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# 2025 UNIVERSITY CLIMATE REPORT

August 15, 2025

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The idea for this report sprung from a visit to a Combined Heat and Power Plant; we were explained how the design, which generates needed electricity whilst using the leftover heat usefully, is much more efficient than doing those two necessary processes individually. This idea that simple ideas can have a great positive impact is core to the founding of the University Climate Report, and our ultimate aim is that the concise, targeted writing of each team leads to not only their development, but also positive change from the side of readers.

An instance that, in itself, makes this entire project worthwhile occurred when I was walking across campus, when a shout called for my attention. George, who had recognised me from a Climate Report Q&A Event we ran, began telling me about different innovations in textile recycling at such a rate that I could not even attempt to process what he was telling me; what struck me most profoundly, though, was his massive irreplaceable grin and pure passion in conveying his team´s progress: he was not earning any money or prestige from his contributions, it was pure curiosity, kindness, and a desire to build a better world for others.

I hope that this essence will grow and multiply, as we make these initiatives open to more people and build more impactful partnerships, and myself feel incredibly honoured and grateful to be in a position to support these initiatives. Importantly, I wanted give a great thanks to the head at each university, who are credited above, and without whom this report would not have been possible, and a special thanks to George Giakoumopoulos for doing the final compilation of reports and ensuring coherence.

**Nicholas Finnemore**
**Head of the 2025 Climate Report**

# An Introduction to our Format

This report has been written in a manner that makes it readable no matter the reader´s level of interest/experience. Alone, the summary provides an overview of each article´s aim, process and findings; reading the article itself will yield the research process of the team, including alternatives they looked into that ended up as infeasible; those interested in the academic underpinning of a given argument can go to the hyperlinked appendix section to read into the details, which is at the bottom of the report.

We recommend looking at the table of contents to see what you might be interested in, and jumping straight to it with the hyperlink! From there you can go to a specific part of the appendix that you are interested in with our in-text appendix referencing.

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# Summary

This report examines the three generations of biofuels as an alternative to fossil fuels in decarbonizing land transportation. The three generations namely, first-generation (food crops), second-generation (waste biomass) and third-generation (algae-based) were assessed on their production methods, advantages, disadvantages and real-world applications in the United Kingdom. Gen-1 biofuels offer immediate compatibility with existing infrastructure but compete with the food demand and cause ecological degradation. Gen-2 biofuels provide a more sustainable alternative but face logistical problems. Lastly, Gen-3 promises the highest oil yield but remains economically unviable. Initiatives are driven by the UK's Renewable Transport Fuel Obligation (RTFO) and private companies to increase biofuel adoption. Case studies of companies like Shell, Greenergy, Vivergo Fuels and Argent Energy are included, illustrating their challenges and solutions to balance sustainability. This report concludes that biofuels play a transitional role in decarbonization with long-term success depending on economic-environmental balance, collaboration and continuous commitment from the public and other stakeholders


# Introduction

Biofuels are fuels produced from biomass and serve as an alternative for fossil fuels. Biofuels, such as bioethanol and biodiesel, are critical to the UK's efforts to shift to a low-carbon economy and meet renewable energy and climate change goals. Biofuels emerged as a long-term strategy for decreasing greenhouse gas emissions in 2005 [1]. Its use has been increasingly implemented in the transportation industry worldwide as a renewable energy source as shown in Figure 1 below [12][26].

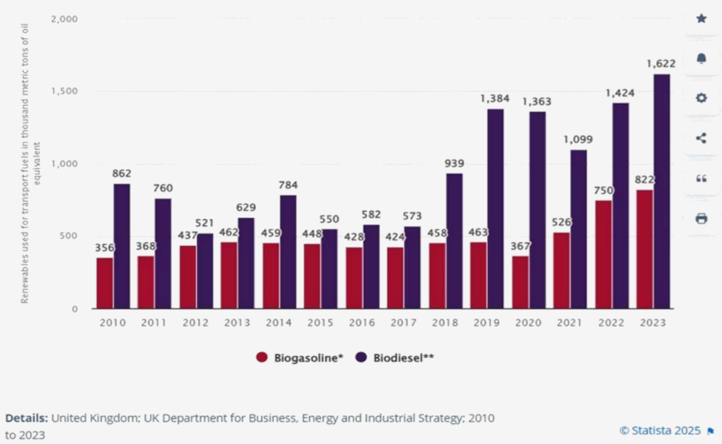


*Figure 1: Renewable energy used as transport fuels in the UK from 2010 to 2023 by type (in 1,000 metric tons of oil equivalent) [2C]*

Burning these biofuels in an engine produces less greenhouse gases and is considered "carbon- neutral" as the carbon emitted to the atmosphere is captured in the previous stage of the biomass' lifecycle. In this report, the sustainability of biofuels as reported by Greenergy – a biofuel supplier will be examined and compared to that of fossil fuels used in cars. This paper investigates the types and necessities of biofuels, production methods, advantages, disadvantages and their viability and utility in the transportation sector of the UK.

# Biofuels

## Types of biofuels

The types of biofuels discussed here are the first-generation, second-generation and third-generation biofuels, each with sources, production methods and sustainability implications, discussed further in this report:

Table 1: List of generations of biofuels and their sources/raw materials [25]

| Generation of Biofuel | Sources |
|---|---|
| **First-generation biofuels** | Corn, sugarcane, and vegetable oils like rapeseed, soybean and palm oil |
| **Second-generation biofuels** | Non-food biomass, including agricultural Residues and waste oils |
| **Third-generation biofuels** | Algae and microorganisms |

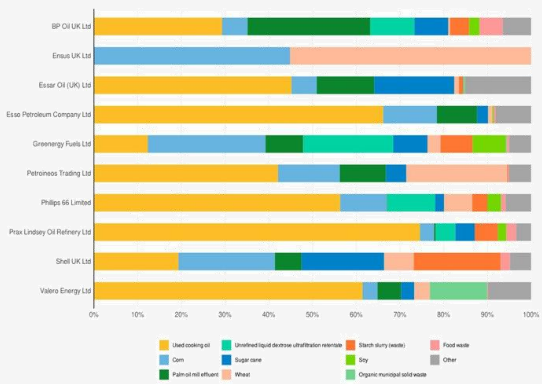


*Figure 2 Feedstock Mix of Top 10 Renewable Fuel Suppliers in UK 2023 [3]*


*Figure 3 Proportion of waste and non-waste feedstock amongst renewable fuel in 2023*

Industry throughout the years has diversified research on biofuels including in the UK, as seen in Figure 2 below, whereas the shift from different generations of biofuels can be seen further in Figure 3, demonstrating the shift in utilizing waste feedstock for renewable fuel production.

According to Figure 2, the top ten suppliers of renewable fuel in the UK use both crops and waste on their biofuels production. The proportion of crops and waste used by each company depends on how much each type of biofuels is produced. As shown in Figure 3, most biodiesel is produced from waste while most bioethanol is crop-based. Most bioethanol is crop-based because crops such as sugarcane, wheat and corn have high starch or sugar content that will facilitate the fermentation process [1]. Therefore, referring to Figure 2, Valero Energy Ltd, for example, produced more biodiesel than bioethanol because the greatest proportion of feed stock used is waste cooking oil.

## *Biofuels in Industry*

Several companies produce biofuels, including Shell, Vivergo and Greenergy. An in depth look into each producer can be found in **Appendix A2**. Table 2 provides a summary of each producer below.

Table 2: Overview of examples of UK Biofuel producers [2]

| Company | Generation of Biofuels | Application |
|---|---|---|
| **Shell** | First and second generation | Produced 9.7 billion liters biofuel in 2023 via its joint venture, Raizen<br>Raizen contributed 3.4 billion liters, an<br>increase compared to last year's 3 billion. |
| **Ensus UK Ltd** | First generation | Among top 10 renewable fuel suppliers<br>Yields 400 million liters of bioethanol and 350 thousand tons of Distillers' Dried Grains with Solubles (DDGS) annually |
| **Vivergo Fuels** | First generation | Supplies 420 million liters of ethanol/year<br>Extracts starch for fuel production while feeding feedstock excess protein and fibres |
| **Greenergy** | First and second generation | Operates 3 biodiesel plants in the UK and Amsterdam<br>Major provider of low carbon transport fuel to independent retailers in Canada, Ireland and<br>the UK |
| **Argent Energy** | Second generation | - Provides B20 used in London's buses;<br>converts waste oils to biofuels |

With each generation of biofuel proving unique benefits in industry, **Appendix A3** entails key advantages associated with each type of biofuel. A summary is provided in Table C below.

Table C: Summary of the advantages and disadvantages of different biofuel generations

| Generation of Biofuels | Advantages | Disadvantages |
|---|---|---|
| | Greenhouse gas emissions reduction | Competition with Food Production |
| | Compatibality with existing infrastructure | Ecological and environmental Impact |
| | Fuel customization and supply chain efficiency | Difficult to take advantage of economies of scale |
| **First-generation** | | High cost for consumers |
| | Higher environmental benefits | Storage and performance issues |
| | Waste utilization and cost-effectiveness | Higher maintenance costs |
| **Second-generation** | Engine compatibility and efficiency | |
| | Year-round production | High production costs |
| | Carbon neutrality potential | Technological and Infrastructure Challenges |
| **Third-generation** | High oil yield and versatility | High energy demands |

The first-generation biofuels provide an immediate and practical solution due to its practicality. The second-generation biofuels mitigate sustainability concerns of its predecessor by repurposing waste materials. Lastly, the third showcases the most promise with highest oil yield, and potential for carbon neutrality [9].

However, though biofuels present a viable alternative to fossil fuels, they come with significant challenges. First-generation biofuels compete with food production and contribute to environmental damage. Second-generation biofuels are more sustainable but require costly storage and maintenance. Third-generation biofuels show great potential but remain far too expensive and technologically challenging. Moving forward, more research and policy incentives will be crucial in making biofuels a practical part of the transition to cleaner energy [10].

# Current Applications in Land Transport

The biofuels transition has driven the increased use of biofuels in transportation. The United Kingdom has already implemented initiatives and policies to integrate biofuels into its transportation sector, aligning with its net-zero emissions target by 2050. This section examines biofuels' use in public land transport and private vehicles.

## *Biofuels in Public Transport*

The United Kingdom's primary transportation systems, particularly buses, are among the earliest adopters of biofuels. Many bus operators use B20 (20% biodiesel, 80% conventional diesel), to reduce emissions. The adoption of bioethanol as an alternative fuel is also expanding, especially in urban areas where air quality concerns are significant.

The London Borough of Hackney (LBH) has used FAME biodiesel in blends of up to 100% for several years and observed significant reduction in CO2. The LBH uses an on-site fuel management system to monitor and analyze fuel consumption and mileage data, allowing them to calculate their carbon footprint on an individual basis [37]

TfL has implemented biofuel-powered buses running on hydrotreated vegetable oil (HVO) and biodiesel from used cooking oil [38]. This initiative has reduced CO2 emissions across TfL's bus network by approximately 10%.

## *Biofuels in Private Vehicles*

E10 (10% bioethanol, 90% petrol) has been introduced as new standard fuel in the United Kingdom. This helps reduce carbon emissions from petrol-fueled vehicles by 750,000 tons annually – the equivalent to 350,000 cars of the road. However, due to incompatibility with older vehicles, there still exist discussions about alternative low-carbon fuels.

The UK, with its limited agricultural land and high energy demands, presents a strong case for adopting algae biofuels. Algae's ability to grow in non-arable land and wastewater aligns with the UK's sustainability goals. The government is developing more policies to support biofuel expansion, including funding research into advanced biofuels and mandating higher biofuel blend requirements. Amongst them, the Biofuel Strategy 2030 aims to improve sustainable biofuel while ensuring compatibility with the existing infrastructure. The UK government, through the RTFO policies, has incentivized biofuel adoption, requiring suppliers to ensure a minimum proportion of biofuels in their fuel distribution.

The UK government has already shown interest in biofuels, investing £389 million in advanced biofuels research through the Department for Business, Energy C Industrial Strategy (BEIS) as part of its Net Zero Innovation Portfolio [14]. However, challenges such as high production cost and food crop diversion concerns continue (Department for Energy Security and Net Zero, 2024). Technological advancements and collaborations with research institutions, like those in the U.S., could drive down costs and establish necessary infrastructure for algae biofuels in the UK. Other countries such as the U.S. are also investing in biofuels. Their efforts are explored in **Appendix A4**.

## *Challenges in the Implementation of Biofuels*

The implementation of biofuels has faced significant economic, ecological and logistics challenges across fossil fuel to biofuel transition. Hence, this segment highlights the different challenges faced by companies mentioned in Section 4.

Biodiesel costs are 70% to 130% higher than petrol and diesel on the wholesale market, adding €17 billion annually to Europe's fuel bill [16]. This leads to either the government or consumer to pay a premium. This brings forth sustainability issues:

- Government subsidies: reliance on subsidies creates long-term fiscal burdens and risk in industry if support is withdrawn [16]
- Consumer premium: passing cost to consumers causes public resistance as seen in protests for fuel price hikes

This is indifferent for companies in the biofuel industry. Recently in 2024, Shell paused their biofuel plant due to high cost and uncertain market conditions. Greenergy also faced issues from rising feedstock costs due to competition for waste oils, forcing investments in supply chain diversification [35] whereas Vivergo Fuels struggled with profitability due to fluctuating bioethanol prices and policy delays [28].

The production of biofuels also requires new processing plants, which entail significant capital expenditure. For instance, Shell paused construction of its 820,000-ton biofuel plant in Rotterdam [39]. Greenergy also invested in pre-treatment upgrades at its Teesside and Amsterdam plants to handle diverse feedstocks [35].

In addition to economic challenges, ecological and logistical challenges exist as well. These are discussed in detail in **Appendix A5**.

# Conclusion

Biofuels prove to be an essential step in the transition away from fossil fuels. Though currently imperfect, different initiatives are blooming to maximize biofuels' role in decarbonization. First- generation biofuels, despite their practicality, are hindered by high carbon footprint, land-use inefficiencies and competition with food production. Second generation, though more sustainable, face logistical challenges and supply chain constraints. Third generation obviously offer the most promising environmental benefits, hosting higher oil yields, integration with carbon capture systems and applications in arable land, though remain the most expensive and technologically immature. These obstacles can be overcome as exemplified by company initiatives like Shell and Greenergy.

Moving forward, a multi-pronged approach is recommended:

1. Continue investing in second-generation biofuels as a scalable option for industrial adoption. Biofuel integration in public transport should be continued and potentially scaled further into logistics and distribution industries.

2. Supporting third-generation biofuel RCD through government incentives and publicizing its benefits could lower production costs and enhance economic feasibility. Hence, the UK would be encouraged to increase its currently low involvement in algae-based biofuel.

3. Limit but strategically utilize first-generation biofuels, especially in regions where infrastructure already supports them. Reliance on this generation should decline competition with the food supply market.

4. View biofuels as a bridge technology. While EVs and hydrogen fuel cells may present more long-term sustainable alternatives, biofuels can already help bridge the gap in sectors that are harder to immediately decarbonize like aviation and marine transport.

Policy delays, economic barriers and competition from rising alternatives like electric vehicles may threaten their long-term viability. Hence, it is important for companies as those stated before, the government and the public to exemplify the industry's adaptive strategies amidst challenges.

While biofuels alone cannot achieve net-zero emission, they can play a strategic and complementary role in decarbonization. Ultimately, the future of biofuels hinges on research and development (RCD), collaboration and a commitment to balance environmental and economic feasibility.

# ANAEROBIC DIGESTION FOR AGRICULTURE

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# Summary

As one of the most significant contributors to the UK's greenhouse gas emissions, the agriculture sector is a critical area for intervention, making the development of bioenergy technologies crucial to achieving the 2050 net-zero target. This paper evaluates anaerobic digestion (AD), a biochemical process that converts organic materials such as agricultural waste into biogas for energy production and nutrient-rich digestate. To assess the technical and economic feasibility, the study also investigates alternative bioenergy technologies, including biomass gasification and biodiesel production via transesterification. Technical analysis is used to address the key operational challenges AD faces, such as feedstock variability, process efficiency, and environmental impacts. This study also examines the economic feasibility, focusing on the necessity of refined policy support, potential incentives, and secondary revenue from the digestate. Despite its current limitations, the analysis concludes that anaerobic digestion represents a sustainable and economical solution for reducing agricultural greenhouse gas emissions in the UK, provided targeted technological improvements and supportive governmental policies are implemented.

# Bioenergy

Bioenergy is defined as energy that is produced from the use of organic materials (Biomass), primarily consisting of plants, agricultural waste and animal waste. It is, therefore, considered to be a renewable energy source as the supply of all the materials can be renewed over time.

The agriculture industry in the UK relies heavily upon the use of fossil fuels, subsequently contributing to it accounting for "10% of the UK's total GHG emissions, 62% of which is produced by livestock, 28% via nutrient management and 10% agricultural fuel use" [1]. Farming inherently causes the production of greenhouse gases due to natural biological processes, such as methane emission from enteric fermentation in ruminant animals and the decomposition of manure. Additionally, nitrous oxide is emitted because of the application of nitrogen-based fertilisers, resulting in the microbial process of nitrification and denitrification. Therefore, it is impossible to eradicate their emission within the sector, but equally imperative to optimise farming techniques to minimise their production.

With the expressed endeavour of the UK government to achieve net-zero greenhouse gas emissions by 2050, the use of bioenergy has been subject to considerable growth as it has emerged as a viable alternative to non-renewable fossil fuels [2]. As shown in Figure 1 (see **Appendix B1**). Most recently, in 2023, the UK managed to produce "14,000 barrels of oil equivalent per day in biofuels, with the installed capacity for bioenergy electricity expanding to around 6.7 gigawatts" [3]. Dedicated measures have been taken and must continue to be pursued to further propagate the adoption of more sustainable farming techniques and reduce the United Kingdom's overall greenhouse gas emissions.

There are many different types of bioenergy. Exploring each of them as a feasible solution will provide better insight into how the UK can improve its renewable energy sector and become more sustainable. Below are three promising types of bioenergy.

# Anaerobic Digester

The primary solution investigated in this report is the anaerobic digester due to its unique potential to address agricultural waste and reduce greenhouse gas emissions. Anaerobic digestion is a process that breaks down organic waste, such as manure, food waste, and crop residues, in the absence of oxygen, and takes place inside a sealed tank called a digester. Microorganisms naturally break down the waste and produce usable biogas and nutrient-rich digestate. This method is simple, reliable, and works well for farms that produce large amounts of organic waste.

Anaerobic digestion (AD) occurs through four key stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [4]. (See **Appendix B2**). The biogas produced can be used to generate renewable energy [5]. By undergoing further processing and purification by removing the low-value constituents of CO2 and water vapour, biogas can be used as vehicle fuel or refined into biochemicals and other energy products [6]. The remaining digestate, composed of both solids and liquids, is rich in nutrients and serves as a fertiliser to improve soil health and natural growth [7]. Digestate can also be used as animal bedding, foundation material for bioproducts and organic-rich compost [7]. By diverting organic waste headed for the landfill, AD reduces the emission of methane and other greenhouse gases and improves the farmer's harvests [7]. Additionally, digestate products can be packaged and sold, providing farmers with another source of revenue [7].

# Biomass Gasification

Biomass gasification is a thermochemical conversion of solid biomass fuel into synthetic gas (Syngas), a combustible fuel that mainly consists of $H_2$, CO, $CO_2$, $CH_4$ and $N_2$ [8]. The gasification process also produces undesired substances and chemicals such as alkali metals, ammonia, sulfur and hydrochloric acid [8]. The syngas produced, also known as producer gas, can be used for power generation in gas engines or as aviation fuel [9]. As shown in Figure 4 (see **Appendix B3**), different biomass contains different combinations of biopolymers and varies in moisture, density, heating value, size and shape. Hence, the type of biofuel used influences the composition of the producer gas [8]. The design of the gasifier will also need to be tailored to the characteristics of the biomass to improve the quality of the producer gas obtained [8].

Biomass gasification provides clear advantages over traditional combustion processes. The combustion of syngas is cleaner and more efficient, as it reduces excess air and heat loss to the exhaust gases [10]. Additionally, the reduced volumetric flow rate of the produced fuel gas results in lower cleaning costs [10].

Though it is a feasible and innovative solution, it presents environmental concerns such as deforestation, air pollution and water pollution [11]. Also, there is no proper system set in place to optimise the gasification process, such that it is not very cost-effective. Technology has not advanced far enough to yield sufficient products that can be applied to solve full-scale issues [11]. Further research has yet to be conducted to develop stronger compatibility between engines and syngas [11].

# Transesterification Process

Another form of biofuel generation is the transesterification process, where triglyceride (oil and fat) is processed with excess methanol at atmospheric pressure and 60

°C. A base catalyst is employed, commonly sodium or potassium hydroxide [12]. This reaction yields three separate fatty acid methyl esters -the desired product- and glycerol as shown in Figure 5 (see **Appendix B4**), which can be decanted after allowing the mixture to settle.

A weakness of the transesterification process used in biodiesel production is that it is highly sensitive to the water and free fatty acid (FFA) content of the feedstock, with even small amounts of water or elevated levels of FFAs being able to significantly impact the reaction, leading to lower biodiesel yields and reduced fuel quality [13]. Achieving low water and FFA content in the feedstock can be challenging and often requires additional processing steps, such as pretreatment and purification, increasing overall production costs.

Another critical consideration in biodiesel production is the use of catalysts, which can raise environmental and safety concerns. Traditional catalysts, such as sodium hydroxide and potassium hydroxide, are effective in facilitating transesterification but are also highly corrosive

[14]. Additionally, the disposal of spent catalysts presents environmental risks, as improper disposal methods, such as discharging them into water bodies or landfills, can lead to soil and water contamination. To address these concerns, ongoing research is exploring alternative catalysts, such as enzyme-based or solid catalysts derived from natural materials [14], which offer reduced environmental impact and improved sustainability.

