008, 1600 ducks died in Canada after flying into a tailing pond (Sutton, 2017).

Nakagawa, Kosai and Yamasue (2022), conducted research into the environmental impact of nuclear power generation via a lesser-known measure; the volume of resources extracted from the lithosphere during the lifecycle of this process. This research had a focus on the mining methods used, the nuclear reactor types, and the type of uranium fuel cycle system used. Furthermore, the different grades of uranium ore mined and their effect on the TMR was assessed. The research found that there is a 26% reduction in resource use when a closed cycle that reprocesses uranium fuel is used, compared to an open cycle that does not reuse its by-products.

As well as the adverse environmental impacts associated with uranium mining activities, some human health and societal issues are also presented. Tailing deposits, coupled with piles of mining debris can become unstable and create landslides which can cause fatalities. Moreover, radioactive particles can be transported through the air via wind, causing kidney disease and lung cancer if inhaled (Dewar et al, 2013). Unfortunately, certain populations are at greater risk of exposure to these health hazards, with black individuals and low-income communities being disproportionately subjected to the hazards of mining. For example, the Native American reservation of Navajoland, is littered with tailing piles, with the United States Environmental Protection Agency mapping 521 abandoned uranium mines on the reservation (Arnold, 2014). Regarding this, uranium mining serves as an avenue for continued environmental racism, with the issue demanding public awareness and close examination. The conditions in which uranium is produced and the social impacts this can cause must be reviewed and corrected in order for nuclear to be classed as sustainable.

3.2. Hydrogen

Greenwald, Zhao and Wicks (2024) assessed the critical mineral and energy demands associated with the production of green H_2 under varying demand scenarios; 100 million tonnes per annum (Mtpa) for a “business as usual” case if green H_2 were to replace current fossil-based production, 500 Mtpa for a “net-zero” case with increased demand (based on the IEA’s Net Zero Roadmaps) (IEA, 2023), and 1,000 Mtpa for a “high growth” scenario where green H_2 would be widely used as a fuel and replace natural gas (Energy Transitions Commission, 2020). For each scenario, they calculated the critical mineral demands required to build water electrolysers and renewable electricity sources to power the electrolysers.

Alkaline water electrolysis (AE) uses Nickel (Ni) catalysts, however, the corrosion of the Ni-based electrodes resulted in the development of membrane-based method, such as proton exchange membrane (PEM) electrolysis. PEM electrolysis involves a solid polymer electrolyte, composed of perfluorosulfonic acids (PFSAs). PEM uses platinum group metals (PGMs) (platinum, Pt; palladium, Pd; and iridium, Ir) as electrode catalysts**,** these raw materials are more expensive than those required for AE. Solid oxide electrolysis cells (SOEC) have the potential to enable higher efficiency H_2 production than AE and PEM (Ni and Leung, 2008), but require transition metals and rare earth elements (REEs), such as, Ni with yttrium (Y)-stabilised-zirconia and strontium (Sr)-doped lanthanum (La)-based manganese (Mn) or iron (Fe) oxides as separator materials.

Greenwald et al (2024) estimated the total mineral quantities required for each H_2 demand scenario described above and found that PEM electrolysers require the least amount of raw material, however, as PEM methods rely on PGMs, it is also the most resource constrained method. Even under the “business as usual” scenario, half of all annual global Ir production is required for sufficient PEM capacity. Restrictions on the production of fluorinate compounds, such as PFSAs (Lim, 2023) only increase the unreliability of PEM as a sustainable method for water electrolysis.

The limited distribution of REE reserves, specifically for La and Y, alongside increasing demand for these elements from other clean energy technologies, challenges the feasibility of scaling up SOECs to meet future demands. AE is the most resource intensive in terms of the total tonnage of materials required, leading to a higher CO_2 footprint associated with its material production (Azadi, 2020).

The environmental and socio-economic impacts of mining these minerals are rarely acknowledged when evaluating energy transition methods and scenarios, but their understanding is crucial as they pose a risk to future supply. Research suggests that PGMs pose the highest level of risk of all minerals required for the energy transition in the mining industry (Lebre et al, 2020). The Bushveld Igneous Complex (BIC) in South Africa is where 91% of global PGM resources are found, accounting for 74% of global platinum production (Schulte, 2023), however, this mining area faces multiple risks, such as energy and water supply, local governance and community relations.