Despite these challenges, biodiesel offers several advantages over conventional petroleum diesel. It produces lower emissions, enhances engine lubricity, and is biodegradable, making it a more environmentally friendly fuel option [15]. Biodiesel can also be blended with petroleum diesel in various proportions, facilitating a gradual transition to renewable fuels while reducing reliance on fossil fuels. A key environmental benefit of biodiesel is its classification as a carbon-neutral fuel, as the $CO_2$ released during combustion is approximately equal to the $CO_2$ absorbed by the oil-producing crops during growth [15]. However, while this balance reduces net carbon emissions, the overall environmental impact of biodiesel production is influenced by other factors, including fertiliser use, oil extraction, refining, drying, and transportation [15], all of which contribute to greenhouse gas emissions. A comprehensive assessment of biodiesel's sustainability requires a life cycle analysis (LCA) to account for emissions at each stage of production (see **Appendix B5**). Nevertheless, biodiesel remains a safer alternative to fossil diesel, as it is non- toxic, rapidly biodegradable, and has a higher flash point [15], reducing the risk of hazardous spills and fires in the event of an accident.

# Anaerobic Digester Technical Analysis

Anaerobic digestion (AD) faces several challenges that impact its efficiency, reliability, and environmental sustainability. One of the primary concerns is feedstock variability, as the physical characteristics of feedstock, such as size and moisture content, must be compatible with the digester technology. Excessively high or low moisture levels can hinder the feeding process and disrupt bacterial activity [4], affecting overall system performance. Furthermore, inhomogeneity of various variables, such as wastewater sludge or food waste, within the same feedstock can contribute to fluctuations in process efficiency, making it difficult to maintain stable operation and reducing the operational efficiency of the technology.

Another significant challenge is low process efficiency, as anaerobic digestion relies on four groups of bacteria working sequentially through four stages of degradation [4]. Each bacterial group requires specific conditions, including temperature, pH, and carbon-to-nitrogen (C/N) ratio, to function optimally. Disruptions at any stage can create cascading effects, reducing overall system efficiency. The accumulation of intermediate compounds such as $NH_3$, VFAs and

LCFAs can inhibit microbial activity [4]. When $NH_3$ exceeds a critical threshold, it becomes toxic to methanogens, which are responsible for consuming VFAs, leading to an imbalance in the process. This results in further VFA accumulation, reduced pH, and decreased methane production, ultimately lowering the efficiency of the digester.

The low quality of the products also presents challenges. Biogas has a lower calorific value compared to natural gas, especially when the $CO_2$ content exceeds 40% [4], reducing its specific energy. Digestate, which consists of unconverted organic material, is often used as a fertiliser due to its nutrient content. However, its high moisture content necessitates solid-liquid separation for easier transportation and storage. Additionally, managing large volumes of digestate remains a logistical challenge [4], requiring expensive, energy- intensive post-treatment processes to create valuable products.

Finally, beyond operational challenges, anaerobic digestion raises environmental concerns. While AD prevents methane from directly escaping into the atmosphere by capturing and utilising biogas, its combustion for energy production still generates other air pollutants such as carbon monoxide, nitrogen oxides, and sulfur dioxide [16]. Another critical issue is the risk of toxic spills, as seen in 2019 when an anaerobic digestate spill in a UK river resulted in the deaths of over 10,000 fish [16]. The UK's Environment Agency has reported a significant increase in severe pollution incidents over recent years, with a rise of more than 50% annually being reported in some years [16].

These inherent challenges are difficult to address, but researchers have been looking into new ways to combat them. For instance, Anaerobic co-digestion enables additional feedstock, including food waste and agricultural residuals, to be processed and generate 87 $TWh^{-1}$ of electricity. The addition of biochar to the digestion process will further improve its efficiency by "facilitating microbial colonisation and increasing nutrient retention" as it can enhance buffering capacity and increase methane production, making it a great solution for single-waste digestion. Further research will be needed to address the lingering issues and for the anaerobic digester to be considered an enticing alternative. The UK government should also implement policies that would ensure the safe implementation and operation of the anaerobic digester and encourage the transition to sustainable practices [17].

# Anaerobic Digester Economic Analysis

As of 2023, the UK currently possesses 723 operational anaerobic digestion (AD) plants of which are estimated to achieve a Biogas production rate of 20 TWh (terawatt- hours) annually. The projected growth of biogas production by 2030 is estimated to increase to 55TWh annually. Corresponding to the creation of 30,000 jobs directly and 30,000 jobs indirectly. Subsequently achieving a 27 MtCO2eq (million tons of $CO_2$ equivalent) [18] reduction in emissions.

The listed benefits and projected data undisputedly demonstrate the positive impact continued adoption of anaerobic digesters will have on the UK's agriculture industry and the environment. However, it is also important to consider it on an individual basis and evaluate the commensurate advantages and difficulties faced by British farmers. The economic potential of a plant depends heavily on the current scale of the farm of interest. Smaller AD plants, 100 kW to 1MW capacities, require a capital cost investment of £500,000 - £2.5 million; larger commercial plants are again estimated to exceed £10 million [19]. Larger- scale farms can mitigate this substantial investment with their access to a wider feedstock of manure, crop and food waste to ensure they can operate their plant at full capacity to maximise energy production. Considering a plant which processes 30,000 tons per year, the sale of electricity, digestate by-products for fertilisers and gate fees could garner a profit of up to £125,000 annually [20]. Conversely, the size of this substantial capital investment, along with their inability to operate the plant efficiently, may exclude many small farms from adopting this technology. They likely produce an insufficient feedstock to maximise capacity and lack sufficient on-site demand to consume the energy produced. Without a further investment in extensive infrastructure that facilitates the export of surplus production, it will likely be wasted. Contradictory government policy decisions have acted as a further impediment to AD's adoption. The dissolution of schemes such as Feed-in-Tariff and Renewable Heat Incentive (RHI) has further disadvantaged smaller farmers [21]. The economic barrier disproportionately affects smaller farmers and is a major barrier to the adoption of the technology.

# Outlook and Conclusion

To incentivise the adoption of anaerobic digesters within the UK's agriculture industry, the government should aim to introduce a series of regulatory measures, such as tax incentives and subsidies, to help farmers. To further expedite the process, they could implement streamlined planning permission for the construction of new AD plants and simultaneously enforce stricter limits on methane emission rates. An integrated approach with both the impact on the individual and the industry must be considered to ensure the future success of the technology. Although it may benefit the industry environmentally, if it is not economically viable for farmers on a personal level, then it can never be widely implemented and will harm the livelihoods of many individuals. The change must not be forced heavy-handedly but rather will take time and encouragement. The continued spread of information about both the major environmental crisis currently faced and the vital role anaerobic digesters may take will be conducive to this end.

# DEEP GEOTHERMAL ENERGY FOR THE UK

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# Summary

Geothermal energy is a reliable and consistent source of low-carbon, renewable energy and heat. It has a low spatial footprint and is always available, independent of the weather. Moreover, many electricity generation schemes can also provide heat - 'combined heat and power'. Across the UK, a range of different technologies have the potential to be deployed to extract geothermal energy, outlined in Figure 1.

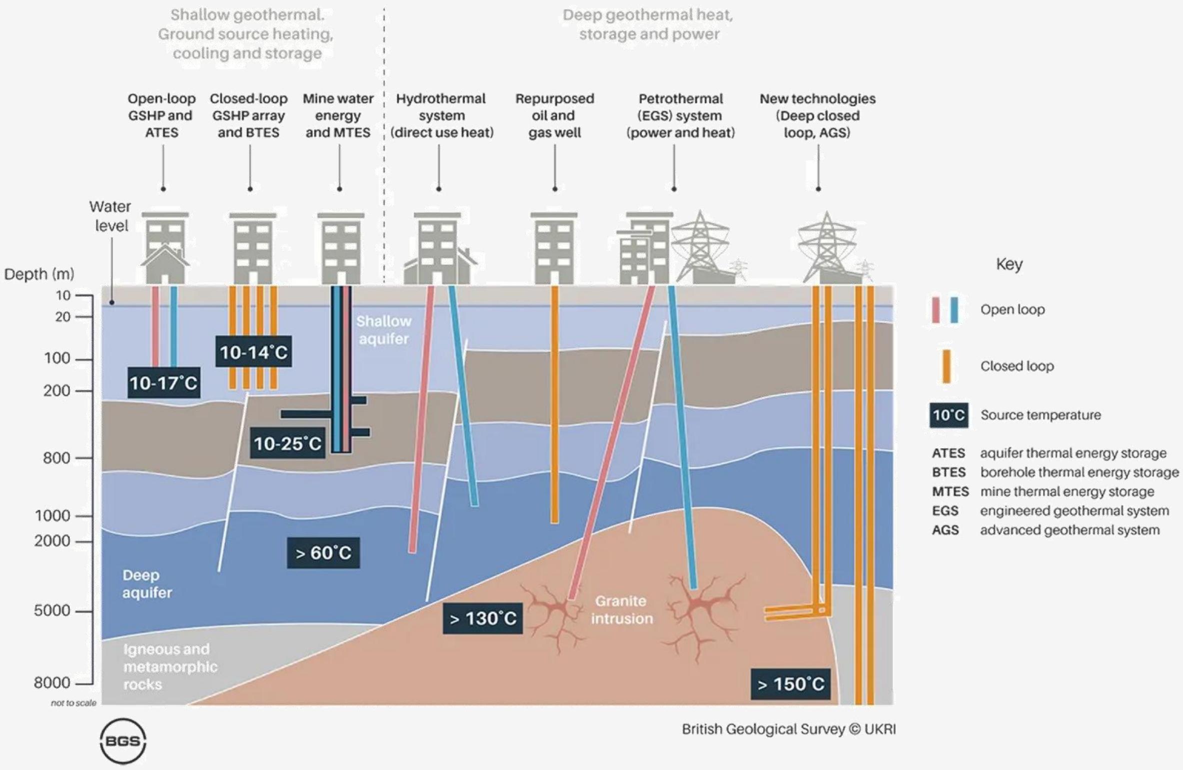


Figure 1. Current geothermal energy extraction technologies in the UK (British Geological Survey).

This report assesses how geothermal energy is used in the UK and the world currently and how it could be used in the future. The **Appendices** go into more detail, covering specific case studies, comparing geothermal potential between regions of the UK and explaining the challenges facing geothermal energy in more detail. The report concludes that geothermal energy is mostly held back by lack of government-led initiatives, despite the latent potential of the technology.

# Introduction

Deep geothermal systems require the drilling of deep wells (>500m) to reach high temperature sources. Although the UK has significant deep geothermal potential in deep sedimentary basins, the current high cost of drilling restricts the areas in which geothermal exploitation is economically viable. Moreover, estimating the economically usable fraction of heat has not yet been possible as more detailed knowledge of the deep surface sources is needed.

There are also geological and financial risks inherent to geothermal projects, which have been identified by stakeholders as a significant barrier. Alongside easier access to project finance, better financial support and risk-sharing mechanisms like those in other European countries can drive development.

New deep geothermal projects could provide an opportunity to transition skills, knowledge and economic activity from the oil and gas sector to renewable technology as the UK moves towards net zero. Projects can contribute to economic growth and boost the local economy, particularly in areas of economic hardship.

# The Present

To comprehend the potential of deep geothermal energy in the UK, it is important to understand the current scope of deep geothermal energy both nationally and globally.

## *How is deep geothermal energy used in the UK now?*

Geothermal heat provides only a small fraction of the UK's total heat demand (0.3% in 2021), yet has one of the lowest carbon footprints compared to other technologies, and could be connected directly into the UK's existing district heating networks. It is estimated that an individual heating project could deliver savings of 2,400-14,000 tonnes of $CO_2$ equivalent per year, equivalent to the emissions of up to 5100 households. The UK's only deep geothermal well for heat is the Eden Geothermal Energy Project (Eden Geothermal). Its primary purpose is as an industrial research project to improve our understanding of deep geothermal, especially in the Cornwall region which has been shown to have particular potential.

Likewise, geothermal electricity generation remains a realm of untapped potential in the UK. As of writing, the only geothermal electricity generation plant under construction in the UK is the United Downs Deep Geothermal Power (UDDGP) project in Redruth, Cornwall (Cariaga, 2024). The plant is expected to generate enough to power 10,000 homes (M., n.d.) and save over 6,500 tonnes of $CO_2$ emissions per year compared to conventional fossil fuel power plants (Gordon, 2024). However, its opening was delayed from late 2024 to early 2025 (Lomax, 2024), with no further updates as of late.

Deep geothermal heat is often co-generated from electricity projects, and could directly complement air and ground-source heat pumps to provide a local and flexible base load for all sectors. The public sector estate is a key target for geothermal heating, given the high heat demand and predictable requirements of large buildings such as hospitals and prisons.

### *How is deep geothermal energy used in the rest of the world?*

The feasibility of deep geothermal energy for heating has been demonstrated across Europe - in Paris, 18% of homes are heated by two deep water aquifers via 50 heating networks (Abesser et al.). The Netherlands has seen an increase from 7 to 31 deep geothermal projects in the last 10 years driven by strong government commitment in the form of clear targets and and policy support measures. Similar strategies could be employed in the UK to drive growth in new geothermal projects, including a simplification of the regulatory framework and a guarantee scheme on drilling risks to increase the competitiveness of the technology.

Other countries have also demonstrated geothermal electricity generation as a means of reducing their carbon footprint. The US installed nearly 4 GWe of geothermal electricity in 2022 (Boyd, 2024, 174), where one geothermal power plant emits roughly 35 times less $CO_2$ per kWh of electricity generated compared to a traditional coal power plant. The aggregate contribution of geothermal power plants led to an annual offset of 22 megatonnes of $CO_2$, 200 gigatonnes of nitrous oxides and 110 kilotonnes of particulates from coal-powered plants in the US (Center for Sustainable Systems, University of Michigan, 2024).

# The Future

An assessment of the future potential of deep geothermal energy in the UK is critical, and can be considered across three key questions. Does the UK have suitable and accessible resources? How can the UK benefit from deep geothermal energy? What hurdles are stopping such a rollout?

### *Does the UK have suitable and accessible resources?*

Only a selection of deep geothermal reservoirs, with high enough temperatures and sufficient energy capacity, are suitable for electricity generation. Geological conditions are equally important: permeable geological conditions are needed for hydrothermal reservoirs, while the rock layers need to be fracturable to create flow paths in petrothermal systems, Nevertheless, various geological studies have helped identify potential deep geothermal hotspots. The most promising are found in central England around Yorkshire and Lincolnshire UK, and southern England around Dorset, Hampshire, and Sussex, offering a mix of Palaeozoic and Mesozoic basins with temperatures beyond 60°C and depths greater than 2km (see **Appendix** for breakdown of UK geothermal resources). Overall, UK geothermal resources alone can produce up to 200% of UK electricity needs.

## *How can the UK benefit from deep geothermal energy?*

The economic and sustainability-related benefits of deep geothermal energy to the UK are currently severely underestimated. Geothermal energy is entirely renewable, with carbon footprints comparable or even lower than more commonly used renewable energy resources like wind and solar. However, its major advantage is temporal reliability: because it is not sensitive to weather conditions unlike wind and solar energy, it is an excellent fallback supply when other weather-sensitive resources are low. Economic benefits are both local and national. Many deep geothermal hotspots coincide with areas of economic hardship, and power plant construction in these areas will bring jobs and offer cheap energy to the area, supporting local development. Fully exploiting the current technology of pad drilling can provide the UK with 20% of its electricity needs. Note that electricity generation is energy and water intensive, and hot-water generation at these power plants could supply a significant portion of home heating.

## *What barriers halt deep geothermal energy in the UK?*

Worryingly, the UK is underperforming in deep geothermal rollout. Deep geothermal projects require high initial capital expenditure, primarily due to drilling. Drilling costs have also been estimated to be higher for wells in the UK than our European neighbours. Consequently, government support is hesitant, inadequate and has little to show. However, the challenge is fundamentally eco-political and not technological. Regulations, funding, investment, supply chain logistics, and data availability sit at the crux of the problem. A clear and actionable governmental initiative, with the following critical components, is required. It must lead the discussion between researchers, financiers, and consumers. It must standardise business models and support investors against financial risk. It must put in place and enforce regulation and legislation.

The potential to combat climate change through deep geothermal technology is promising. Compared to other renewables, the stability and predictability of deep geothermal power generation presents an invaluable opportunity to diversify and secure the UK’s energy portfolio. Therefore, more government support in developing deep geothermal energy in the UK is essential.

# Conclusion

Deep geothermal energy development in the UK shows underperformance, despite strong incentives. Only two sites are under development: the UDDGP under construction and the Eden Project, which lacks grid connection. Given plentiful and accessible natural resources, attractive economic and environmental benefits, and favourable international experience favourable; the question is not whether the UK should invest in deep geothermal energy, but why has the UK not done so? The primary factor that emerges from this report is the lack of government-led initiative, both economically and socially. Insufficient governmental support nullifies incentives to accrue critical geothermal data, invest in deep geothermal technology, and rally conversation between stakeholders, experts, and policy-makers, and without legal regulation progress is difficult. International experience has demonstrated the potential of a functional and well-rounded governmental-spearheaded geothermal initiative, and would mark a tough but critical milestone in the UK's path to net zero.

# ALTERNATIVE FUELS FOR THE SHIPPING INDUSTRY

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June 30, 2025

IMPERIAL

# Summary

Maritime shipping consumes around 400 megatons of petroleum fuels yearly and corresponds to 80% of world good transport by volume (Tan et al., 2022). This fuel consumption is expected to double by 2030, with no alternative for bulk international shipping. Many countries are seeking to decrease the impact of shipping as it corresponds to around 3% of global yearly CO2 emissions (Watanabe, Cherubini and Cavalett, 2022), with most goals aiming for a net zero by 2050. This research paper reviews the application of hydrogen, ammonia, and biofuels in the shipping industry.

Hydrogen is a promising alternative due to its high energy density with costs and supporting infrastructure being the main drawbacks. Biofuels, especially when mixed with conventional fuels, are already commonly used in many transportation industries and can be used in container ships. However, cheaper production pathways need to be developed to make them cost effective. Finally, ammonia has established manufacturing and distribution, but more work needs to be done to remove harmful $NO_x$ gasses from its vapour before it is used.

# Hydrogen

## *Introduction*

'Is hydrogen worth the hype?' is a topic debated by many news media and organisations. With limited production of green hydrogen, high cost and scarce application in daily life, recently there are more speculations that hydrogen is not the future of energy it once promised to be. There are several key advantages of hydrogen, starting with the quick refuelling time. For example, to recharge an FCV it takes around 5 minutes, which is equivalent to current ones powered by internal combustion engines. Yet the main advantage of hydrogen is its versatility, as it can be used in a very wide range of fields, from agriculture to power supply, chemical production to transportation.

Hydrogen production and storage will be investigated in the **Appendix D2**, along with the mechanism of a suitable method of application of hydrogen in shipping. The summary of the method along with its advantages and weaknesses will be reviewed below.

## *Method for application of hydrogen in shipping industry*

For the maritime industry using hydrogen, hydrogen combustion engines or hydrogen fuel cells are both theoretically possible and environmental-friendly relative to the heat engine used currently. In this investigation, we will focus on hydrogen fuel cells. Not only that it is more popular in transportation industries, but the technology is also more advanced and has lower safety concerns.

There are a few types of hydrogen fuel cells to choose from, for example alkaline fuel cells (AFCs), molten carbonate fuel cells (MCFCs), proton-exchange membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs), and solid oxide fuel cells (SOFCs).

Table 1. Comparison between types of fuel cells (Ohta, 2009) (Tse et al., 2011) (Peng et al., 2021) (Han et al., 2016) (Wagner et al., 2023)

| Type of Fuel Cells | AFC | MCFC | PAFC | SOFC | PEMFC |
|---|---|---|---|---|---|
| **Efficiency** | 61% | ~50% | 42.5% | ~60% | 40- 55% |
| **Operating Temperature(°C)** [1] | 100 | 550-700 | 200 | 700-1000 | 80-100 |

Among all types of hydrogen fuel cells, PEMFC is the most suitable as the operating temperature is lowest among all, allowing a faster start up time and related safety concerns, making it suitable technology for short distance transportation.

PEMFC is also shown to perform normally in extreme weather conditions, which a fast, successful start is still possible under 20-25°C (Tao et al., 2024) and is known for being silent and little to no vibration. With a short refuelling time, fuel cell vehicles (FCVs) gives a longer driving range against electric vehicles (EVs) with current technology, as it has higher energy density. Therefore, it can be deduced that ships with PEMFC have a reasonably long range. With the example of MV Sea Change, a net-zero PEMFC ship proven to work, PEMFC is undoubtedly one of the leading alternatives in green energy generation. This piece of exciting, cutting-edge technology is explained further in the **Appendix D2**.

## *Advantages of Hydrogen in shipping industry*

Starting with its advantage, hydrogen as the leading green energy has already been proven to be applicable in transportation sector, with established examples in shipping industry. As it has been deemed as the future of energy internationally, with the increasing number of projects regarding every aspect of hydrogen worldwide, there have been significant improvement in technology in this decade. It is more than likely that this rising source of energy would be more dominant in the age of net-zero, which the development in storage, production, transport and infrastructure would also accelerate the use of hydrogen in shipping. The advantages of PEMFC and the 3GW of hydrogen projects currently in the UK are explored in **Appendix D2**.

To sum up, hydrogen has huge potential as an energy generation method, with the rising of renewable energy, water electrolyser projects and applications of PEMFC. With the versatility of hydrogen allowing it to be used in many fields and sustainability property it has, the development of hydrogen is foreseen to be rapid which also accelerates the usage of hydrogen in UK ships. There are areas to be developed within different steps in hydrogen as alternative fuel, completely replacing current ones, including increase production by hydrolysis, building more supporting infrastructure, improving PEMFC design, etc., but nonetheless it has been proven to be a promising technology.

# Biofuels

## *Introduction and Overview*

Biofuels is a term coined to describe fuels made from biomass. They are categorised by the type used to produce them. First generation biofuels are made from crops, second generation from waste or byproducts and third generation from algae. There is many different processing methods used to produce them, and each resultant fuel has its own advantages and disadvantages. A deep dive into each generation biofuel is in the **Appendix D3**.

The main advantage presented by biofuels is the simplicity of their integration, many can be used in the same systems currently running ships either instead of or alongside petroleum fuels (Bengtsson, Fridell and Anderson, 2012). This makes them a good option to rapidly decarbonise shipping without the need to overhaul engine systems. The two main biofuel types used are liquified biogas and biodiesel, which are interchangeable with liquified natural gas and marine diesel oil. Current studies show that the use of biofuels can reduce shipping emissions from 65% to 87% (Watanabe, Cherubini and Cavalett, 2022) and greatly reduce particulate emissions. However, biofuels offer large concerns as well with biofuels being 50 to 100% more expensive than traditional fuels and having low energy density Bengtsson, Fridell and Anderson, 2012). These drawbacks have led to biofuels being dismissed as an option when considering long term decarbonisation.

In an industry study (Bach et al., 2021), it was found that pathway models estimated for a sector mix of 20% biofuels for decarbonisation by 2030. This is quite small considering that many ship owners consider that they will reduce biofuel use after the initial transition periods ends. Currently, there is minimal investment and developments in the sector, based off of a study of the norwegian market, few new patents in the biofuel sector have been filed in 2009. This, along with other factors, means that the price of biofuel is stagnating around $750/ton compared to the under $500/ton of fossil fuels. As technology is implemented, such as third generation biofuel production, this price is unlikely to decrease as algae is more expensive than current feedstock so over the short term (<20 years) the price will likely increase. This in turn will only alienate current biofuel users and investors. A deep dive into the production of biofuels, the costs, and the government regulations is included in the **Appendix D3**.

## *Conclusions*

The biofuel sector is well established, both in terms of technologies and production. There is opportunity for growth both in countries without existing renewable sectors, and in feedstock scaling. However most established sectors are unlikely to see significant growth, this is from a mix of regulations pushing for alternative fuel sources, expensive feedstock and production, and a lack of interest from the shipping industry. Most of the growth in the biofuel sector is likely to be focused on sustainable aviation fuel and road transport fuels, as biofuels have a good foothold in the latter already and the former is one of the more feasible ways to decarbonise aviation.

This is not to say biofuels won't be present in shipping in the coming years. The interchangeability of biofuels with fossil fuels is a large reason why they already are so established in all fuel industries. They allow for a simple alternative to fossil fuels, with the main downside being cost, and make a great transition fuel to renewable sources. Their role in shipping is likely to stay the same as it is now: a way to reduce emissions by mixing biofuels into fossil fuels. Increasing the ratio of biofuels is a simple way to reduce emissions and stay on track with goals, while other technologies can be developed and implemented.

Biofuels are a crucial part of the renewable fuel industry, and the main fuel alternative currently available to consumers. In order to keep them a good option, a focus has to be put onto shifting to different feedstocks and cheaper production pathways. This will help reduce cost and scale the biofuel industry up to meet increasing demand. They will likely stay a significant fuel in coming years as shipping is gradually decarbonised and will continue to contribute heavily to other transportation sectors.

# Ammonia

## *Introduction and Overview*

Ammonia is seen as an attractive option for alternative fuels in the shipping industry because of its relatively low greenhouse gas (GHG) emissions, high energy density (22.5MJ/kg) that is comparable to carbon-containing fuels, and competitive cost. It also already has an established and reliable infrastructure for production, storage and distribution due to its industrial use for fertiliser synthesis. Furthermore, it can be readily stored by cooling it to -33°C at atmospheric pressure and has a narrow flammability range to be stored onboard safely. These factors explain why ammonia is seen as one of the most promising low-emission fuel options, provided that safety and toxicity issues can be resolved.

## *Production of ammonia*

Most of the nearly 180 Mt of ammonia produced globally every year are generated via reforming of natural gas (72%) or coal (26%), resulting in approximately 500 Mt of carbon dioxide (CO2) emissions. This accounts for almost 2% of global $CO_2$ emissions, therefore new directions must be pursued to reduce the carbon footprint of ammonia production. These routes could involve using fossil fuel feedstocks with carbon capture, and storage (CCS) technologies (blue ammonia) or electrolytic hydrogen production using renewable feedstocks (green ammonia). Two methods of producing ammonia are discussed in detail in the **Appendix D4**.

## *Costs of Producing Ammonia*

The production costs of green ammonia is always higher than grey ammonia due to the higher energy consumption and high electricity prices caused by the capital cost of electrolysers.

However, it is expected that green ammonia will become cost competitive with market prices as the technology improves and subsidies are put into place. The increase in costs for blue ammonia is due to the high capital and operating costs associated with the carbon capture plant.

## *Current projects/future developments*

For ammonia to be an effective replacement for current fuels there is a fair amount of development required before it can be implemented on such a large scale, whilst still providing the positive benefits over current fuels. A key development needed is the engines compatible to use ammonia for propulsion. The leading examples of current projects globally:

- MAN Energy Solutions: The company has conducted trials using carbon-free ammonia as fuel with a two-stroke diesel engine and plans to provide ammonia propulsion for maritime operations by 2026.
- WinGD: Collaborating with Alfa Laval, WinGD has developed test systems for ammonia-fueled engines, including fuel valve trains and vent treatment systems. The Alfa Laval FCM Ammonia fuel supply system is expected to be validated by the end of 2024, with the first marine deliveries anticipated by the end of 2025. [ShipUniverse, 2025]

These developments are crucial for the integration of ammonia as a viable marine fuel. It would also be a huge step forward in order for ammonia to become a larger percentage of shipping fuels used, as without compatible engines, ships cannot transition to this fuel type. Furthermore, without the development in the combustion and emission control of adapted engines, we cannot limit the negative emissions non-green ammonia can cause.

Furthermore, many other forms of infrastructure must be developed to allow an increase in the use of ammonia in the industry safely. For example, global ports are beginning to prepare for ammonia bunkering, which is the process to store and supply ammonia to maritime vessels. Although this involves several safety considerations surrounding ammonias toxicity, deep regulations and operational challenges need to be overcome before these are implemented. Many developers are unsure of this as well as the fact that local considerations specific to each port need to be confronted before the large infrastructure is built.

Despite these challenges, the benefits of using ammonia are seen in industry and there is increasingly positive momentum favoring ammonia's usage in the future. Ammonia as an alternative is not seen as just hype but more of a long-term strategy for major players to decarbonise the shipping industry. The International Maritime Organisation has set absolute restrictions on greenhouse gas emissions to 20% below 2008 baseline levels in 2030, 70% in 2040 and net-zero in 2050. This increased pressure on maritime companies to reduce emissions will drive a dependence of using ammonia as an alternative.

Although we are not fully ready for this transition just yet, as with today's current technology the use of ammonia will result in the emission of nitrous oxide and $NO_x$ emissions, which are potent greenhouse gases and the leading cause of ozone depletion. Therefore, more development is required in these engines and exhaust management before ammonia can be implemented on a large scale as a replacement for fossil fuels.

The UK has only very recently (March 2025) accepted the world's first dual-fuelled ammonia-powered vessel to its shores. Our Maritime Minister has announced the UK SHORE programme, committed to supporting the technology and alternative fuels needed to make zero-emission shipping a reality and establishing the UK as a clean energy superpower. These initiatives are huge steps forward for the UK to develop the necessary technology to house the increased use of ammonia in the future.

# Conclusion

This report highlights the critical role that alternative fuels (biofuels, ammonia, hydrogen) must play in the decarbonisation on the shipping industry. Each fuel has its own distinct benefits and challenges. Biofuels provide an immediate solution that can be easily utilized with current infrastructure, though their long-term sustainability depends on a large variety of feedstock sources. Green hydrogen is a zero-carbon fuel with high energy density, but it faces high production costs and complex storage requirements. Green ammonia has an established infrastructure for manufacturing and distribution and simpler storage requirements, but development is required for safe handling of $NO_x$ emissions, and engine modifications.

To unlock the full potential of these fuels, the UK government must take a proactive and strategic role. Policy support should focus on maximising energy efficiency, directly mandating quotas of zero-carbon fuels in the shipping industry similar to the ReFuelEU Maritime regulations, scaling up production of zero-emission fuels, and investing in new vessels capable of running on zero-emission fuels.

Beyond policy that encourages the use of green fuels, care must be taken to develop production in the UK specifically. Many fuels used currently are shipped into the UK and transported by trucks to their location of use, which can counteract the impact of using green fuel in the first place. Hydrogen faces these issues the most, with the high volume required for fueling. Underground pipes have been suggested as an alternative method of transport for hydrogen (Department for Energy Security & Net Zero, 2023), which would reduce transport costs and efficiency – but this may be expensive to set up. The alternative to fuel transport is on-site production, examples of this with hydrogen already exist. These include either an on-site production of hydrogen by electrolyser, or a naphtha-based gas that contains high composition of hydrogen, which a denser gas is transported then separate by pressure swing adsorption in situ (Towngas, 2023). The simplest method is still to decarbonise road transport alongside shipping, but other routes must still be considered and explored.

The UK government is already falling behind as shipping sector emissions are only being included into the UK Emissions Trading Scheme (ETS) by 2026, while the EU ETS has included them from April 2023. A coordinated strategy that includes an optimal combination of the different types of fuels will position the UK as a global leader in maritime decarbonisation.

# POTENTIAL OF DIFFERENT GEOTHERMAL ENERGY SOURCES

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# Summary

Geothermal energy in the UK presents a promising yet complex pathway toward a sustainable and secure energy future. Although the initial capital investment is high, the long-term benefits of this renewable resource (from stable, continuous energy production to significant reductions in greenhouse gas emissions) make it a compelling option in the transition away from fossil fuels.

An evaluation of the following types of geothermal energy:

1. shallow source
2. mine water
3. petrothermal or EGS
4. hydrothermal geothermal energy

has been conducted, and conclusions have been reached about the current state of geothermal energy's availability and it's prospects in the future in terms of governmental regulations and financing.

By investigating the current growing trends in geothermal energy and heating consumption in the United Kingdom, as well as evaluating ongoing and planned geothermal projects in terms of financial viability and energy production and reliance both in the United Kingdom and globally, the intention was to identify potential sites for further geothermal research for district heating and energy generating schemes and the potential of this renewable source of energy in the future. **Appendix E** contains more information.

# Methods

## 1. *Shallow source geothermal energy*

Shallow-source geothermal energy harnesses the naturally stable temperatures found just below the Earth's surface to provide heating and cooling solutions. This technology, often implemented through ground-source heat pump systems, offers a renewable, low-impact alternative to conventional energy sources for residential, commercial, and industrial applications. Its accessibility and relatively lower installation costs compared to deep geothermal systems make it a promising option for reducing reliance on fossil fuels in urban environments.

### Costs

The development of geothermal energy involves significant exploration and development costs. Drilling, which forms a major portion of these expenses, can be prohibitively expensive. In addition, comprehensive geological surveys and feasibility studies are essential to identify suitable sites, with costs around £0.5 million per study and substantial annual investments needed to keep pace with technological advancements. Once a viable site is identified, the installation phase includes the construction of power plants and the procurement of specialized equipment such as turbines and heat exchangers, with reported installation costs in 2021 of around $3,991 per kW of energy produced. These systems typically have lower installation costs than deep systems and offer a high return on investment, especially in residential applications. International case studies suggest they can save up to £400–£700 per year per household, making them economically attractive in the long term.

Typical Cost Breakdown [23][24][25]:

- Drilling and Borehole Installation: 35%
- Heat Pump Installation: 30%
- Distribution System (Pipes, Radiators, etc.): 20%
- Monitoring and Maintenance: 10%
- Contingencies: 5%

## **2.** *Mine Water Geothermal Energy*

Mine water geothermal energy involves the use of water from abandoned, flooded coal mines to provide sustainable heating and cooling solutions. These mines, which are no longer in operation, often contain large volumes of water that have naturally warmed to temperatures between 10°C and 15°C. By utilizing heat pump systems, this energy can be extracted and used for heating residential, commercial, and industrial buildings, through open-loop configurations. This innovative approach capitalizes on existing underground infrastructure, reducing the need for new resource exploitation [2].

**Costs**

The financial aspect of mine water geothermal energy is pivotal in assessing its viability. The costs of establishing a mine water energy project are significant; for instance, the Lancaster Wines project required an investment of £3.5 million, with a payback period estimated at five years. A major advantage is that this energy source has been shown to deliver heat at 5% below the price of gas heating, offering substantial savings, especially during a cost-of-living crisis. However, the upfront costs and inherent risks have limited its application primarily to large-scale housing developments. Current feasibility studies suggest that a minimum of 1,500 homes is necessary for a district heating scheme powered by mine water energy to be economically viable.

Typical Cost Breakdown [23][24][25]:

- Drilling and Exploration: 30%
- Heat Pump Installation: 25%
- Network Infrastructure: 20%
- Maintenance and Monitoring: 15%

- Contingencies: 10%

## 3. *Deep Geothermal Energy - Petrothermal Energy and Enhanced Geothermal Systems (EGS)*

Petrothermal energy is a type of geothermal energy that exploits the heat stored in hot dry rocks (HDR) deep within the Earth's crust. Unlike conventional geothermal systems, which rely on naturally occurring reservoirs of water and steam, petrothermal systems involve creating an artificial geothermal reservoir by injecting water into deep, hot, dry rock formations to extract heat by harnessing existing or artificial fractures and planes of weakness. This process expands the scope of geothermal energy, allowing its use in regions without natural geothermal reservoirs, and could be instrumental in achieving the UK's carbon neutral goals by unlocking the untapped energy beneath its geological formations.

**Costs**

Deep geothermal energy systems involve substantial initial investments, primarily due to the complexities of deep drilling and reservoir development. Drilling costs alone can constitute over half of the total capital expenditure, with expenses reaching approximately $10 million per well, and a 20% failure rate further elevating financial risks. The National Renewable Energy Laboratory (NREL) estimates that the average overnight capital costs for near-hydrothermal field EGS range between $7,770/kW and $22,501/kW, while deep EGS projects (3 km to 6 km depth) can escalate to $20,848/kW to $49,155/kW.

Despite these high upfront costs, EGS offers the advantage of providing continuous, reliable baseload power with minimal operating expenses, as it does not require fuel inputs. Ongoing technological advancements and increased investment are anticipated to reduce these costs over time, enhancing the economic feasibility of deep geothermal energy [3]. Petrothermal and Enhanced Geothermal Systems involve very high initial capital costs, with drilling alone reaching up to $10 million per well and failure risks adding further financial uncertainty. However, once operational, they provide continuous baseload energy and low operating costs, offering strong ROI over longer periods, especially as technologies advance.

Typical Cost Breakdown [23][24][25]:

- Drilling and Well Construction: 50%
- Reservoir Stimulation (e.g., hydraulic fracturing): 20%
- Power Plant Infrastructure (turbines, heat exchangers): 15%
- Monitoring, Seismic & Environmental Systems: 10%
- Contingencies: 5%

## 4. *Deep Geothermal Energy - Hydrothermal energy*

Hydrothermal geothermal energy refers to geothermal systems that use naturally occurring hot water or steam trapped in underground reservoirs. These resources form when groundwater is heated by the Earth's internal heat and becomes stored in porous rocks or fractures. Hydrothermal systems are the most commonly used type of geothermal energy and can be tapped for electricity generation or direct heating, depending on the temperature and pressure of the fluid.

**Costs**

Petrothermal projects face high upfront capital costs. However, it's important to note that drilling technology often faces limitations beyond 175°C due to the sensitivity of onboard electronics, which can constrain access to ultra-high-temperature reservoirs and increase engineering complexity. For example, a Durham, UK proposal estimated constructing four 9.5 km wells at $143 million to produce 13 MWe, resulting in an LCOE of about £115/MWh [4]

Additionally, extensive resource assessments—costing around £0.5 million per study, totaling roughly £25 million annually—are necessary [6]. Installation expenses include building the power plant and procuring equipment like turbines and heat exchangers, with IRENA reporting an installed cost of $3,991 per kW in 2021. Despite these high initial investments, geothermal power benefits from low operational costs and provides a stable, continuous energy supply, in contrast to the lower upfront but intermittent output of wind and solar [7]. Hydrothermal systems, such as the Southampton District Energy Scheme, offer more moderate costs compared to EGS, but are geologically limited to specific regions. They still offer stable long-term returns by utilizing natural aquifers with minimal additional development.

Typical Cost Breakdown [23][24][25]:

- Exploration and Drilling: 40%
- Power Generation Equipment (binary/flash systems): 25%
- Surface Infrastructure & Distribution: 20%
- Monitoring and Operations: 10%
- Contingencies: 5%

# Conclusion

Geothermal energy is an especially promising energy source and a sustainable solution for meeting our climate goals, as well as our heating and electricity needs. With multiple geothermal technologies available and constant engineering and technological advancements in the field, it truly holds great potential. Shallow geothermal systems and mine water heating provide cost-effective and scalable district and residential heating options through the use of heat pumps, offering favourable returns on investment (ROIs).

On the other hand, deep geothermal systems, which harness underground aquifers (hydrothermal systems) or utilise either artificial or existing fractures in high-temperature rocks (EGS and petrothermal systems), can be efficient enough for electricity production as well. These systems pose great potential for industrial use in sectors with intermediate energy consumption. However, these technologies require substantial initial investments due to the high costs of exploration, drilling, and reservoir development. Despite this, they remain favourable in the long term, thanks to lower operating costs and a continuous energy supply once operational.

A friendlier political and financial environment, combined with the United Kingdom's advantageous geological and geothermal conditions, not to mention cutting-edge technological advancements, could significantly boost this energy sector. In the short term, shallow source and mine water geothermal energy systems remain the most financially, economically, and energetically viable options. Ultimately, successful deployment will depend on strategic investment, streamlined regulations, and increased public and governmental awareness of geothermal energy's benefits and challenges.

# SOLAR SOLUTIONS FOR THE SHIPPING INDUSTRY

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# Summary

The UK transport industry emitted 148 $MtCO_2e$ in 2023, with 11.6 $MtCO_2e$ from shipping. While specific UK shipping energy demand data is unavailable, the global shipping industry consumed 8.7 exajoules in 2021, all from fossil fuels. Given shipping's essential role in goods transportation, reducing its emissions is crucial to achieving Net Zero by 2050.

This report explores four key mechanisms that utilize solar energy for fuel production and maritime applications: solar-powered fuel synthesis, battery energy storage systems (BESS) with hydrogen integration, direct solar propulsion, and supplementary solar photovoltaic (PV) systems. Each mechanism uses solar energy in a unique way, combining it with other technologies to address different energy demands, vessel sizes, and operational environments.

It concludes that supplementary PV systems are the simplest to install and have the quickest payback period at the cost of less savings in emissions Solar-power fuel production is deemed the most promising for long range trips despite the large area requirements and large capital expenditure, whilst BESS with hydrogen integration and direct solar propulsion remain solutions better suited to niche short range trips.

This report has an **Appendix** for each method. Feel free to look at these for more information on any technology.

# Methods

## *1. Solar-Powered Fuel Production*

This technology uses concentrated solar power (CSP) to drive thermochemical reactions that transform carbon dioxide ($CO_2$) and water ($H_2O$) into synthetic hydrocarbon fuels, such as synthetic diesel or jet fuel.

A key case study is Synhelion, which has developed and tested this technology using AI-optimized heliostats, advanced thermal storage, and novel redox materials (chemicals that repeatedly undergo oxidation and reduction) selected through quantum simulations. The entire process is carbon-neutral, as it recycles $CO_2$ from industrial sources or direct air capture.

## *2. Battery Energy Storage Systems (BESS) with Hydrogen Integration*

Used on vessels like the Energy Observer, this system combines solar panels, lithium-ion batteries, electrolysers, and hydrogen fuel cells into a single energy ecosystem that ensures both clean energy generation and long-term storage. Here's how it works:

- Solar Energy Capture and Storage: Photovoltaic (PV) panels convert sunlight into electricity which is stored in lithium-ion batteries.

- Electrolysis and Hydrogen Storage: When solar power exceeds immediate needs, it is used to split water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$) via electrolysis. Stored hydrogen is later used in proton exchange membrane (PEM) fuel cells, where it reacts with oxygen to generate electricity, heat, and water.

This layered system allows for short-term flexibility through batteries and long-term reliability through hydrogen storage. It reduces noise, eliminates fossil fuels, and supports autonomy in remote or protected marine environments. However, system integration is complex, requiring robust control systems (like SCADA and EMS), specialized crew training, and careful hydrogen handling due to its high flammability and low density.

## *3. Direct Solar Propulsion*

This mechanism, as demonstrated by PlanetSolar, uses solar panels to power electric motors directly, without relying on combustion engines or hybrid systems. The system includes photovoltaic panels and electric motors.

PlanetSolar showcased the feasibility of a 100% solar-powered transoceanic voyage, proving that fuel-free and emission-free navigation is possible. However, solar energy's low power density (typically 100–250 $W/m^2$ under ideal conditions) means that very large panel areas are required for modest propulsion. This limits its use to small vessels with low-speed requirements (e.g., 5 knots cruise speed), and it is not scalable for large cargo ships that need megawatts of power.

## *4. Supplementary Solar PV Systems*

In this approach, solar energy is used to support auxiliary electrical systems—not propulsion—aboard conventional ships. For example, the Auriga Leader uses a solar array (~40 kW capacity) integrated with a hybrid power system that includes diesel generators and nickel-metal hydride (NiMH) batteries.

While solar panels on large ships contribute only a small fraction of total energy needs (~0.3%), they offer measurable fuel savings and lower emissions. However, they are affected by space constraints, salt corrosion, shading, and alignment challenges at sea.

Table 1: Summary of our technical findings.

| Mechanism | Primary Function | Energy Storage | Scalability | Emissions | Challenges |
|---|---|---|---|---|---|
| **Solar-Powered Fuel** | *Synthetic fuel production* | *Thermal & chemical* | *High (industrial)* | *Net-zero* | *Land use, solar intermittency* |
| **BESS + Hydrogen Integration** | *Zero-emission propulsion & storage* | *Batteries + hydrogen* | *Medium (modular)* | *Zero* | *System complexity, hydrogen storage* |
| **Direct Solar Propulsion** | *Pure solar-powered navigation* | *Batteries* | *Low (small vessels)* | *Zero* | *Low power density, range limits* |
| **Supplementary Solar PV** | *Support ship electrical systems* | *Batteries (NiMH)* | *Medium (retrofit)* | *Reduced* | *Low contribution, marine wear* |

# Technical and Economic Feasibility Comparison

Evaluating solar-powered alternatives for maritime applications requires considering both technological maturity and financial viability. While each solution has a role, they differ significantly in scalability, efficiency, and cost-effectiveness depending on the vessel type and operational profile.