Figure 1 Mogalakwena Mine in South Africa is one of the largest PGM producers in the world.
Mine profile: Mogalakwena | Anglo American

Mogalakwena mine as pictured above, located on the Northern Limb of the BIC, is one of the world's largest PGM producers (MDO, 2024). The site has low annual rainfall (620 mm) and has a hot semi-arid climate (SRK Consulting, 2019). However, the mine consumes 66 megalitres (ML) of water per day, whilst only 26% of residents have piped water access to their dwellings which has led to social unrest, vandalism and disruption of mining activities.

Mines within the BIC area are 90% dependent on national utility coal-fired power stations, producing high GHG emissions (IPA, 2024). There is a national energy crisis in South Africa due to the poor performance of the coal-fired power stations and the lack of roll-out of renewables due to political factors (Kruger and Alao, 2022).

Waste is another significant environmental challenge faced, in 2022 Mogalakwena mine extracted 84.7 million tonnes (Mt) of rock but only utilised 13.9 Mt. Subsequently, the mine has eight waste rock dumps covering a total area of 2,182 hectares (ha). Tailings are stored in three onsite tailing storage facilities, failure of which is one of the key risks to the mine. If a landslide were to occur, there would be a significant impact on the twelve villages that are within a 1 kilometre (km) radius (GRID-Arendal, 2023).

Ultimately, these risks could increase operating costs and limit PGM production, having a significant impact on the global supply of PGMs and subsequently the supply of H_2 (Cole, 2023).

3.3. Lithium-Ion

Lithium is an increasingly popular material onboard ships to limit GHG emissions. However, the adverse environmental and socio-economic impacts that arise during the production of lithium could outweigh the positive reduction in emissions during operations.

Lithium exists as salts or compounds within underground deposits, clay, brine, mineral ore and seawater. It is traditionally extracted via evaporative brine processing, whereby lithium-rich brine is pumped into substantial surface ponds for solar evaporation (Lithium Harvest, 2024).

Water consumption is a significant environmental impact associated with lithium extraction, consuming approximately 500,000 gallons of water per metric ton. South America's 'Lithium Triangle' contains over half the world's supply of lithium under its salt flats; however, it is one of the driest places on Earth. This leads to excessive water use, in proportion to the regions supply, during mining activities. For example, in Chile's Salar de Atacama, lithium mining consumed 65% of the region's water (Institute for Energy Research, 2020).

 https://doi.org/10.24868/11179

Figure 2 An aerial view of the brine pools and processing areas of the lihtium mine on the Atacama salt flat, in the Atacama desert of northern Chile. *South America's 'lithium triangle' communities are being 'sacrificed' to save the planet | Euronews*

Mining has brought the benefits of revenues to the State funds and profits for local businesses, however, the excessive water use has led to ecosystem degradation and forced residents to migrate and abandon ancestral settlements due to water scarcity effecting their livelihoods (Romero, Smith and Vasquez, 2009).

Furthermore, the use of evaporation ponds exposes toxins to the environment (Figueroa et al 2013). Tibetan mines have experienced the leak of toxic chemicals, such as hydrochloric acid, from the evaporation pools into the water supply and in Nevada, scientists found lithium mine toxins in fish 150 miles downstream from the lithium production site (Institute for Energy Research, 2020).

Hard rock mining is another traditional lithium extraction method, whereby it is extracted from clusters of crystals or rocks. Once the ore is mined, it undergoes crushing, concentration, and chemical treatments, such as leaching and roasting, to receive the lithium concentrate. This method creates chemical waste and contaminates groundwater, rivers and soil. Furthermore, the carbon footprint is increased through transportation of the crushed rock to China for processing.

Moreover, open-pit mining alters and disrupts the natural environment which significantly impacts the visual aesthetics of an area. Subsequently, this can impact tourism rates and the livelihoods of residents through reduced income, recreational space and cultural ties to the land.

4. Strategic Implications on Naval Shipping

Applying these green alternatives to the maritime industry is a technical challenge due to the IMO's regulatory framework and availability of ports. The need to adopt alternative fuels within the RN stems from the requirement to diversify its energy source, to maintain an omnipresent and effective combat capability. Sourcing the most cost-effective solutions to obtain energy availability and accessibility require robust policies and strategies, and management of the strategic tension between investing in the infrastructure for alternative fuels and funding survivability and combat capability improvements (DNV, 2022).