## *1. Solar-powered Fuel*

**Technical Feasibility**

Solar fuel offers a technically feasible pathway to carbon-neutral liquid fuels using concentrated solar energy to drive thermochemical reactions. Producing 1 liter of solar diesel requires between 26–38 kWh of solar input, depending on system efficiency. For industrial-scale operations, this translates into a land use requirement of approximately 0.5–1.1 km² per 100 barrels/day, which aligns with Synhelion's pilot project estimates.

**Economic Feasibility**

Target production costs range from $1.00–$1.10 per litre, primarily due to capital costs and the energy-intensive process. Compared to current diesel prices (~$0.30–$0.40/L), this is around 2.5 to 3 times more expensive. However, applying a carbon tax of $100/tonne $CO_2$ could bring effective costs down to around $0.83/L, significantly improving competitiveness.

## *2. Battery Energy Storage Systems*

**Technical Feasibility**
Batteries are highly efficient, offering 90% round-trip efficiency, and well-suited to small vessels or auxiliary power. A typical 1 MWh system can power a small electric vessel for about 12 hours at cruise speed. However, scaling to larger vessels becomes impractical due to weight and volume constraints—a 10 MWh system could weigh over 67 tons.

**Economic Feasibility**
With marine battery systems now costing around $150–200/kWh, a 1 MWh installation would cost approximately $200,000. Over its lifespan (≈4 GWh of total energy delivered), the levelized cost can be as low as $0.05 per kWh, five times cheaper than generating electricity from diesel (~$0.25/kWh). Moreover, using 1 MWh of battery power per day avoids up to 210 tons of $CO_2$ per year, offering further value under carbon pricing.

## *3. Direct Solar Propulsion*

**Technical Feasibility**
Direct solar propulsion, where PV panels drive electric motors, is viable for small vessels. Generating 40 kW of power—enough for basic propulsion—requires around 1,000 $m^2$ of solar panels. For large ships needing several megawatts, the required surface area (200,000–300,000 $m^2$) vastly exceeds available deck space, limiting this method to niche use cases like research vessels or recreational boats.

**Economic Feasibility**
For small-scale vessels, installing solar propulsion systems costs roughly $144,000, including PV and battery storage. If used regularly, the payback period can be just a few years, assuming fuel savings of $900/day. For less intensive use, the return on investment may extend to several decades.

## *4. Supplementary Solar PV Systems*

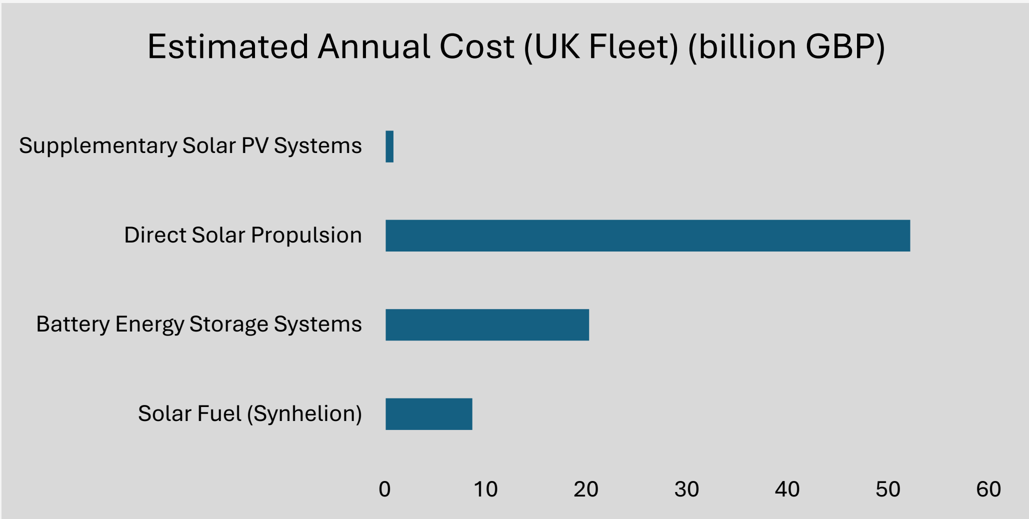
**Technical Feasibility**
Large cargo ships can host 5,000–10,000 $m^2$ of PV panels, enough to generate around 300 kW under ideal conditions. While this isn't sufficient for propulsion, it can meaningfully offset auxiliary loads (e.g., lighting, HVAC, navigation), improving overall vessel efficiency and reducing generator use.

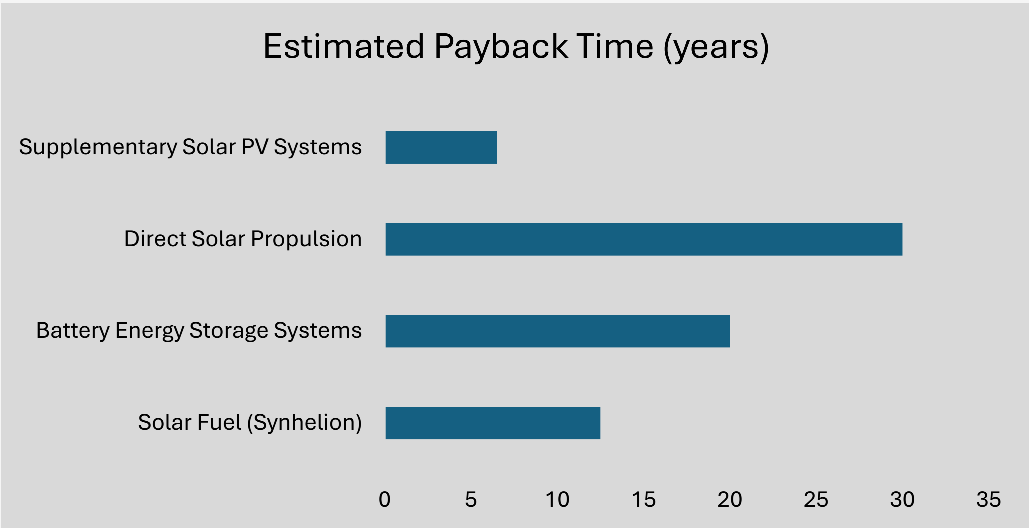
**Economic Feasibility**
A 300 kW marine-grade PV system costs about $585,000, including installation. If it offsets just 5% of daily fuel use, the annual fuel savings could exceed $900,000, yielding a payback period of less than one year. Even with more conservative assumptions, returns within 6–7 years are achievable. Environmentally, the system can avoid over 300 tonnes of $CO_2$ per year, further supporting green credentials.

Table 2: Summary of costs; see **appendix** for details of calculation.

| Method | Estimated Annual Cost (UK Fleet) (billion GBP) | $CO_2$ Reduction Potential ($MtCO_2$) | Estimated Payback Time (years) |
|---|---|---|---|
| **Solar Fuel (Synhelion)** | *5.8–11.6 [1]* | *~11.6 [2]* | *~10–15 [3]* |
| **Battery Energy Storage Systems** | *17.4–23.2 [4]* | *~11.6 [2]* | *~15–25 [5]* |
| **Direct Solar Propulsion** | *46.4–58.0 [6]* | *~11.6 [2]* | *>30 [6]* |
| **Supplementary Solar PV Systems** | *0.58–1.16 [7]* | *~1.16 [8]* | *~5–8 [7]* |

# Summarising Figures



# Conclusion

While all four solar-powered technologies offer promising routes toward decarbonising maritime energy, their suitability varies significantly depending on vessel type, operational range, and economic priorities.

**Solar fuels** stand out for their compatibility with existing marine infrastructure and long-distance voyages, offering an energy-dense, drop-in alternative to fossil diesel. However, their high production cost and large area requirements currently limit widespread adoption—though future scaling and carbon pricing could close this gap.

**Battery storage** delivers excellent efficiency and low lifecycle energy costs, making it a solution for short-haul trips. Yet, its limitations in energy density and onboard weight make it impractical for large-scale propulsion on ocean-going vessels.

**Direct solar propulsion** shows clear feasibility for small or slow-moving vessels but faces severe space and energy constraints at commercial scale. It remains a niche solution with limited application to large ships.

**Supplementary PV systems** provide a practical and cost-effective way to reduce fuel consumption and emissions, especially when used to offset auxiliary loads. While not sufficient for propulsion, they offer some of the quickest financial returns and environmental benefits from all the options assessed.

In summary, there is no single "one-size-fits-all" solar energy solution for maritime applications. Instead, a hybrid approach, combining solar PV, batteries, and potentially solar fuels, offers the most flexible and realistic path forward—balancing near-term feasibility with long-term sustainability.

# ENERGY STORAGE

# LONG TERM FEASIBILITY OF LFP BATTERIES FOR ENERGY STORAGE

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# Summary

The increasing reliance on renewable energy sources requires the development of energy storage technologies that are both efficient and sustainable. Lithium iron phosphate (LFP) batteries have emerged as a potential option due to their safety, cost-effectiveness, and environmental benefits. This study does a full lifecycle analysis, comparing LFP batteries against NMC and Na-ion alternatives. We assess their technical performance, economic feasibility, and long-term viability, particularly for grid-scale energy storage applications. Our findings emphasize LFP's advantages in terms of safety, longevity, and cost stability, whilst sodium-ion batteries show excellent flexibility to grid variations.

The study also looks at cascading use strategies for LFP batteries, such as second-life applications, and the importance of predictive life modelling with deep learning approaches. Economic feasibility research demonstrates a downward cost trend for LFPs, driven by advances in manufacturing and recycling technology. Solid-state batteries may outperform LFP in the future, but LFP is still a viable and scalable choice for energy storage today. This study offers important insights for policymakers, manufacturers, and energy stakeholders when choosing sustainable battery technologies for long-term deployment.

## Technological Comparison with NMCs:

Lithium-ion (Li-ion) batteries are the main type of commercial rechargeable battery, widely used in consumer electronics, electric vehicles (EVs) and renewable energy systems. There are many different types of lithium-ion batteries, of which 2 of the most used are Lithium Ion Phosphates (LFPs) and Nickel-Manganese-Cobalt (NMC) batteries. LFPs and NMCs are similar, meaning that in order to assess the use of LFPs, NMCs need to be considered as well. Below is a summary of the key differences between them, with more in-depth information on Li-ion batteries and each type given in **Appendix G1**.

Comparing LFP and NMC:

1. Energy density
   On average, NMC batteries have higher energy densities (150-200 Wh/kg) compared to LFP batteries (100-150 Wh/kg) [6] This makes NMC batteries better suited for applications requiring longer runtimes and more compact designs.

2. Cycle life
   LFP batteries have exceptionally long-life cycles. They can typically last up to 5000 or even 6000 charge-discharge cycles [30]. NMC batteries have shorter lifetimes, usually lasting around 2000-2500 charge-discharge cycles [30].

3. Cost

NMC batteries are more expensive than LFP batteries. This is because they require metals like Ni, Mn and Co. Cobalt is particularly expensive due to its volatile supply chain - around 70% of global Co production (as of 2021) is in the DRC (according to the UGS Mineral Commodity Summary), a country that is notoriously corrupt and unstable.

4. Safety
   LFP batteries are safer than NMC batteries due to their higher thermal stability and resistance to thermal runaway. Despite being chemically stable, NMC batteries also release Oxygen, which makes them vulnerable to catching fire or exploding. No such issue is there for LFP batteries [29]. LFP batteries showcase higher temperature tolerance than NMC batteries, being more able to operate at extreme temperatures [29].

Table 1: Strengths and weaknesses of LFPs and NMCs.

| Cathode Material | Strengths | Weaknesses |
|---|---|---|
| **Lithium Iron Phosphate (LFP)** | Very safe; tolerant to abuse<br>Acceptable thermal stability<br>High current rating<br>Long life cycle | Low energy density due to low operating voltage and energy capacity |
| **Lithium Nickel Manganese Cobalt Oxide (NMC)** | High energy density due to Ni<br>Low internal resistance due to Mn<br>Can be tailored to offer high energy density by varying composition of cathode | Ni has low stability<br>Mn offers low energy density<br>Very expensive due to the volatile supply chains of Co |

Source: Automotive Batteries 101, WMG University of Warwick (2018)

Another important aspect of battery technology is waste management. This is a huge concern around Li-ion batteries and therefore an LCA would not be complete without it. A whole section on the waste management of Li-ion batteries can be found in **Appendix G2.**

## Feasibility Comparison with Na-ion Batteries

### Technical feasibility

The role of a grid-scale storage system is to store energy and resupply it back to the grid when needed. This is especially useful as we move towards the renewable sector for power generation, for example when harnessing solar or wind power, where energy outputs are dependent on the weather and other uncontrollable factors. For example, solar power will have greater output during the daytime, and the storage system will be charged and then resupply the power to the grid when demand rises. [10]

What factors make a good grid-scale storage solution? [11]

1. **High energy density**, this solution regardless of what technology is used, needs to be able to store large amounts of energy in a reasonably sized facility, in order to be significant enough to support the fluctuation of the grid.

2. **Specific cost of energy** (consider it £ per unit of energy stored), it needs to be economically feasible to build and financially sustainable to operate.

3. **Power output,** or more specifically rate of discharge, is how fast a battery can release its energy back to the grid. This dictates how quickly it can react to any fluctuations within the grid and to supply energy accordingly.

4. **Cycle life**, the number of times a battery can discharge and recharge before the capacity of this system falls below its functional threshold, caused by cell degradation. In the instance of LFP, it is typically caused by a loss in active material (i.e. the Lithium ions in the cell) due to electrode's structural changes. One of the causations is the growth of the SEI (solid electrolyte interphase), a crucial component of the battery, that decreases the active Li-ions present, leading to mechanical stress and increased resistance. [12]

5. **Round trip efficiency,** during the cycle of charging and discharging, some energy is released from the cycle, or absorbed due to internal resistance, electrochemical inefficiency, heat generation and other factors.

6. **Temperature tolerance**, when the cell is below the range, its capacity could decrease in turn due to the lower electrochemical reaction rates and increased internal resistance due to an excess of ionic mobility when above the range.[13]

In continuation of the previous comparison of the NMC and LFP, we will use the 'Energy storage technology and Cost characteristics report' [14] from 2019 etc., to compare which of the three technologies: LFP, sodium-ion, general NMC are most suitable for grid-scale storage

Table 2: Cell chemistry specifications.

| | LFP | Sodium-ion | NMC |
|---|---|---|---|
| **Energy density (Wh/kg)** | 90-120 | 75-160 | 150-220 |
| **Cost per energy (£/kW)** | 215 | 520 | 300 |
| **Max rate of charge [16]** | 1C (fully charged in 60 mins) | 3C (fully charged in 15 mins) | 1C (fully charged in 60 mins) |
| **Max rate of discharge [16]** | 15C (full output in 4 mins) | 20C (full output in 3 mins) | 10C (full output in 6 minutes) |
| **No. of cycles** | 2000-5000 | 1000-3000 | 1000-2000 |
| **Round trip efficiency** | 90-95% | 85-90% | 90-95% |
| **Functional temp. range [17]** | -20-60 °C | -40-100 °C | -20-60 °C |

Looking at the numerical data, Sodium-ion battery technology dominates in adaptability in fluctuation (as demonstrated in the charging and discharging rates) as well as adaptability in different temperature environments, which makes it the best option in terms of performance. However, cost will also be a major consideration, with LFP and NMC available at a cut of sodium-ion's cost. However, LFP would be the better intermediate alternative of the two, as it has a much greater cycle life which will require less replacement in the long term, hence a lower maintenance cost.

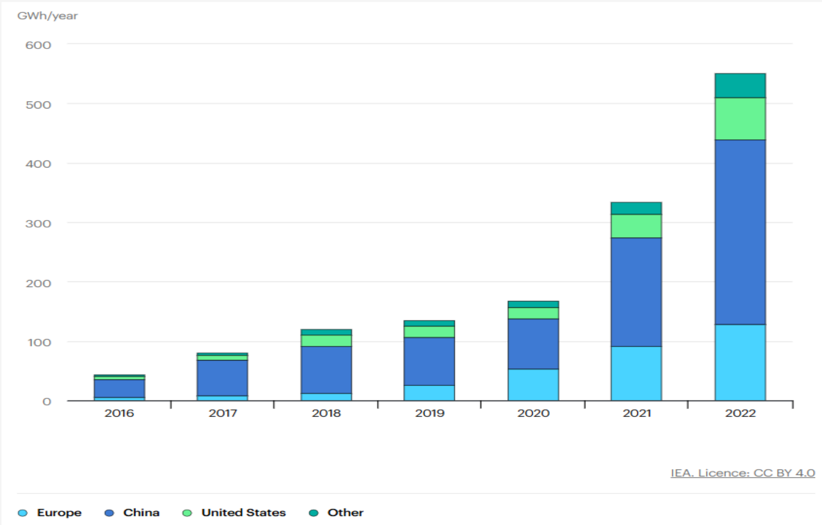
### Economic feasibility

Looking at the historical cost of LFPs from their conception to today, just like all other batteries, this figure is declining primarily due to greater advancements in their technologies. LFPs do not require any precious metals such as cobalt or nickel. This means any fluctuations in the raw material costs of LFPs have a smaller impact on their production cost. Looking into the future, this trend of reduced costs should continue as the technology continues to expand its market share. However, it would be unjust to say that there isn't any uncertainty in the long-term feasibility of LFP. This is due to the continued development of other battery technologies, primarily solid-state batteries. What's more, geopolitical dynamics and advancement in battery recycling are factors to be considered in this forecast. [18][19]

To evaluate the economic feasibility of LFPs today, a generic 10-year ROI analysis has been undertaken in **Appendix G3**. The results show that a 313% return on investment is already possible within a 10-year period, meaning there is already a strong economic case for the use of LFPs.

### Market Dynamics

From IEA's 2023 global EV outlook, we can see the demand for battery technology has been on the rise with LFP expanding its market share. This helps us understand the demands and competition of LFP and allows us to understand the factors that influence the opportunities in this industry. This shows there is an increase in the adoption rate of LFP, mainly due to an increased demand in the EV sector. This is made possible due to the cost of LFP manufacture decreasing year on year due to improvements in the technology.




Electric LDV battery capacity by chemistry, 2018-2022, IEA, Paris

# Conclusion

The aim of this review has been to assess the long-term feasibility of LFPs within an ever-growing market for rechargeable and recyclable batteries. Throughout this review we have highlighted that LFPs have shown great promise as a low cost, reliable and long-term solution for energy storage. Their primary use in EVs illustrates that they have found their place within the market as they account for 34% of all electric batteries within EVs worldwide [23].

Furthermore, the way in which they are re-purposed through the process of cascade utilisation shows promise as a way of maximising their use before more traditional (and expensive) lithium-recycling procedures take place.

Compared to NMC and Na-ion technologies, LFP batteries excel at being a lower cost - longer lifespan alternative. However, it would be unreasonable to ignore the anticipation for solid-state batteries which are expected to hit the global market sometime between 2026-2027 [24]. From initial research these are expected to outperform all existing battery technologies in energy density, number of rechargeable cycles and charging/discharging rates. However, it is our belief that this alternative will be significantly higher in cost for many years to come, allowing LFPs the opportunity to continuously improve and increase their market share.

# SAND BATTERIES FOR ENERGY STORAGE

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# Summary

As governments set ambitious decarbonisation targets (net-zero by 2050 in the UK), the transition to renewable forms of energy has become increasingly urgent. One of the greatest challenges in this shift lies in the intermittent nature of renewable energy production and therefore the need for efficient yet sustainable energy storage systems implementable in the UK's electric grid [15]. This study explores the potential of sand batteries, an innovative form of high temperature thermal energy storage in operation since 2022 and developed by Polar Night Energy in Finland, as a viable solution to store energy in its thermal form. This study provides a technical overview on the operating principles of sand batteries and compares it with other thermal storage technologies including sensible heat storage (SHS), latent heat storage (LHS) and thermochemical energy storage (TES). This comparison includes their Technological Readiness Levels, possible applications (industrial/district heating), advantages and potential challenges for their implementation within the UK. In addition, this study also analysis different business models for energy storage deployment, drawing insights from comparisons between the UK, USA and European markets to evaluate the commercial feasibility of sand battery adoption in the UK. Moreover, a technical feasibility assessment was conducted, including consideration for sustainable sand sourcing and its scalability as well as integration withing the UK's currently existing heating and energy infrastructures.

The findings suggest that sand batteries are a promising long term storage solution for the UK due to their high operating temperatures, low maintenance requirement and use of abundant low-cost materials that can be sourced sustainably. In addition, their compatibility with the UK's heating demand (from 70° to 400°) combined with their proven performance in industrial and district heating for large scale demand, make them a strong option for energy storage. Furthermore, by evaluating sand battery thermal energy storage for UK heating applications (70–400°C), using two system scales (2 MW/200 MWh and 10 MW/1,000 MWh) benchmarked against Polar Night Energy projects; results showed round-trip efficiencies of ~85–90% and levelized costs of ~£66/MWh and ~£49/MWh. Finally, despite ~7% monthly thermal decay, seasonal storage remains feasible. Sensitivity analysis highlights the impact of scale, cycling frequency, and electricity price variability on economic performance.

However, the study of how resistance systems and materials degrade over time remains limited due to a lack of available data, and this issue continues to be overshadowed by the predominant focus on accidental thermal runaway. Lastly, while these systems are well-suited for the heating industry and district heating, they are not yet suitable for small-scale housing and are still under development in terms of converting heat back into electricity.

# Explanation of the relevant technology

Sand battery technology is an emerging thermal energy storage solution that utilizes sand as the primary medium to store excess energy in the form of heat [40]. This system works by converting surplus electricity, which often generated from intermittent renewable sources like wind and solar and then converted into thermal energy via resistive heating. The heat is then stored for several hours or months with minimal thermal losses in a well-insulated container filled with sand, which can reach temperatures of up to 500–600°C [39].

The heat can then be extracted on demand via a heat exchanger, producing hot water, steam, or hot air at temperatures up to 400°C. Due to the sand's high specific heat capacity, low cost, and abundance, it offers a highly efficient and sustainable option for long-duration energy storage. The stored heat can later be extracted for applications such as district heating or industry heating and although individual residences may not accommodate large sand storage systems, community or building-scale installations offer a viable alternative [40]. Finally, sand batteries could possibly in the future be converted back into electricity, making this technology particularly attractive for decarbonizing heating systems and enhancing grid flexibility [40].

Sand batteries are classified as Sensible Heat Storage (SHS) because they also hold sensible heat within a solid or liquid medium. The benefits of SHS include its scalability for large areas, versatility for various applications, and established reliability. However, it suffers from limited space, and smaller systems experience greater heat loss, making them unsuitable for long-term storage [40].

However, sand batteries are still a new technology, meaning that there is still much ongoing research. The specific heating mechanisms are one area of interest that are still being developed. Also, specific insulation and containers for the sand component of the sand battery are being researched for improvement. The major area of research in the field revolves around final conversion of thermal energy to electricity using thermophotovoltaics [40].

# Comparison with current and potential technologies

## 1. *Technical Comparison of Thermal Energy Storage (TES) options*

While this study primarily focuses on sand batteries as a new mode of energy storage, there are other TES methods that can be explored which vary in Technology Readiness Level (TRL) (**Appendix H1**) and application. TES can be placed into 3 categories: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), Thermochemical Energy Storage (TCES) [2], [5], [7],[10]. SHS stores energy in the form of temperature, LHS in the form of energy released during phase change (e.g evaporation) and TCES in the form of energy released during chemical reactions.

It must be noted that, besides sand and water, all these methods are limited to a finite number of storage cycles due to corrosion and material degradation over time [5]. A comparison of SHS, LHS and TCES can be found in **Appendix H1**. A summary is found in the table below.

Table 1. Summary of TES comparison

| Method | Application | TRL | Examples in UK | Advantages | Challenges |
|---|---|---|---|---|---|
| SHS – Sand | Industrial and district heat, grid-scale storage | 6 | University research | High-temperature storage, long life cycle, safe, sustainable, low cost | Impurities in sand reduces energy density and efficiency, lower energy density than molten salt, large space required, insulation challenges |
| SHS – Molten Salt | Industrial processes and heat, high-temperature storage | 6 | Limited UK deployment | High energy density in SHS, proven in CSP plants | High upfront cost, safety and sustainability of materials, corrosion and degradation risk |
| SHS – Water-based TTES | District heating, low- temperature storage | 9 | District heating facilities | High maturity, low-tech, low maintenance | Not scalable, low energy density, limited to 100 C, space-intensive |
| LHS – Phase Change Materials | HVAC, small/medium-scale thermal storage | 7-9. 4 for grid usage | Hospitals, buildings, eco-homes | Compact, high energy density | Slow charge/discharge cycles, material degradation, limited scalability for grid use |
| TCES | Long-term storage with high temperature range | 3-5 | University research | Ultra-high energy density, near-zero energy loss, indefinite storage | High technical complexity, unproven at scale, costly materials, more research needed |

| | | | | | |
|---|---|---|---|---|---|
| | | | | duration | |

## 2. *UK Business Model Analysis*

In the United Kingdom, the Sand Battery, technically termed Sensible Heat Storage (SHS), represents a well-established model, particularly illustrated by the hot water tanks utilized in over 11 million households. These systems efficiently store heat for domestic hot water and are increasingly integrated with district heating networks and renewable energy sources, such as heat pumps. The UK currently operates approximately 1,765 district heating schemes, predominantly at smaller scales. SHS facilitates the shifting of heating demand to off-peak hours, enhancing grid flexibility. However, challenges remain, including limited residential space, exacerbated by the prevalence of combi boilers, and the relatively low energy density linked to water-based storage [10]. Despite these challenges, the UK's established infrastructure and increasing demand for low-carbon heating solutions position it as a significant benchmark for SHS adoption.

The applicability of sand batteries extends to industrial sectors, supplying process heat below 400°C for various applications, including food processing, brewing, and chemical manufacturing. This integration allows for a transition away from fossil fuel dependence while enhancing operational efficiency by facilitating the storage of excess high-grade waste heat from industrial processes. Characterized by simplicity and low maintenance, this technology serves as a robust solution for both residential and industrial heat supply in the UK.

An in-depth market analysis of the UK, its regulatory framework and examples of SHS currently under use is provided in **Appendix H2.** A country-by-country analysis of business models for sand battery systems focusing on technical fit, market needs, policy alignment, financials, business structure, and regional challenges, can be found in. **Appendix H3** specifically discusses the United States, mainland Europe, India and China.

## 3. *Analysis on the technical feasibility of the sand batteries*

To assess the technical feasibility of our sand-battery system, we took as our primary reference the two scales proposed by Polar Night Energy [44].

It was essential to choose Polar Night Energy, being the first commercialised sand-battery company to demonstrate a viable, high-temperature thermal storage solution, in order to evaluate how the technology would perform under UK conditions. The greatest challenges lie in sourcing and integrating high-performance components (resistive heaters, insulation, heat-exchangers) so as to maximise energy conversion and retention while minimising losses. This reference framework enables us to examine every subsystem, to derive overall round-trip efficiency as the product of input conversion, storage retention, and heat extraction, and to explore how scale-dependent effects and operational limitations shape system performance. With this base, we scale two models: the 2 MW/200 MWh "small scale" system and the 10 MW/1 000 MWh "large scale" system. In addition, an in-depth analysis of the required sand sourcing and raw material availability can be found in **Appendix H4**.

The sand battery system is composed of 3 main components: the resistive heaters, the silo and the heat transfer mechanism. These 3 components are explained in **Appendix H5**. The considerations introducing this chapter enable us to make the following assumptions for technological feasibility:

Table 2: Assumptions for scalability of the system and efficiencies

| **Parameter** | **Small Scale** | **Large Scale** |
|---|---|---|
| **Power Capacity** | 2 MW | 10 MW |
| **Energy Capacity** | 200 MWh | 1 000 MWh |
| **Resistive Heater Efficiency** | 98 % | 98 % |
| **Storage Retention Efficiency** | 90 % | 92 % |
| **Heat Extraction Efficiency** | 90 % | 98 % |
| **Operating Temperature** | 500–600 °C | 500–600 °C |
| **Annual Cycle Count** | 100 cycles/year | cycles/year |

To characterise our sand battery's round-trip efficiency, we broke the system into three sequential stages, input conversion, storage retention, and heat extraction, and then simply multiplied their individual efficiencies. From this analysis, we arrive at overall

RTEs of approximately 85 % for the 2 MW unit and 90 % for the 10 MW system, in line with Polar Night's values. The analysis can be found in **Appendix H3**.

## 4. *Analysis on the economic feasibility of the sand Batteries*

To evaluate the economic feasibility of our sand-battery system, we again based our study on the two scales demonstrated by Polar Night Energy [44].

It was essential to use Polar Night Energy's commercial model in order to assess capital and operational costs within a UK market context. The key challenge is balancing upfront investments in core components (heating elements, insulation, structural works) against expenses (maintenance, energy input, labor) to achieve a competitive cost per kWh. This framework allows us to apply a Levelized Cost of Storage methodology, annualising CAPEX via a capital-recovery factor, summing OPEX, and incorporating our efficiency model, to both scaled systems.

**Economic feasibility of scaling up sand batteries**

**Appendix H6** contains an analysis on the effect of policy on economic feasibility whilst **Appendix H7** contains an analysis of the Levelised Cost of Storage (LCOS), the RTE for economic feasibility and the limitations and losses of sand battery systems. A summary of these results is provided below:

The scalability of sand batteries remains compelling under our refined assumptions and calculations. By increasing system size from 2 MW to 10 MW, fixed costs for site preparation, insulation and control hardware are spread over a larger storage volume, driving down the Levelized Cost of Storage to approximately £49 per MWh for the 10 MW/1 000 MWh unit (versus £66 per MWh at 2 MW/200 MWh). Even so, very large installations can face greater construction complexity, land requirements and upfront CAPEX, particularly for high-performance insulation and refractory linings that limit thermal losses.

Sand's abundance keeps material costs low, but securing high-temperature, chemically stable grades, and pairing them with vacuum-enclosed, multi-layer insulation, can raise expenses if not optimized. Operationally, sand batteries excel at rapid ramping to meet fluctuating heat demands in industrial processes or district-heating networks, yet more frequent cycling heightens maintenance and energy-input costs, raising LCOS. Systems co-located with existing heat-demand infrastructure achieve higher utilisation, and thus lower cost per kWh, than remote sites with intermittent use.

Overall, under our assumptions of 90 percent round-trip efficiency, 100 full cycles per year, and our CAPEX/OPEX breakdown, a large-scale sand battery is cost-competitive with established thermal storage technologies, with clear pathways to further cost reductions through continued improvements in insulation, control strategies and equipment scaling.

### Optimisation for implementation

We recommend integrating advanced grid-management and control systems to optimize when the battery charges and discharges. By automatically taking in energy during periods of low cost or surplus generation and releasing it when demand or prices peak, the system maximises its economic value. Such end-to-end automation is essential for sustaining high efficiency over long storage durations and ensuring the sand battery remains financially viable.

# Conclusion

This study highlights sand batteries as a highly promising solution for long-duration, low-cost thermal energy storage in the UK. Their capacity to store heat at high temperatures using abundant, sustainable materials, alongside minimal maintenance requirements and strong compatibility with existing district heating infrastructure, positions them as a scalable, affordable and practical option for both industrial applications and residential heating systems.

To fully unlock the potential of sand batteries, governments and industry leaders must prioritise the development of pilot projects, particularly in industrial zones and local heating networks. These initiatives are essential to validate the technology's performance and reliability under UK-specific environmental and operational conditions. Moreover, the current lack of policies supporting specifically the installation of sand batteries highlights the need for political action.

Our technical analysis demonstrates that system round-trip efficiency improves from roughly 85 percent at a 2 MW/200 MWh scale to 90 percent at 10 MW/1 000 MWh, driven by lower relative heat losses and optimised heat-exchanger design. Economically, a Levelized Cost of Storage of approximately £66 /MWh for the smaller system falls to £49 /MWh at larger scale, thanks to economies of scale and that capitalise on low-price renewable power. Seasonal decay, around 7 percent per month, remains manageable for multi-month storage, with optimised insulation, for this preliminary analysis.

Finally, further research is needed to assess the long-term efficiency and durability of the storage material, especially as the systems scale, and to harness seasonal potential for long storing periods. Establishing this evidence base will support future investment and inform policy design aimed at supporting the widespread adoption of sand-based thermal storage.

# AMMONIA FOR LONG DURATION ENERGY STORAGE

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June 30, 2025

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# Summary

Long-duration energy storage (LDES) poses the largest barrier to widespread renewable energy integration. Without being able to store the energy from variable sources like wind turbines and solar photovoltaics for long periods of time, a grid is susceptible to black outs. In this report, ammonia is considered as a method of LDES and compared to the more commonly discussed energy vector: hydrogen. The report finds that ammonia has several advantages over hydrogen, such as widespread infrastructure already in place to transport and store ammonia, whilst also having drawbacks such as $NO_x$ emissions. Overall, it concludes that, whilst more promising than other energy vectors, it is hindered currently by its emissions of $NO_x$. Advancements fixing this problem could easily see widespread adoption of ammonia as a method of energy storage along with other heat-based and short-duration energy storage methods.

# Introduction

As the share of electricity generated by renewables such as wind turbines and solar photovoltaics continues to rise, grid operators increasingly face the challenge of maintaining grid stability. With wind and solar now accounting for 33% of the UK's electricity generation, maintaining a stable and reliable power supply during periods of minimal sunlight and wind flow has become more critical than ever (IEA, 2020). Unlike conventional power plants, renewables are inherently variable and less responsive to grid fluctuations, necessitating additional backup generation capacity to ensure a reliable energy supply. Batteries have emerged as the dominant solution for short-term storage and grid stabilisation. Battery costs have declined significantly over the past 10 years, making short-duration storage commercially viable.

However, scaling storage capacity beyond 12 hours - defined by the National Energy System Operator (NESO) as long-duration energy storage (LDES) - remains an unsolved challenge (ESO, n.d.). However, if the UK transitions to a net-zero grid, LDES will be the only viable solution to smooth out intermittencies and improve grid stability, further explored in **Appendix I1**. Large-scale deployment would capture excess energy during high electricity production periods and release it when demand exceeds supply.

Fossil fuel-based backup generation remains the primary solution to grid intermittency, but it is expensive, carbon-intensive, and contributes to volatile energy prices (Ambrose, 2025). The forced curtailment (further explained in **Appendix I1**) of renewable energy further undermines efficiency, resulting in the waste of surplus electricity that could otherwise be stored for future use. This issue is particularly prevalent among Scottish wind farms due to inadequate transmission capacity to population centres in England (Atherton et al., 2023). Developing and implementing tech

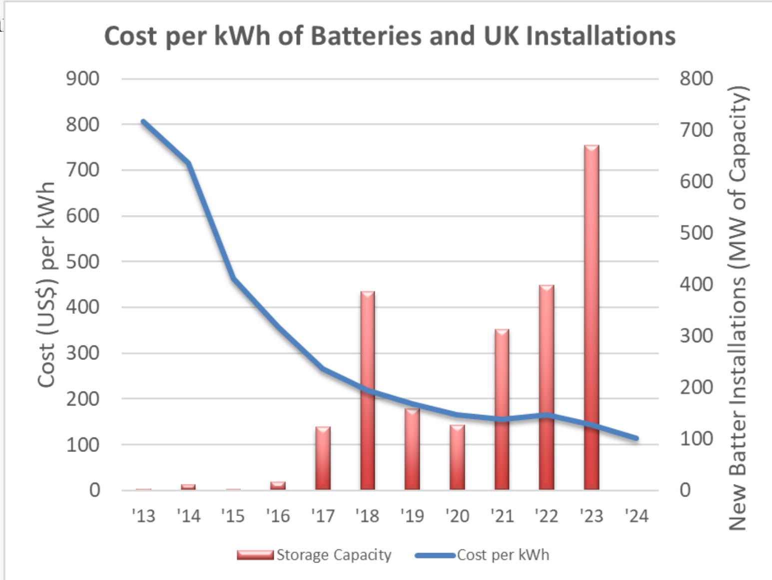


**Figure 1**: Cost per kWh compared to the new installed capacity in the UK (World Energy Outlook, 2024; REPD Database, 2025)

economically viable and scalable LDES solutions would allow governments to phase out costly fossil fuel contracts, store excess renewable energy and release it when demand peaks, enhancing grid stability, advancing net-zero targets and reducing curtailment.

Green hydrogen has been a significant focus as a potential LDES solution in recent years. However, the following chapter demonstrates key challenges associated with hydrogen storage, including the high energy demands of liquefaction and the inefficiencies of compressed storage. As an alternative, the chapter highlights the potential of ammonia as a carbon-free hydrogen carrier, offering a viable pathway for long-duration energy storage and integration into the future energy systems.

## *Hydrogen and Other Storage Options*

Produced through electrolysis, green hydrogen is generated using surplus renewable electricity to split water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$). The hydrogen can be stored and later converted back into electricity, either through combustion in a gas turbine, mirroring the process used for natural gas, or via a fuel cell, where hydrogen reacts with oxygen to generate electricity and water. Despite its potential, green hydrogen faces significant challenges, particularly in storage. Each of the two primary storage methods has considerable drawbacks.

Compressing hydrogen requires high-pressure tanks engineered to keep the hydrogen at pressures significantly exceeding those used for compressed natural gas (CNG) (US Department of Energy, n.d.). This method of storage can be expensive and poses a safety risk resulting from containment failures and hydrogen flammability. Liquid hydrogen, in turn, demands continuous cooling at minus 253.15°C, almost a hundred degrees colder than Liquified Natural Gas (LNG), representing a significant infrastructure challenge (Müller et al., 2024; EIA, n.d.). The liquid hydrogen suffers from continuous boil-off and the cooling itself consumes approximately 40% of the stored energy, further reducing its usefulness (Serpell et al., 2023). While the costs of electrolysis and fuel cells are declining, the storage barrier remains a major obstacle to scaling hydrogen as an LDES solution.

Beyond hydrogen, several other technologies are being explored to address the need for LDES. Pumped Hydro Storage is the most established form of large-scale storage, which uses excess energy to pump water to a higher elevation and release it later to generate electricity. Despite its efficiency and maturity, geographical limitations hinder widespread deployment in the UK.

Compressed air storage is yet another technology that is quite efficient and simple. This is in use in the UK in a few places but requires faces geographical limitations as natural salt caverns are required for the storage.

Among emerging alternatives, ammonia has gained attention as a potential solution for overcoming hydrogen storage challenges. Ammonia can serve as a hydrogen carrier, offering higher energy density and easier storage compared to pure hydrogen. In the following sections, we will explore how ammonia could play a crucial role in long-duration energy storage, despite being at an early stage of development.

## *Ammonia*

Several molecules have been proposed as long-term energy carriers (this topic is explored in **Appendix I2**): instead of using hydrogen directly, they use green hydrogen as a starting point to synthesize more practical compounds. Ammonia, methanol, formic acid, methane, and synthetic hydrocarbons have all been proposed. Most of them are also suggested as fuels to decarbonise the transport sector - especially shipping and aviation, which are difficult to electrify.

Amongst these, ammonia is the only carbon-free molecule and its potential as an energy carrier is supported by its impressive characteristics. It can be liquified under mild conditions, especially compared to hydrogen and with a volumetric energy density that is 45% higher than liquid hydrogen, it offers efficient energy storage in a relatively compact form (The Royal Society, 2020; Serpell, 2023). Furthermore, ammonia has been produced on an industrial scale since the early 20th century for industrial processes and to be used as fertiliser. Therefore, the UK already possesses significant ammonia infrastructure, including major import terminals at ports, like Immingham, and established storage facilities across industrial centres. This also means that the technology surrounding ammonia storage and transport is already mature compared to hydrogen.

Green ammonia ($NH_3$) is produced using reacting green hydrogen molecules ($H_2$) from electrolysis with nitrogen molecules ($N_2$) available in the air. This process is explained in **Appendix I3** and **Appendix I4**. When the power stored through ammonia needs to be released, it is converted back from a liquid to a gas. There are then two options for how to burn the fuel. Ammonia can be burned directly or co-fired with natural gas through speciality turbines that are under development by companies such as Mitsubishi Power (Mitsubishi Power, 2021). Meanwhile, Bord Gais Energy's Whitegate power plant in Ireland is pioneering ammonia co-firing in conventional power generation (Bord Gais, 2023).

However, while directly firing ammonia doesn't release any carbon, it creates another problem as it produces $NO_x$ gases (Gubbi et al., 2023.). $NO_x$ has a large global warming impact, with molecules like $N_2O$ a warming potential 298 times that of $CO_2$ (Statistics Netherlands, n.d.). Any direct-fire electricity generation using ammonia therefore, needs to control or capture the exhaust gases. The alternative is to turn the ammonia back into hydrogen through a process known as "cracking" and then burning the hydrogen directly in co-firing or a specialised gas turbine (Serpell et al. 2023).

Ammonia exhibits advantages in storage and transport, partially due to our experience in dealing with it and trading it internationally. Its ability to act as both energy storage and a commodity makes it a more flexible solution to our storage problem, as excess ammonia not needed for energy storage could be shifted to industrial and agricultural customers. Efficiency and affordability gains are still required for green ammonia to be an economically viable LDES option. Still, when you compare it to hydrogen, it appears to be the better path to take.

# Conclusion

Looking ahead, no single technology will solve the challenge of long-duration energy storage alone. The future UK grid will likely rely on a portfolio of storage solutions, including pumped hydro, thermal storage, hydrogen carriers like ammonia and methanol, and advanced battery chemistries. The next decade will determine which technologies can scale affordably, integrate effectively into our energy infrastructure, and provide the reliability needed to transition to a 100% renewable-powered grid. If ammonia can overcome its remaining hurdles, it could emerge as a key enabler of stable, low-carbon electricity systems in the UK.

# WASTE MANAGEMENT

# TRAWLING NETS: REDUCING PLASTIC IN THE OCEAN

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# Summary

Throughout humanity's history, countless communities have relied on oceans for nutrition, trade, and economic stability. Far more than just a source of food, oceans also function as a vast carbon sink, absorbing excess carbon from our atmosphere. However, modern fishing practices, particularly the use of non-biodegradable nets and bottom trawling, threaten marine ecosystems.

Each year, an estimated 640,000 tonnes of plastic-composed fishing gear enters oceans, with over 1250 kilometres of nets lost in UK waters alone [1], [2]. Once adrift, this gear can persist for up to 600 years, continually trapping and killing marine life in a process called ghost fishing [3], [4]. The root causes of this waste are intentional, illegal dumping of these nets as well as unintentional losses at sea. Beyond the ecological costs, the financial burden is also significant. A single day spent recovering ghost gear can cost around £1,000, often removing only about 100 kg of nets [5]. Moreover, UK studies show that for fishermen to implement biodegradable fishing gear, some level of financial incentive would be required [6]. At the same time, global demand for seafood continues to rise, placing fishermen under pressure to meet market needs, often without adequate measures to prevent or retrieve lost nets.

Additionally, bottom trawling is a prevalent fishing technique accounting for 32% of recorded EU catch. It is responsible for severe ecosystem disruption, high bycatch rates, and carbon release from the seabed disturbance, comparable to industrial emissions [7].

This report explores three key preventative strategies to reduce fishing-related ocean waste and promote sustainable practices. First, the use of biodegradable polymers such as PBSAT and PHA is examined as a replacement for nylon-based nets. These materials decompose in marine environments over 1–4 years, lowering the risk of ghost fishing and microplastic pollution. Second, the development of hydrodynamic and modular net designs is proposed to reduce bottom trawling, bycatch, and carbon emissions. Innovations such as pressure-sensitive escape hatches, adaptive mesh geometry, and Autonomous Underwater Drones (AUDs) improve net lifetime and minimise ecological disruption. Third, the implementation of unique identifiers, including RFID tags and QR codes, is evaluated to improve net retrieval and enforce accountability of illegally discarded gear.

To turn these ideas into practice, four steps are proposed. Within five years demersal fleets should phase in PBSAT or PHA nets, helped by gear-exchange subsidies matched to vessel size. By 2030 all new trawlers must use nets with new mesh designs and geometries, and at least 40% of current vessels should be retrofitted through low-interest loans. A national and international RFID standard must be enforced at ports, with fines equal to the replacement cost of untagged gear. Finally, fuel-tax rebates should depend on verified tow logs showing less than one percent seabed contact.