Nuclear propulsion offers many strategic benefits to a naval vessel, such as travelling long distances at high speeds without refuelling which allows quicker response to distant contingenices. The lack of exhaust gases mitigates the challenge of infared detectablility that occurs with fossil-fuelled ships. However, strict regulations on maintenance and operator training have led to nuclear being a burden for sustenance. This, coupled with the great risks of radioactive waste, will create extra cost and logistical pressures for the navy, which may not be practiceable.

Hydrogen fuel cell technology has the potential to become more widely adopted on naval ships in the coming years. With H_2 having a lower volumetric energy density compared to diesel, ships would need to store larger quantities of hydrogen to obtain the same level of endurance as diesel-powered ships. This results in larger or multiple storage tanks being required onboard which will take up valuable provisions space (H2 IQ, 2024).

Moreover, naval ships will only be able to refuel at specific ports that have the appropriate infrastructure in place, which may not always be practiceable and could disrupt operations.

Furthermore, a primary challenge for better-powered vessels is thermal runway. This occurs when a battery is subject to high temperatures, which can occur from a high current discharge rate or being exposed to external heat sources (Bureau Veritas, 2021). The inherent risks of lithium batteries, such as fire and explosion, means that it is crucial that containment strategies are in place for successful deployment. A safe strategy to transport, store and charge lithium batteries is key in preventing battery failure and to enhance operational readiness (NAVSEA, 2023). A Battery Management System (BMS) is a safety measure that monitors the voltage, temperature and current of batteries. A BMS is ideal for navy ships as it also enables operators to optimise energy use and availailability whilst also increasing battery lifetime.

5. Conclusion and Comparison to Oil and Gas

The alternative fuels discussed in this paper are relied upon to decarbonise the shipping industry and reach net zero targets by 2050. Whilst these alternatives mitigate the impact of in-service carbon emissions, the environmental and socio-economic impacts associated with their production must not be overlooked if they are to be categorised as sustainable.

Here we discuss some of the main challenges of these alternative systems against oil and gas to give a broad understanding and implication of their environmental impact and evaluate whether these alternatives are a sustainable solution for the shipping industry.

Oil and gas are the largest sectors in the world, employing millions of people and with products used in most major industry sectors. The environmental impacts are well known from oil spills to GHG emissions, hence the demand to source an alternative.

Nuclear power, green hydrogen, and lithium have become increasingly advertised as the solution to decarbonising the shipping industry and reaching the net zero targets by 2050. However, to become completely reliant on these as fuels we must be conscious of the environmental impacts associated with their production, as we are with oil and gas, and identify mitigation methods so that we are not just replacing one problem with another.

An environmental challenge that is shared among the production of all the discussed alternatives and oil and gas is water usage, waste and contamination. Excessive water usage in areas where it is already scarce, such as for lithium mining in Chile and PGM mines in South Africa, alongside wastewater as a by-product of mining activities and subsequent contamination to soil are detrimental to the local environment and wildlife. This, partnered with the impact on residents who depend on these assets for their livelihood being forced to migrate, results in adverse socio-economic challenges. As with the human health impacts of uranium mining, certain populations are at greater risk of exposure, with low-income individuals being disproportionately subjected to the hazards of mining.

In 2022, the production, transport and processing of oil and gas resulted in 5.1 billion tonnes (Gt) CO_2 -eq, which accounted for 15% of total energy-related GHG emissions (IEA, 2023). Advocates of alternative fuels, such as green hydrogen, misguide consumers by promoting the low carbon properties. Whilst this may be the case, it masks the fact that hydrogen has a significantly higher GWP than CO_2 as it increases the quantity of other GHGs.

In conclusion, the Royal Navy strive to create one of Earth's greenest fleets, having already used existing technological innovations to reduce its impact on the environment. However, the long-term challenge of resourcing a sustainable method of propulsion remains key. With many alternative fuels and power systems emerging on the market, it is crucial that the integrity of each is examined prior to agreement. A system promoted as being the 'green' option may be masking unsustainable production practices that outweigh the benefits in the long-term.

Acknowledgements

The author would like to thank colleagues at BMT for their encouragement and support, specifically the Environmental Services team and Dr Thomas Beard.

The views expressed in this paper are that of the author and do not necessarily represent the views and opinions of BMT.

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