Together, these measures chart a scalable path to lower fishing waste and promote more responsible, future-proof seafood production.

# Material Alternatives to Nylon-Based Nets

The environmental impact of synthetic fishing nets often is from ghost gear with nylon-based lost gear enduring up to decades. Since the loss of some fishing gear is inevitable, this has driven research into biodegradable alternatives to reduce marine pollution, with a target life span of 1-4 years.

Materials that combine strength, flexibility and biodegradability include PBSAT (Polybutylene Succinate-Co-Adipate-Co-Terephthalate), PHA (Polyhydroxyalkanoates) and Nano-Cellulose. Although Nano-Cellulose has strong mechanical properties, its high cost and limited research and current viability makes it difficult to use for fishing nets compared to PBSAT and PHA.

Table 1. Comparison of potential material alternatives to commercial nylon trawling nets based on key performance and environmental factors. Cost is ranked from 1 (lowest) to 4 (highest).

| Material | Biodegradability (marine environments) | Mechanical Strength | Flexibility | Degradation Byproducts | Cost |
|---|---|---|---|---|---|
| **Nylon (Conventional)** | Non-biodegradable | High | High | Microplastics | 1 |
| **PBSAT** | Biodegradable | Moderate | High | Minimal microplastics | 2 |
| **PHA** | Biodegradable | Low | High | $CO_2$ and water | 3 |
| **Nano-Cellulose** | Potentially biodegradable | High | Moderate | $CO_2$, water, and natural organics | 4 |

From **Appendix J1** (containing analysis of PBSAT and PHA), we concluded that PBSAT and PHA are the most suitable for biodegradable fishing nets. PBSAT offers marine biodegradability and mechanical strength, while PHA provides eco-friendly decomposition and flexibility. A blended PBSAT-PHA fishing net would balance durability, waste reduction, and environmental sustainability, making it an optimal solution for reducing plastic waste in marine ecosystems.

# Optimising Trawling Net Design

Current commercial trawl nets use large trawl doors (also known as otter boards) attached to sides of the net mouth to generate hydrodynamic forces, which pull the net laterally apart, maximising its opening width. Since the trawl's position is fully dependent on the boat, it often gets pulled off-axis, increasing drag and fuel consumption. On the other hand, pelagic (midwater) trawling is widely practiced and ensures the net is fully off the seabed. Yet, this cannot fully replace bottom trawling as it doesn't target demersal species (living on the seabed).

Semi-pelagic trawls offer a hybrid solution, allowing vertical adjustment to fish near the seabed without dragging gear along it [13], [14]. Nets are kept off the seabed through hydrodynamic floatation devices and smart weight distribution, reducing sediment disruption whilst maintaining catch efficiency. The BENTHIS project has trialled replacing conventional demersal trawl doors with novel curved pelagic ones which hover over the seafloor. While this innovation has led to a modest reduction in fuel consumption, the surface area of gear sweeping along the seabed remains unchanged, as it is primarily dictated by the ground rope, requiring further optimisation [15].

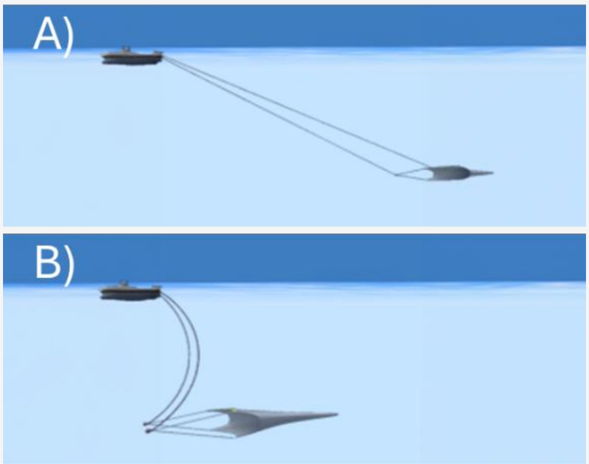

Figure 1. Comparison of A) conventional trawling, which drags along the seabed, and B) trawling using Ecotrawl Autonomous Underwater Drones (AUD), which steer the net off the seafloor, reducing drag, sediment disruption, and bycatch.

In 2016, a Norwegian startup developed Ecotrawl, an innovative trawling system to improve commercial trawling net sustainability by reducing bottom trawling, by-catch, and fuel consumption. As illustrated in Figure 1, instead of traditional trawl doors, Ecotrawl uses electrically powered Autonomous Underwater Drones (AUDs) to propel the net with a direct, in-line pull, making the net's movement independent of the boat. A trawler control system collects sensor data and controls the AUD units using side and depth rudders, allowing for precise net positioning and depth control to avoid the net dragging along the sea floor.

This system doubles steerability compared to commercial nets, enhancing fishing accuracy while minimising both bottom trawling and bycatch. As a result, catch volume increases by 20%, while the removal of bottom trawling reduces fuel consumption by 30%, lowering $CO_2$ and $NO_x$ emissions and improving profitability. Ecotrawl is currently conducting studies to further optimise thruster manoeuvrability before commercialising its technology. [16]

Real-time GPS mapping with seabed scanning can be integrated together, allowing for dynamic adjustments in net depth. This comes under the term 'seabed impact detection technology', where vessels can identify when nets are in contact with the ocean floor, allowing the operator to immediately rectify the issue, preventing unnecessary damage.

In addition to these efforts which are aimed at reducing conventional bottom trawling, a lot of research has been done into how to reduce bycatch. **Appendix J2** discusses how pressure sensors, adaptive modular mesh design and knot orientation can reduce bycatch and improve fuel efficiency.

# Net Traceability and Identification Technologies

Unique identifiers, ranging from simple manual labelling to advanced tracking technologies like Radio-Frequency Identification (RFID), are becoming essential tools in improving transparency and accountability within the fishing industry. When integrated with existing systems, these technologies can help monitor fishing activities and hold large companies accountable for illegal practices, such as the dumping of fishing nets into the ocean. However, enforcing such measures presents significant challenges, particularly due to the complexities of legislating international waters and the lack of standardized regulations across different jurisdictions [21].

Two of the most used unique identifiers in supply chain tracking are QR codes and RFID tags. QR codes, or Quick Response codes, are two-dimensional barcodes that can be scanned using cameras or smartphones. They provide a simple and cost-effective way to store and share traceability information, such as a product's origin, sustainability certifications, or compliance with fishing regulations [22]. In contrast, RFID tags operate through wireless communication, consisting of two main components: a transceiver, which stores and transmits data, and a reader, which captures and interprets this data. Unlike QR codes, RFID technology does not require a direct line of sight to be scanned, making it a more secure and efficient tracking method [23].

Despite their advantages, both QR codes and RFID tags come with challenges and limitations. One of the primary concerns is network dependency. Both technologies rely on internet or satellite connectivity to function effectively, which can be a significant obstacle in remote ocean environments where network coverage is unreliable [21]. Additionally, security risks must be considered. QR codes are vulnerable to tampering and can be easily replaced, leading to potential data manipulation. While RFID offers a higher level of security, it is not immune to hacking or electromagnetic interference, which could compromise the integrity of the data (Deloitte, 2022). Another important factor is durability. Although RFID tags are generally more resistant to physical wear and tear than QR codes, they are still susceptible to water damage if their protective casing is breached. Maintaining these tracking systems requires ongoing investment, a cost that some companies may be reluctant to bear [23].

Recognizing the potential of these technologies, the Marine Management Organisation (MMO) is currently exploring the use of QR codes and RFID tags to enhance consumer confidence in seafood products. A hybrid approach is being considered, where QR codes serve as a low-cost method for sharing basic traceability information, while RFID tags provide more detailed data storage and real-time monitoring of fishing equipment [24]. This dual system could create a more comprehensive and accessible tracking network, improving oversight in the fishing industry.

Looking ahead, advancements in tracking and security technologies are expected to improve the feasibility of unique identifiers in the fishing sector. Innovations such as waterproof RFID casings, self-powered tracking systems, and blockchain integration could enhance data security, reduce the risk of manipulation, and enable more reliable tracking, even in international waters. Additionally, the use of automated satellite monitoring and AI-driven tracking networks could provide real-time enforcement capabilities, helping regulatory bodies detect and address illegal fishing practices more effectively.

While unique identifiers offer a promising solution for promoting sustainability and accountability in the fishing industry, significant challenges remain in scaling these technologies for widespread adoption. More research is needed to assess the economic feasibility, regulatory implications enforcement mechanisms, particularly those requiring international and governmental cooperation. Additionally, the long-term viability of implementing technologies like QR codes and RFID tags across the global fishing supply chain must be assessed. However, as technology continues to evolve, these systems have the potential to revolutionize seafood traceability and contribute to a more transparent and responsible industry.

# Conclusion

Trawling nets are responsible for significant marine waste worldwide, with ghost fishing and bottom trawling contributing greatly to biodiversity loss, and carbon emissions. To combat this, three preventative solutions have been evaluated. Firstly, nylon nets should be replaced with biodegradable alternatives, particularly PBSAT-PHA blends, which balance durability with environmental degradation. Secondly, nets should have modular designs that reduce drag, bycatch, and the likelihood of structural failure by incorporating hydrodynamic shaping and adaptive mesh sizing. The Ecotrawl system, which replaces trawl doors with steerable autonomous underwater drones, would greatly improve precision trawling and minimise seabed impact by offering better control of net depth positioning. Thirdly, all nets should be equipped with unique identifiers (e.g., RFID or QR codes) to enable traceability, facilitate retrieval, and enforce penalties for illegal dumping. However, this requires regulatory bodies to enforce their adoption.

Without the implementation of such solutions, the environmental and economic damage caused by ghost nets and bottom trawling will continue to escalate, undermining both ocean health and the long-term viability of the fishing industry.

# RECYCLING TEXTILE WASTE

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June 30, 2025

# Summary

Textile waste is a significant environmental and economic problem, primarily due to its contribution to landfill pollution, resource depletion and challenges in recycling. A substantial portion of discarded textiles ends up in landfills, where synthetic fibres like polyester can take hundreds of years to decompose, releasing harmful greenhouse gases and toxic chemicals into the environment [10]. Additionally, textile production requires extensive resources; for instance, manufacturing a single cotton T-shirt consumes over 2,700 liters of water, exacerbating water scarcity issues [35]. Synthetic fabrics also contribute to microplastic pollution, as they shed tiny plastic particles during washing, which enter waterways and pose risks to marine ecosystems [4]. The rise of fast fashion has intensified the problem by encouraging overconsumption and frequent disposal of garments, with many items worn only a few times before being discarded [13]. Recycling textiles remains a challenge due to the complexity of separating blended fibers, chemical treatments, and inconsistent waste management systems [30]. Beyond environmental concerns, the textile industry's reliance on low-cost labour and mass production often results in poor working conditions, making textile waste not only an ecological issue but also a social and ethical one [5].

This report will address and compare solutions to the textile waste problem we are facing with regards to three materials – cotton, polyester and wool. It concludes that composting is the most effective method to recycle cotton, primarily due to efficiency, affordability and scalability, and that enzyme assisted processes and treatment are the most effective ways to recycle polyester and wool respectively. These enzyme-based processes are preferred despite their higher costs due to their speed and ability to fully degrade polyester and wool.

In this report each section has a complimentary **appendix** for more technical information on the method discussed. Feel free to use this for more context around each technology.

# Cotton

## *Fungal Degradation*

Fungal degradation presents a sustainable and efficient solution for managing cotton waste by utilising fungi that produce cellulase and ligninase enzymes to break down cellulose into simpler sugars. These fungi, including Aspergillus, Trichoderma, Fusarium and Penicillium species, demonstrate strong enzymatic activity, making them valuable for large-scale waste treatment. The process begins with fungal colonisation, followed by enzymatic hydrolysis of cotton fibres into glucose and other by-products, which fungi absorb as nutrients. However, challenges such as synthetic fibre contamination and inhibitory dyes must be addressed through pretreatment methods like mechanical shredding, alkaline treatment, and enzymatic hydrolysis to enhance fibre accessibility. Industrial-scale implementation requires optimisation of fungal strains, growth conditions and cost-effective strategies to improve degradation rates. Despite these challenges, this method supports a circular economy by reducing textile waste and promoting sustainable recycling. With ongoing research and technological advancements, this method holds great promise for mainstream adoption in textile waste management.

## *Bacteria Degradation*

Cotton is primarily composed of cellulose, a complex carbohydrate made up of long chains of glucose molecules linked by glycosidic bonds. Certain bacteria, such as *Cellulomonas* spp., *Bacillus* spp., and *Streptomyces* spp., have evolved to break down cellulose efficiently by secreting specialised enzymes called cellulases and hemicelluloses [19]. Biodegradation by bacteria shows promising results, up to 77% of cotton weight is lost in just 90 days, in better conditions, this could be significantly accelerated [16]. The cost of bacterial degradation for cotton textile waste varies depending on factors such as the type of bacteria used, processing conditions and scale of implementation. Studies indicate that bio-scouring, a bacterial treatment method, can cost around $0.35 per kilogram of processed cotton [6]. While this method eliminates the need for harsh chemicals and has lower energy consumption due to mild operating conditions [8], the cost of enzyme production and operational expenses can make it more expensive than other methods [6].

## *Compost system*

Composting is a natural process that decomposes organic waste into nutrient-rich soil amendments. Cotton, primarily composed of cellulose, is 100% biodegradable, making it an ideal material for composting. Various composting methods, including aerobic, anaerobic, and vermi-composting, can be used to break down cotton waste efficiently while promoting sustainability. Traditional cotton waste disposal methods, such as landfilling and incineration, contribute to greenhouse gas emissions and environmental degradation [14]. Composting, particularly aerobic composting, is a more sustainable alternative, as it accelerates decomposition while reducing methane emissions. The thermophilic stage in aerobic composting ensures faster breakdown, pathogen elimination, and minimal odour production. While anaerobic composting retains more nitrogen, it produces methane, a potent greenhouse gas. Vermi-composting, which uses worms, further enhances nutrient cycling [20]. In terms of cost, composting systems significantly reduce long-term waste management expenses and reliance on landfill, making them a cost-effective solution. Studies suggest that aerobic composting of organic waste can cost between $25 and $50 per tonne (approximately $0.025 to $0.05 per kilogram), depending on the system used and local infrastructure. [37]

## *Conclusion*

The **compost system** is the most effective method for breaking down cotton, offering advantages in efficiency, affordability and scalability. By utilising both fungal and bacterial activity, it speeds up decomposition while generating nutrient-rich compost that benefits soil health. In contrast, fungal and bacterial degradation require controlled conditions and may incur higher costs, making them less practical for large-scale use. Although fungi and bacteria can degrade cotton efficiently, they often rely on specific strains or carefully managed environments, limiting their accessibility. Overall, composting provides a well-rounded, low-impact, and easily managed solution, making it the ideal choice for cotton waste disposal. The table below summarises the advantages and disadvantages of each method discussed.

Table 1: Pros and Cons of Cotton Degradation Methods

| Methods | Pros | Cons |
|---|---|---|
| **Fungal Degradation** | • Sustainable & Eco-Friendly – Uses natural fungal enzymes to break down cotton, reducing landfill waste.<br>• Efficient Breakdown – Fungi like *Aspergillus* and *Trichoderma* produce strong cellulase and ligninase enzymes, speeding up degradation.<br>• Circular Economy Support – Converts waste into reusable sugars, promoting recycling and resource recovery.<br>• Scalable Potential – Can be adapted for industrial use with optimized fungal strains and growth conditions.<br>• Reduces Chemical Use – Compared to harsh chemical treatments, fungal degradation is a milder, greener alternative. | • Contamination Issues – Synthetic fibres (e.g., polyester) and dyes can hinder fungal activity, requiring pretreatment.<br>• Slow Process – Natural degradation takes time; industrial scaling needs faster, optimized methods.<br>• Pretreatment Costs – Mechanical shredding, alkaline treatment, or enzymatic pre-processing add expenses.<br>• Sensitivity to Conditions – Fungi require controlled temperature, pH, and moisture for optimal performance. |
| **Bacterial Degradation** | • Efficient breakdown – Up to 77% weight loss in 90 days.<br>• Eco-friendly – Uses enzymes instead of harsh chemicals.<br>• Low energy – Operates under mild conditions.<br>• Bioremediation – Cleans soil/water of cotton waste. | • Costly enzymes – ~$0.35/kg, pricier than other alternatives.<br>• Slow without optimization – Speed depends on conditions.<br>• Sensitive environment – Needs controlled pH/temperature.<br>• Limited to pure cotton – Synthetic blends hinder efficiency. |
| **Compost System** | • Cotton is 100% biodegradable, making it well-suited for composting.<br>• Composting offers a more sustainable alternative to landfilling and incineration. | • Anaerobic composting releases methane, a greenhouse gas contributing to global warming. |

| | | |
|---|---|---|
| | • Aerobic composting reduces methane emissions in comparison to anaerobic methods.<br>• The thermophilic stage in aerobic composting accelerates decomposition, eliminates pathogens, and minimises odour.<br>• Produces soil amendments that support nutrient cycling, particularly through vermi-composting.<br>• Lowers long-term waste management costs and reduces dependency on landfill sites. | • Composting requires specific conditions (e.g., temperature, moisture) to be effective.<br>• Only suitable for biodegradable textiles such as cotton, not synthetic fibres. |

# Polyester

## *Microbial PET Degradation*

Microbial PET degradation can be done by wild types such as Bacillus sp. and genetically modified organisms such as E.Coli [2]. The main advantage is that these simpler molecules can be a precursor in PET production, facilitating recycling [25]. This method can contribute to reduction in toxic waste. However, it is difficult to implement on an industrial scale as it is time-consuming and low yields of only 45% of mass being reduced during a year. This can be improved through pre-treatments which could involve physical and chemical processing methods. This could lead to higher costs and production of side products, which can be harmful to the environment or require further processing before they are released into the environment. The cost of genetically modified organisms is very high, and it is difficult to maximise the degradation environment to gain high yields and high rates of degradation. To solve this, genetically modified organisms can change structures and properties of enzymes to facilitate the increase of degrading efficiency [2].

## *Enzyme assisted processes*

Enzyme-assisted processes provide a greener way to modify and break down polyester, making plastic recycling more sustainable. Special enzymes like cutinases and lipases can break certain chemical bonds on the surface of polyester, improving how the material interacts with dyes and adhesives [29]. In a more advanced process, enzymes can fully break down PET plastic into its original building blocks—terephthalic acid (TPA) and ethylene glycol (EG)—so they can be reused to make new plastic, reducing waste [34]. Unlike traditional chemical methods, enzyme-based processes work at lower temperatures and mild pH levels, making them more energy-efficient and eco-friendly. However, enzyme production and processing can be costly, with estimates ranging from \$4 USD to \$6 USD per kilogram of PET treated, though ongoing research aims to make it cheaper [33].

## *Mixed waste processing*

Recycling mixed textile waste presents a significant challenge due to the presence of multiple fibre types, dyes and contaminants that require extensive pre-sorting. A novel method uses microwaves and a zinc oxide (ZnO) catalyst to break down polyester and spandex from mixed textile waste into their basic building blocks in just 15 minutes at 210°C [11]. Then, formic acid dissolves nylon for easy recovery, while cotton remains as a solid and is separated. Polyester depolymerisation is a quick process, however energy, purification and solvent recovery cost leads to high costs ranging from \$1.1 to \$2.7 per kg [11].

## *Conclusion*

**Enzyme-assisted processes** are the most efficient method for polyester degradation, as they break down PET into reusable monomers within hours or days under optimised conditions. While microbial PET degradation is a promising alternative, it is slower and requires specialised microbes, making it less practical for large-scale applications at present. Mixed waste processing – the most widely used method – is cost-effective and highly scalable but often leads to incomplete degradation, with environmental concerns such as landfill accumulation or incineration. Although enzyme-based methods are currently expensive due to production costs, they offer a controlled and sustainable approach with minimal environmental impact. Overall, enzyme-assisted degradation holds the greatest potential for efficient and eco-friendly polyester recycling, while microbial degradation may become a viable option with further advancements.

Table 2: Pros and Cons for Polyester Degradation

| Methods | Pros | Cons |
|---|---|---|
| **Microbial PET Degradation** | • Eco-friendly – No toxic waste or high GHG emissions.<br>• Closed-loop recycling – Breakdown products can reuse for new PET.<br>• Uses natural/GMO microbes – *Bacillus*, engineered *E. coli* enhance efficiency. | • Slow & low yield – Only ~45% mass loss/year; needs pretreatment.<br>• High costs – GMOs and enzyme optimization are expensive.<br>• Risk of harmful byproducts – May need extra processing.<br>• Scalability challenges – Hard to maintain ideal conditions industrially. |
| **Enzyme Assisted Processes** | • Eco-friendly – Operates at low temps & mild pH, reducing energy use. | • High enzyme cost – 4–4–6/kg PET, limiting scalability.<br>• Slow reaction rates – Requires optimization for industrial speeds. |

| | | |
|---|---|---|
| | • Precise breakdown – Cleaves polyester into reusable TPA & EG (closed-loop recycling).<br>• Surface modification – Enhances dye/adhesive bonding for textile upcycling.<br>• Non-toxic – Avoids harsh chemicals used in traditional methods. | • Sensitivity – Performance depends on temperature/pH stability.<br>• Pretreatment needs – Crystalline PET may require melting/mechanical prep. |
| **Mixed Waste Processing** | • Utilises wild-type microbes (e.g., Bacillus sp.) and genetically modified organisms (e.g., E. coli) to break down PET.<br>• Produces simpler molecules without generating toxic waste or significant amounts of greenhouse gases.<br>• The simpler molecules generated can serve as precursors for PET production, supporting closed-loop recycling.<br>• Contributes a decrease in toxic waste levels. | • Difficult to scale up industrially due to slow degradation rates and low efficiency, only around 45% mass reduction over a year.<br>• Pre-treatments (physical and chemical) may be required to improve efficiency, potentially increasing costs and generating environmentally harmful by-products.<br>• Genetically modified organisms are expensive to develop and maintain.<br>• Achieving optimal degradation conditions is difficult, and current methods yield limited results.<br>• Enzyme structures and properties must be engineered to improve degradation efficiency, requiring advanced genetic modification. |

# Wool

## *Fungal Degradation*

Fungal degradation of wool waste presents a sustainable solution by utilising keratinolytic enzymes. This process has promising applications, including composting, where fungi enhance the breakdown of keratin, improving soil quality; and recycling, where degraded wool can be repurposed into hydrolysates for fertilisers, bioplastics, or amino acid sources. However, wool's resistance to degradation poses challenges, requiring optimised conditions for fungal growth and enzyme activity. Additionally, dyes and chemical treatments in wool hinder microbial action, necessitating pre-treatments to improve efficiency. Future advancements in fungal degradation include enhancing keratinase production to accelerate breakdown and integrating biological and chemical treatments to optimise wool waste management.

## *Enzymatic treatment*

Enzymatic treatment uses proteases and lipases—special enzymes that help break down proteins and fats respectively. This method helps modify fibres, improve cleaning and separation of materials for better waste management [31]. However, the costs of hydrolysis is a significant factor. According to a study in *Journal of Cleaner Production*, it shows that using enzymes like Alcalase 2.4L costs approximately €0.783 per kilogram of wool, compared to chemical hydrolysis with sodium hydroxide, which costs around €0.199 per kilogram, making enzymatic treatment nearly four times more expensive [12]. However, these methods are environmentally friendly, as they operate under mild conditions and produce biodegradable by-products [1]. Also, enzymes act selectively, preserving fibre quality for reuse.

## *Bioaugmentation*

Bioaugmentation is a biotechnological approach that enhances the degradation of pollutants by introducing specific microorganisms into a contaminated environment [17]. It is commonly used in wastewater treatment, soil remediation, and organic material breakdown. This method can also be applied to wool degradation, where specialised microbes accelerate the breakdown of keratin, the primary protein in wool fibres. Traditional degradation can take months to years, whereas bioaugmentation can break down wool fibres in weeks under optimised conditions [3]. In terms of cost, bioaugmentation has been shown to improve the economics of waste treatment. For instance, a study indicated that bioaugmentation could enhance the economics of corn waste anaerobic digestion by $27–$34 per dry tonne of waste. Additionally, bioaugmentation reduces the need for chemical treatments and extensive landfill disposal, making it a more sustainable and cost-effective solution [38].

## *Conclusion*

The best method for breaking down wool is **enzymatic treatment** since, in the right circumstances, enzymes like keratinases effectively convert wool into amino acids and peptides. This approach guarantees speed and accuracy, which makes it ideal for industrial application. The advantages and disadvantages of all the methods are summarised in the table below.

Table 3: Pros and Cons of Wool Degradation methods

| Methods | Pros | Cons |
|---|---|---|
| **Fungal Degradation** | • Sustainable – Uses natural fungal enzymes to break down tough keratin.<br>• Versatile outputs – Produces peptides/amino acids for | • Slow process – Keratin is highly resistant, requiring long degradation times. |

| | | |
|---|---|---|
| | fertilizers, bioplastics, or compost.<br>• Soil improvement – Enhances compost quality by accelerating wool decomposition.<br>• Eco-friendly – Avoids harsh chemical treatments, reducing pollution. | • Sensitive conditions – Needs optimal pH, temperature, and moisture for fungal activity.<br>• Dye/chemical interference – Pre-treatments may be needed to remove contaminants.<br>• Cost & scalability – Large-scale enzyme production and process optimization remain costly. |
| **Enzymatic Treatment** | • Eco-friendly process - Operates under mild conditions (lower temps/pH) with biodegradable byproducts.<br>• Fiber preservation - Selective action maintains wool quality for better reuse potential.<br>• Effective cleaning - Lipases remove oils while proteases break down fibers into reusable peptides/amino acids.<br>• Safer alternative - Eliminates need for harsh chemicals like sodium hydroxide. | • High cost - €0.783/kg (vs €0.199/kg for chemical treatment) – around 4 times more expensive compared to Bioaugmentation.<br>• Slower processing - Requires more time than chemical methods. |
| **Bioaugmentation** | • Involves introducing specific microorganisms to accelerate the breakdown of pollutants, including wool.<br>• Significantly speeds up wool degradation—from months or years (naturally) to weeks under optimised conditions.<br>• Utilises keratinolytic microorganisms (e.g., Streptomyces species) that produce enzymes capable of breaking down keratin in wool fibres.<br>• Reduces the need for chemical treatments and landfill disposal.<br>• Offers a more economical solution by minimising reliance on conventional disposal methods and chemicals. | • Effectiveness depends on maintaining optimised environmental conditions for microbial activity.<br>• Requires specific strains of microbes and controlled application, which can be technically demanding.<br>• Most effective for protein-based fibres like wool, less applicable to synthetic materials.<br>• May involve technical challenges in managing microbial populations and monitoring degradation progress. |

# METHANE REMOVAL USING METHANE PYROLYSIS

UCL Energy Society

UCL

June 30, 2025

# Summary:

Greenhouse gas (GHG) emissions have been consistently increasing since the industrial revolution. Despite increased efforts since the 2000s, GHG emissions, mainly carbon dioxide ($CO_2$) and methane ($CH_4$) have continued to increase. In this paper we will focus on $CH_4$, the second largest contributor to climate change. While $CH_4$ has a relatively shorter lifespan in the atmosphere than $CO_2$, it traps more heat (IEA, 2022).

Pyrolysis is examined as the method of removing $CH_4$ from the atmosphere. The mechanism by which it works is examined to determine technical feasibility and government policy is examined to determine financial feasibility. It is concluded that the government should invest in pyrolysis to both remove $CH_4$ from the atmosphere and generate green hydrogen, a major aspect of its Net Zero plan.

# Introduction

Despite the recent efforts and global cooperation through the Paris Agreement and other means to reduce carbon dioxide ($CO_2$) and greenhouse gas (GHG) emissions, the levels of $CO_2$ are steadily increasing to reach around 37.5 billion tonnes of $CO_2$ ($GtCO_2$) in 2024 (Global Carbon Budget, 2024), an increase of 0.8% from 2023. In 2000, GHG emissions reached 25.5 $GtCO_2$.

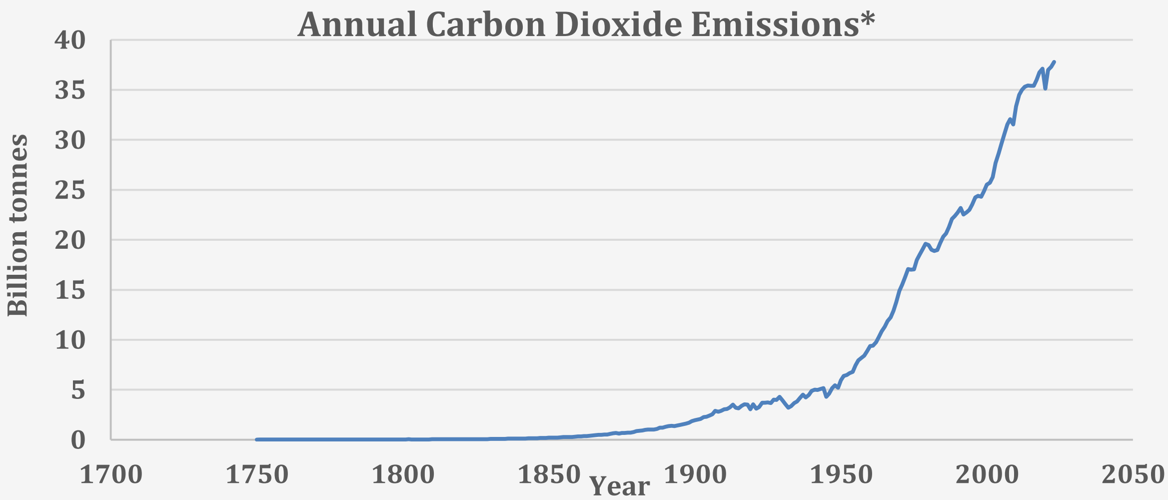


Figure 1: Annual Carbon Dioxide Emissions, Source: Global Carbon Budget (2024) *Land-use emissions are not included

What makes the situation more perplexing is the significantly larger size of investments in green technologies compared to brown technologies. Since 2016, the money poured into clean energy has surpassed the amount of investment in fossil fuels, with no profound impact on GHGs emissions in the atmosphere, as evident in figure 1 and 2 (IEA, 2024).

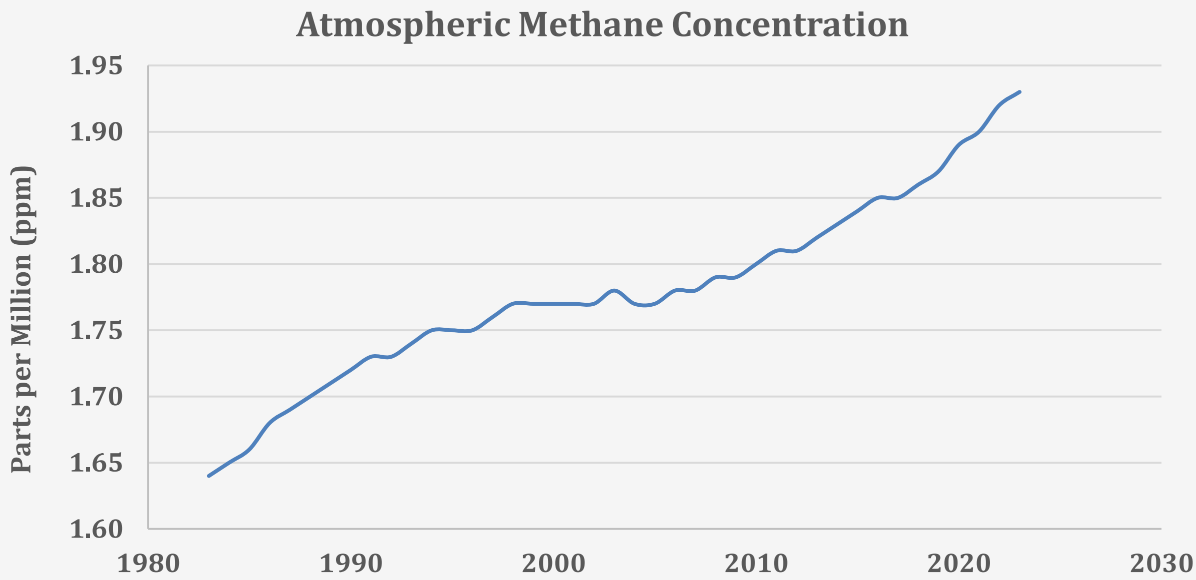


Figure 2: Annual Methane Emissions, Source: World Resources Institute (2025)

Thus, we need more efforts not only to reduce the on-going GHGs emissions, but to remove harmful gases from the air. While the technology is available, the cost to implement such technologies is very high. To incentivize investments in climate technologies, this paper illustrates reasons why governments should encourage investment in developing pyrolysis technology for the absorption of GHG emissions, mainly with regards to prospect stakeholders' benefits from the creation of valuable carbon materials and low-carbon hydrogen.

# Technology Utilisation Processes

Pyrolysis is a thermochemical process that decomposes chemical compounds at high temperatures into elements. The direct mechanism by which methane pyrolysis occurs and the various types of it are explored in **Appendix L1**. Overall, methane pyrolysis decomposes methane into hydrogen and carbon, both of which have many uses that will be explored later.

Currently there is no mature technology to capture methane from the air. However, that does not mean that reducing methane emissions is impossible. Methane emissions from anthropogenic sources are nearly 50% worldwide, and it is likely to increase in the future due to the growing global populations and the subsequent growing demand for food. If we narrow the focus down on the UK, 48% of methane emissions in 2023 are reported to come from agriculture. And this has remained more or less the same in the last six years (Royal Agriculture Society of England, 2023). Therefore, a technology to capture methane from landfills and farming is crucial and can be further developed in the UK to reduce methane emissions. Bennaman, a Cornwall-based company, has developed a technology to capture methane from farming, and has piloted a project in Cornwall (Royal Agriculture Society of England, 2023). The uses of captured methane in the project were limited to generating electricity and heat. But methane could be used as well to produce low-carbon hydrogen and carbon materials.

Currently, hydrogen in the UK is produced from natural gas (without carbon capture) and is utilized in chemicals manufacturing and industries. (Department for Business, Energy & Industrial Strategy, 2021). Producing hydrogen via alternative processes, i.e. methane pyrolysis, can help the UK achieve its targets and produce carbon-free hydrogen.

According to Research and Market analysis (2025), carbon materials' market size last year was estimated at $18.3 billion, and it is projected to grow to $27.5 billion by 2030. The growth may infer the technological advancement in utilizing carbon materials in a wide range of applications.

Graphite, for example, is critical for manufacturing electric vehicles' batteries (Nzereogu, 2022). Graphene, a carbon allotrope that conducts heat and electricity, would soon emerge in the optical electronics market (de la Fuente, n.d.). Moreover, research is ongoing to test semiconductors made of graphene to succeed silicon (Barzler, 2024). Carbon nanotubes research is penetrating different fields, including energy and environment, sensors and electronics, and biomedical applications (Hughes et al., 2024). Lastly, carbon fiber, known for its high strength and lightweight, is emerging in wind turbine blades manufacturing (Zhang et al., 2023). In conclusion, methane pyrolysis is important for the double advantage of eliminating harmful gases from the air, and producing critical carbon-based materials.

It is worth noting that Hazer Group, based in Australia, has started producing hydrogen and synthetic graphite from its demonstration plant utilizing catalytic pyrolysis. Hazer Group is aiming to produce annually 100 and 380 tonnes of hydrogen and graphite, respectively. Furthermore, ADNOC, a NOC in UAE, has partnered with UK's Levidian to produce low-carbon hydrogen and graphene via a plasma pyrolysis of methane.

# Policy, Regulations, and Incentives

The UK has a strong incentive to invest in methane pyrolysis as a means of decarbonisation from a policy perspective. The Climate Change Act of 2008, amended in 2019, stated the UK's commitment to achieve net zero emissions by 2050. As of July 2024, however, while the UK's territorial emissions have halved from its levels in 1990, most of their delivery indicators for decarbonisation are off track for what is required to meet their 2030 interim target and 2050 Net Zero target (Climate Change Committee, 2024). Methane represented 14% of total UK greenhouse gas emissions in 2022, a percentage that has remained stable since (Department for Energy

Security and Net Zero, 2024). Due to its potency as a greenhouse gas[1] as well as the difficulty of inhibiting the sources of emissions,[2] decreasing the concentration of methane in the atmosphere is the most efficient method to pursue national targets in combating climate change and recompense for off-target delivery indicators.

Aside from their international obligations to achieve Net Zero targets, further incentives exist for the UK to invest in the research and industry application of methane pyrolysis. For instance, energy security can be improved by capturing the hydrogen product from the methane pyrolysis reaction and using it to enforce a circular economy of hydrogen power. Methane has a higher potential than carbon dioxide to reinforce a circular energy economy for the UK, increasing its attractiveness as a compound to be pyrolysed. Methane and carbon dioxide both produce carbon upon undergoing pyrolysis. However, while carbon dioxide produces oxygen as its other non-carbon product, methane produces low-carbon hydrogen that can be used for clean energy production. Hydrogen is a clean energy carrier that enables reduced reliance on fossil fuels to generate power.[3] As such, hydrogen-fuelled energy is a critical component of the UK's strategy to achieve their net zero target: the 2021 UK Hydrogen Strategy stated that the UK will focus on increasing hydrogen production to 5GW by 2030 as well as improving the accessibility of hydrogen power throughout the 2020s (Department for Business, Energy & Industrial Strategy, 2021). Therefore, using methane pyrolysis for climate change brings the dual benefit of capturing carbon for industry applications and producing greater levels of hydrogen to be used for clean energy, a circular approach that reduces emissions by fostering the sustainable reuse of resources.

The environmental potential of methane pyrolysis can be realised through investment efforts in research and market implementation by the UK government. Direct financial support such as targeted grants, subsidies, and R&D tax credits can reduce early-stage risk. For instance, funding for methane pyrolysis development can be derived from the UK's Net Zero Innovation Portfolio, a £1 billion fund dedicated to finance low-carbon technology development. Public-private partnerships and co-investment schemes can accelerate innovation, as demonstrated by the EU's Innovation Fund for clean energy projects. Additionally, integrating methane pyrolysis into the UK Hydrogen Strategy and setting standards for low-carbon hydrogen would create regulatory

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[1] Methane is responsible for 30% of the rise in global temperatures since the Industrial Revolution. In 2022, its concentration in the atmosphere is around 2.5 times greater than its pre-industrial levels. (International Energy Agency)

[2] Out of the 570 Mt of annual global methane emissions logged in the Global Methane Budget, 40% come from natural sources such as wetlands and oceans. Therefore, reducing the concentration of methane already present in the atmosphere can more effectively mitigate the impact of methane emissions than inhibiting the sources of methane production. (International Energy Agency, 2021)

[3] Hydrogen fuel cells generate electricity by combining hydrogen and oxygen atoms. The hydrogen interacts with oxygen in an electrochemical cell, much like a battery, creating electricity, water, and a small amount of heat. (US Energy Information Administration)

certainty. Finally, supporting pilot plants through programmes like the UK's Industrial Energy Transformation Fund can bridge the gap between research and commercial deployment.

# Conclusion

Given the need to accelerate decarbonisation and manage methane emissions, methane pyrolysis offers a practical solution that combines environmental and economic benefits. By converting methane into low-carbon hydrogen and valuable carbon materials, the technology reduces a significant greenhouse gas while generating resources important for energy security and advanced industries. Although investment and policy support are necessary to address technological and cost challenges, these measures would help the UK meet its Net Zero commitments and strengthen its position in the hydrogen economy and carbon-based material markets. Incorporating methane pyrolysis into the UK's climate strategy represents a pragmatic step towards sustainable growth and global climate objectives.

# RECYCLING AND WASTE MANAGEMENT OF ASEPTIC CARTONS

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June 30, 2025

IMPERIAL

# Summary

Aseptic cartons are widely used for packaging perishable food and beverages due to their ability to preserve freshness and extend shelf life. Comprising multiple layers of paperboard, polyethylene (PE), and aluminium, they provide essential barrier properties but pose significant challenges for waste management and recycling. The complex structure of these cartons makes material separation difficult, often leading to low recycling rates and environmental concerns.

Traditional recycling methods such as hydrapulping allow for the recovery of paper fibres, while plastic and aluminium components are typically repurposed or incinerated for energy recovery. However, inefficiencies in these processes, including contamination and polymer degradation, hinder sustainability efforts. Alternative approaches, including bio-electrochemical systems, pyrolysis, and chemical recycling, present innovative solutions with the potential to enhance recycling efficiency and energy recovery.

This paper explores the challenges and advancements in aseptic carton waste management, focusing on improved recycling techniques, energy recovery methods, and strategies to mitigate contamination. By integrating emerging technologies with existing recycling practices, this study aims to identify more effective and environmentally sustainable approaches for handling aseptic packaging waste. It concludes that either different (more easily recyclable) materials need to be used, or that new techniques such as chemical separation and catalytic pyrolysis need to be adopted and scaled to the point of profitability.

# Paper

## *Recycling paper from aseptic packaging*

Aseptic cartons, commonly used for liquid food packaging, consist of multiple layers of materials, including paper, plastic, and aluminium. The recycling process of aseptic cartons requires specialised procedures due to their composite nature. This process is explained in **Appendix M1**.

Recycling paper from aseptic cartons contributes to resource conservation by reducing the demand for virgin wood fibres, thereby mitigating deforestation. It also results in significant energy and water savings. On the other hand, one of the main challenges in recycling aseptic cartons is contamination and the diminishing quality of the paper each cycle. **Appendix M2** explains the benefits and challenges of recycling paper further.

An alternative to recycling is composting, particularly for cartons with biodegradable coatings. Paper-based materials decompose under aerobic conditions, contributing to soil health when properly managed. Whilst the presence of contaminants such as inks poses similar difficulties, composting has many benefits; such as enhancing water retention and providing essential nutrients. **Appendix M3** goes into the benefits and challenges of composting in more detail.

To enhance sustainability, alternative materials to conventional paper structures are also under exploration. For instance, bio-based polymers such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA) offer composability while retaining barrier properties. Additionally, water-soluble barrier coatings combined with cellulose-based substrates can be used in place of laminated paper layers. These alternatives are designed to be fully recyclable or biodegradable under industrial composting conditions, reducing contamination and improving end-of-life outcomes. Table 1 summarises the pros and cons of each method discussed.

**Table 1.** Comparative summary table of the pros and cons of the methods, also listing the key facts

| Method | Pros | Cons | Key facts |
|---|---|---|---|
| **Recycling** | Recovers paper fibres<br>Reduces virgin wood use<br>Saves energy and water | Contaminant removal is difficult<br>Fibre degradation<br>High processing cost | 60% less energy used<br>80% less water (Smith et al., 2019) |
| **Composting** | Enhances soil health<br>Diverts waste from landfills<br>Supports carbon sequestration | Not suitable for plastic/aluminium layers<br>Requires optimal C:N ratio<br>Slower for coated/lignin-rich paper | Composting takes 6-12 weeks<br>Requires shredding and aeration |
| **Alternative Materials** | Fully compostable and recyclable<br>Reduces contamination<br>Supports circular economy | May require specialised processing<br>Performance vs. cost trade-offs | PLA and PHA degrade in industrial compost<br>Research ongoing for barrier efficiency |

## *Converting paper into energy*

Incineration, also known as direct combustion, is a widely used method in which wastepaper is burned at high temperatures to generate heat, which is then converted into steam for electricity production. Despite its efficiency in waste volume reduction, this approach has notable drawbacks, including pollutant emissions (e.g. $NO_x$, $SO_2$, and particulate matter), energy inefficiency, and challenges related to residual ash disposal (Zhang et al., 2020). The net electrical efficiency of modern waste-to-energy plants via incineration typically ranges from 20% to 30% (Arena, 2012), and while this process provides immediate energy, it suffers from relatively low energy conversion efficiency and environmental impact concerns.

To address some of these issues, anaerobic digestion (AD) presents a biological alternative by utilizing microbial activity to break down cellulose in paper. This process can achieve an overall energy efficiency of approximately 35% to 45% when coupled with combined heat and power (CHP) systems (Appels et al., 2008; Li et al., 2021), surpassing direct combustion under certain configurations. Additionally, the residual digestate produced in AD can be repurposed as a nutrient-rich fertilizer, improving the sustainability profile of the method.

A comparative analysis of direct combustion and methane generation indicates that while AD systems require longer processing and controlled anaerobic conditions, they offer higher energy yields from the same mass of cellulose and generate significantly fewer pollutants. However, high initial costs, substrate pre-treatment needs, and slower kinetics may hinder immediate scalability. A more detailed thermodynamic and economic comparison is provided in **Appendix M4**.

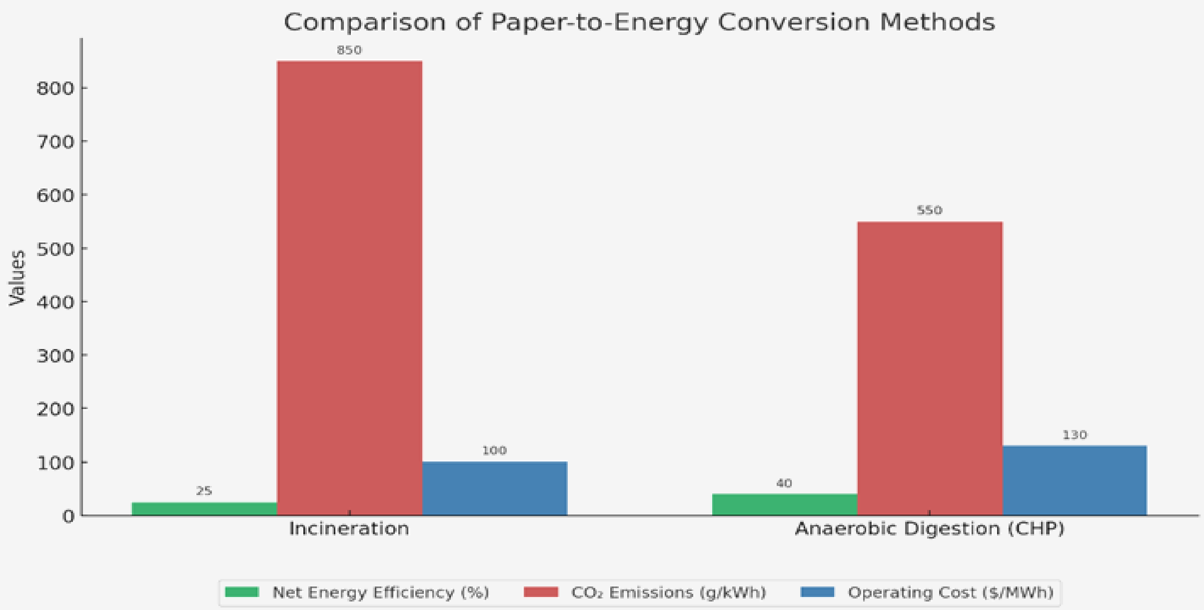


**Figure 1.** Comparison of incineration and anaerobic digestion. Data compiled from Arena (2012), Appels et al. (2008), Zhang et al. (2020), and Holm-Nielsen et al. (2009).

Another promising waste-to-energy technique is pyrolysis, which decomposes organic materials in an oxygen-free environment at high temperatures, producing bio-oil, syngas, and biochar. Unlike incineration, this method provides diverse energy outputs while significantly reducing emissions, making it a more environmentally friendly alternative (Williams & Jones, 2019).

Other methods such as gasification and refuse-derived fuel (RDF) production offer ways of turning the paper into fuels which can later be burnt to improve energy efficiency. However, they both face similar logistical and financial challenges. In depth explanations of the processes, their benefits and challenges can be found in **Appendix M5**.

To further improve the sustainability of paper-to-energy conversion, advanced carbon capture technologies (ACC) can be integrated into existing waste-to-energy processes to mitigate $CO_2$ emissions. Alternatively, bio electrochemical systems (BES) technology could offer a biodegradable and low-waste solution for converting paper waste into electricity in the future. However, currently, this method remains in the experimental stage and requires further advancements to improve its efficiency and commercial viability (Wang & Zhao, 2021). **Appendix M6** and **Appendix M7** cover the mechanisms by which BES and ACC work respectively.

Collectively, all these methods illustrate the diverse pathways available for converting wastepaper into energy. While traditional approaches like incineration continue to be widely used, emerging technologies such as BES and advanced carbon capture offer promising alternatives that could enhance both energy efficiency and environmental sustainability.

# Plastic

## *Recycling the plastic from Aseptic packaging*

Aseptic packaging is made up of multiple layers, including polyethylene (LDPE), and aluminium foil. The polyethylene component, with its inner and outer layers, complicates the process as separating the polyethylene from other components and recycling it effectively remains difficult.

In the UK, plastic waste recycling remains a pressing issue. In 2023, only 52.5% of plastic waste from packaging was recycled, while the remaining portion was either sent to landfill or incinerated (GOV.UK, 2022; Plastor, n.d.). Recycling of polyethylene from aseptic cartons primarily relies on two methods: mechanical recycling, which is the most commonly employed technique (Al-Salem, Lettieri, & Baeyens, 2009), and chemical recycling, which represents a developing field with emerging potential. **Appendix M8** and **Appendix M9** explain the mechanism of mechanical and chemical recycling respectively.

Recycling is primarily difficult due to two main reasons: contamination and degradation. Contamination is the presence of unwanted extra substances (such as food residue) which compromise the quality of the recycled polyethylene, and degradation is the process of plastics losing their desired propertied slowly with each recycling cycle. Solutions such as better systems to detect contaminants, self-cleaning plastic films, nanoparticle doping to reduce degradation, and use of alternative materials exist and are currently being researched. A study into all the challenges with recycling and their respective solutions can be found in **Appendix M10**.

Overall, while recycling polyethylene from aseptic packaging remains a complex challenge, advancements in mechanical and chemical recycling, along with innovative strategies to mitigate contamination and degradation, offer promising pathways to enhance the sustainability of this material. Additionally, exploring alternative plastics that are more recyclable than polyethylene could further improve the recycling process. Continued research and technological development will be essential to enhancing recycling efficiency and ensuring a more circular economy.

## *Improving efficiency of converting plastic into energy*

Processes of breaking down plastic like polyethylene and converting it into useful resources have gained more attention as the current practices such as incineration emits greenhouse gases and harmful gases that detriment the environment and increase climate change.

Pyrolysis and bacterial metabolism are considered as the more energy efficient ways of disintegrating plastics and converting them into fuel. Other processes such as gasification require a significant amount of energy to sustain the high temperature (500-1300°C) required to convert plastic feedstock into gas mixture, especially with material such as polyethylene that has a high thermal stability. In contrast, pyrolysis operates at lower temperature (300-650°C) although the energy consumption is still high, the end products of the process can provide energy for pyrolysis, reducing the reliance on the heating sources (Saebea et al., 2019).

While bacterial breakdown of plastic is more energy efficient, as it does not require a significant input of energy, optimal conditions need to be maintained for bacteria to metabolise. The process also has limitations such as low yield and slow rates, making it an overall a less efficient approach of converting plastic waste into fuel and challenging to scale up (Yang, 2023). Additionally, the feasibility of this approach is also subject to the availability of bacteria that are able to produce enzymes which facilitates the breakdown of plastic and whether the plastic is able to act as a substrate and allows bacteria to grow on (Cai, 2023). Moreover, enzymes are typically specific to one type of plastic, but not the other, it is therefore less effective in breaking down mixed plastic waste.

Pyrolysis is the most promising method of converting plastic into energy; however, two types exist. To minimise the energy input for pyrolysis, catalytic pyrolysis is the most energy efficient approach to convert plastics into oil. However, uncatalysed thermal pyrolysis has the benefit of obtaining a higher oil yield than catalytic pyrolysis (although the end products require further refinements). Hence, balances between the two approaches are essential to maximise yield, energy efficiency and cost-effectiveness, which are the key considerations in fuel production. Analysis of factors that have an impact on the oil produced are therefore important to determine the optimum conditions and approaches to carry out pyrolysis. An in-depth study into the mechanisms of pyrolysis, their environmental impact, ways to maximise their efficiency, and their economic feasibility can be found in **Appendix M11**.

## *Aseptic carton separation*

Hydrapulping is the predominant method for extracting paper fibres from aseptic cartons. In this process, cartons are introduced into a hydrapulper—a large, cylindrical vessel equipped with an impeller at the bottom. The hydrapulper operates by agitating the mixture of cartons and water, generating hydraulic forces that separate the paper fibres from the polyethylene and aluminium layers, resulting in a slurry. During the pulping process, no chemicals are added; the separation relies solely on mechanical agitation. The separated paper fibres are then screened through a perforated plate beneath the rotor, allowing the fibre-rich slurry to pass through while retaining larger contaminants. The extracted fibres are subsequently cleaned to remove any residual impurities and processed into new paper products such as tissues, paper towels, and cardboard. This method effectively recovers high-quality cellulose fibres for reuse (Robertson, 2021).

Following the extraction of paper fibres PolyAl can be processed through several methods. The first method is mechanical processing. The PolyAl residue undergoes cleaning to remove any remaining paper fibres. Subsequently, a wind shifting process separates three-dimensional caps and closures from two-dimensional films. The films, containing both low-density polyethylene (LDPE) and LDPE/aluminium composites, are then agglomerated and pelletized or granulated into a new raw material. These pellets can be utilized in manufacturing products such as plastic crates, pallets, and construction materials. The average composition of PolyAl without contaminants is approximately 63% LDPE, 11% aluminium, 19% high-density polyethylene (HDPE), and 7% polypropylene (PP). Mechanical recycling provides a practical use for the composite material without necessitating the separation of its components (Packaging Europe, 2021). An alternate approach is chemical recycling. This method involves dissolving the polyethylene using specific solvents, allowing for the separation and recovery of aluminium. The process typically includes dissolving the polyethylene in a solvent, precipitating it out, and then separating the aluminium for further purification. The recovered polyethylene and aluminium can then be repurposed for new applications. While effective, this process requires careful handling of chemicals and management of resulting waste streams (Shoaie and Bazargan, 2025).

Lastly, techniques such as pyrolysis involve heating the PolyAl mixture in an oxygen-free environment, causing the polyethylene to decompose into gases and oils while leaving behind aluminium residue. This process not only recovers aluminium but also produces energy-rich byproducts. Innovative approaches, such as microwave-induced pyrolysis, have shown promise in enhancing the efficiency and commercial viability of this method (Robertson, 2021).

The recycling of aseptic cartons involves a combination of hydropulping to reclaim valuable paper fibres and various PolyAl recovery techniques to manage the remaining plastic and aluminium components. Advancements in these recycling processes continue to improve the sustainability and efficiency of managing aseptic carton waste.

# Conclusion

Although notable progress has been made in recycling and energy recovery from aseptic cartons, their complex multilayer structure continues to limit processing efficiency. To address this, future efforts should focus on redesigning cartons using mono-material or biodegradable alternatives to simplify separation and improve recyclability.

Advancing this goal will also require greater adoption and scaling of innovative recycling methods, such as catalytic pyrolysis and chemical separation techniques. Additionally, collaboration between researchers, industry, and material developers will be essential in translating promising technologies, like bio-electrochemical systems, into practical, scalable solutions.

By aligning design, research, and implementation, we can shift from coping with waste to preventing it, supporting a more sustainable and circular approach to aseptic packaging.

# GOVERNMENT POLICIES

# POLICY FOR WIND ENERGY AND LONG DURATION ENERGY STORAGE

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June 30, 2025

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# Summary

The UK government has committed to the goal of reaching net zero by 2050 and a 68% reduction in emissions by 2030 [1]. One critical aspect needed to reach this goal is to adopt renewable energy at scale. In the past years, renewable energy generation capacity has expanded significantly in the UK. Whilst the UK currently has the largest capacity for offshore wind energy in Europe, and the second largest overall wind energy capacity in Europe [2], the UK government is looking to further expand these capacities significantly until 2030. However, to fully benefit from the extent of expanding wind production, an increase in energy storage capacity is required as well, to balance the grid and mitigate intermittency.

For both technologies, there is a gap between the targets the UK government has set and their current trajectory. Therefore, we will examine ways to bridge this gap through policies. While wind energy technology is relatively mature, due to the effect of policies, such as the Contracts for Differences (CfD) established in the UK, many types of energy storage technology are still in their infancy, and their development could benefit significantly through increased support.

Our main insights are summarised below:

1. The UK government aims to have 50 GW of offshore wind installed by 2030 [3], however current projections show that only 35.5 GW will be installed by 2030 [2]. The main policy supporting wind energy development is the CfD scheme, which provides revenue security for developers. A major challenge for wind energy is permitting and planning with many more projects in the pipeline than can be accepted [4]. Currently, the UK government is introducing reforms to accelerate the permission process, but it remains to be seen how effective they are in practice. Hence, these policy reforms need to be evaluated iteratively, to evaluate if the pain points really are addressed.

2. While current targets to double LDES by 2030 are already ambitious, even more is needed to replace the current 35GW of gas to reach net-zero targets. Stronger policy support is required to foster especially less mature storage technology. For example, the addition of formal targets for the cap and floor scheme and the inclusion of smaller projects and less mature technologies in the cap and floor scheme could help address newer storage technology projects. Furthermore, a more comprehensive policy mix could help address energy storage development overall, such as financing and grid connection challenges.

# Wind Power Policy

The UK government has made significant progress in promoting renewable energy, with wind power accounting for over 30% of total electricity generation in 2024 [5]. While the UK's 31.6 GW of installed wind capacity has significantly displaced fossil fuels, achieving a clean power-system by 2035 will require a tripling of offshore wind capacity and doubling of onshore installations [6]. The rapid scaling required brings to the fore critical issues of system integration: the inherent intermittency of wind generation, combined with aging grid infrastructure and complex investment landscapes, creates a range of challenges that current market structures struggle to address effectively.

This section evaluates how the UK’s policy framework – particularly the Contracts for Difference (CfDs) scheme and planning reforms – is rising to meet these challenges. We assess whether incremental improvements to existing mechanisms can deliver the required transformation, or if more radical market redesign will be necessary to maintain Britain’s position as a global wind energy leader. The analysis focuses particularly on the tension between long-term investment signals and short-term deployment bottlenecks, with implications for policymakers worldwide pursuing similar clean energy transitions.

## *Wind energy in the UK: Current status and scaling challenges*

The UK's wind energy capacity reached 31.6 GW in 2024 (15.7 GW onshore, 15.9 GW offshore), with 1.9 GW added that year alone. However, this progress masks an urgent challenge. While WindEurope forecasts 59 GW of installed overall capacity in the UK by 2030 (23.5 GW onshore, 35.5 GW offshore), current trajectories suggest the UK will fall short of its 2030 targets [2]. The Climate Change Committee recommends that at least 50 GW of offshore wind would be needed by 2030 in order to meet the UK’s climate goals [7]; this aligns with the government’s goal of reaching 50 GW of offshore wind by 2030 [3]. This looming shortfall persists despite ambitious political commitments, including Labour's 2024 pledge to quadruple offshore wind capacity [8] and the Chancellor's recent removal of planning barriers for 16 GW of projects [9]. Additionally, the halt of major projects, such as recently of the 2.4 GW Hornsea 4 project by Ørsted, further exacerbates the gap between target and currently planned capacity. According to Rasmus Errboe, the chief executive of Ørsted, the project halt is due to macroeconomic developments, higher risks and challenges for the supply chain [10]. Achieving the required acceleration in deployment demands a fundamental overhaul of planning systems, supply chains, and grid infrastructure to transform ambitious targets into operational turbines. With the 2030 deadline approaching, the UK has less than 5 years to prove whether its policy framework can catalyse the build-rate required.

## *Contracts for difference (CfDs)*

The Contracts for Difference (CfDs) scheme has revolutionised the UK's wind energy sector by creating a stable investment environment through its innovative pricing mechanism. Under this mechanism, a ‘strike price’ (reflecting the long-run marginal cost of electricity) is agreed between the energy producers and government. If the wholesale electricity price falls below the agreed strike price, the government will pay the difference between the strike price and the wholesale electricity price to the developer. However, at times when the market price is higher than the strike price, the wind farm compensates the government. This ensures a stable revenue stream for renewable energy generators, mitigating risks from variable electricity prices and making wind projects more attractive to risk-averse financiers, such as banks [11]. The resulting shift in investor composition has provided easier access to cheaper finance and led to a reduction in the cost of capital for wind power projects. This elegant risk-sharing model has achieved remarkable results, driving offshore wind costs down by 22% by 2020 to a record of £31/MWh [12] .

For offshore wind, the CfD scheme has been particularly successful at driving down costs through competitive auctions. Onshore wind, initially excluded from CfD auctions, was reintroduced in 2021, reflecting its cost competitiveness and potential to contribute to national energy security. By providing revenue certainty, the CfD scheme enables developers to secure financing and plan long-term investments, accelerating the deployment of both onshore and offshore wind projects. Currently, the government is proposing reforms to the CfD, such as increasing the length of contract terms [13].

Ofgem, the UK's energy regulator, plays a critical role in overseeing pricing mechanisms for wind power. The regulator ensures fair CfD auctions and compliance with grid connection requirements. Ofgem's recent reforms such as the 'first ready, first connected' approach, aim to reduce connection delays, enabling a faster project deployment. Delivery bodies such as the Low Carbon Contracts Company (LCCC) manage CfD payments and ensure the smooth operation of the scheme. By providing clear regulatory oversight and efficient delivery mechanisms, the UK can create a stable environment for wind power investment.

The government has also allocated significant funding to support wind power technologies. Initiatives like the Offshore Wind Growth Partnership (OWGP) provide financial and technical support to supply chain companies, fostering innovation and reducing costs. Onshore wind projects benefit from grants and subsidies aimed at repowering existing sites with more efficient turbines.

Looking ahead, the CfD scheme must evolve to maintain its effectiveness. Technology-specific auction pots could support floating wind development, while simplified bidding processes might better accommodate community energy projects. Introducing dynamic strike prices that respond to supply chain inflation could preserve investor confidence amid economic volatility. When combined with complementary initiatives like the Offshore Wind Growth Partnership and turbine repowering incentives, a refined CfD system could aim to deliver the 50 GW offshore wind target.

## *Planning and permitting challenges*

While CfDs have successfully reduced the risk of wind energy investments for developers, their potential could be undermined by planning and permitting bottlenecks. Grid access is an important hurdle, with WindEurope in 2024 identifying wind energy projects with 145 GW that are still waiting for the assessment of their grid connection in the UK. Grid access includes the initial grid connection as well as curtailment due to grid congestion [4].

The current government is already working on addressing the planning and permitting problems. For example, new ways of filtering grid connection requests have been proposed which would enable the elimination of projects that move slowly or are stalled from the transmission connection queue [4]. The UK government is also considering less strict eligibility criteria for the consent of planning fixed-bottom offshore wind projects [13]. While there is a significant amount of potential capacity in the pipeline, up to 93 GW for offshore wind alone, as of 2023 [3], the process from identifying a suitable site to a project being ready to apply for a CfD can be slow [14]. The changes made in the last year to support offshore wind and accelerate permitting are headed in the right direction. However, over the next years, the development of further wind energy projects needs to be followed closely to identify if the pain points, especially if permitting and planning really have been addressed. This can be done in close cooperation with industry, e.g., consulting project developers, grid companies and wind manufacturers but also taking into account local communities' concerns.

### *Broader policy alignment*

Realising the full potential of wind energy demands a holistic policy framework that extends beyond pricing mechanisms such as CfDs and permitting procedures. The UK's Clean Power 2030 Action Plan [6] underscores the need to align wind power incentives with net-zero emissions targets. Complementary policies such as tax credits, grants, and streamlined planning permissions can reduce barriers to entry for new projects. For example, encouraging wind power participation in capacity markets—where they can provide grid services such as frequency regulation and load balancing—enhances their economic viability while improving grid stability. This integration supports a more resilient and flexible energy system capable of accommodating higher shares of renewables.

## Long-duration Energy Storage Policy

Whilst wind power encapsulates some of the key issues of increasing renewable capacity, meeting renewable energy targets itself brings its own challenges for the electricity transmission and distribution networks. As the UK grid's renewable energy share increases, so does the demand for *flexibility* in the electrical grid. This requires technologies which, according to the UK government 'Clean Power 2030: Action Plan' [6], can, in addition to supplementing the country's electricity when low in wind and sun, provide 'essential grid services such as inertia, voltage support, short circuit and demand response'. In this section we analyse how coherent the UK's policy is for supporting technologies which can fulfil this role, through firstly discussing the overall targets and secondly the mechanisms for achieving them.

### *Defining targets*

Whilst gas has traditionally filled the niche of providing flexibility in the electricity ecosystem, the drive towards Net Zero and concerns about energy security make building more gas power plants infeasible. According to the Action Plan [6], the UK's strategy for 2030 is to maintain the current 35 GW fleet of gas plants, and use *long-duration energy storage systems* (LDES) and other low-carbon 'dispatchable' technologies (such as hydrogen-to-power and biomass fuels) to inject another 5-15 GW of flexible power capacity into the grid, depending on how ambitious the renewables penetration targets are. In these 2030 scenarios, LDES will comprise 4-6 GW of this *non-gas* flexible power, requiring a 30-100% increase of the current LDES capacity of 2.9 GW. To achieve the upper end of this range is already an ambitious goal for the next five years, but it should be noted that 6 GW of LDES is still dwarfed by the 35 GW of gas that the report acknowledges ultimately needs to be phased out, albeit over a longer time-span.

To get a sense of the nature of the challenge, it is useful to more precisely define the term 'long-duration energy storage'. The *Energy Act 2023* [15] narrowed the definition of 'electricity storage' to 'energy that has been converted from electricity and is stored for the future reconversion into electricity', thereby excluding most thermal energy storage from this specific legislative bracket. In terms of 'how long is long', Ofgem recently decided that only LDES systems which can discharge for a minimum of 8 hours will be eligible for cap-and-floor schemes [16] (as will be discussed in more detail later). This is presently more realistic than the most ambitious ideas around seasonal energy storage, but still longer than many battery systems can comfortably discharge over. Nevertheless, batteries remain an attractive option given their high technological maturity. LDES therefore effectively refers to 1) established but site-limited technology such as pumped hydro, 2) less mature but potentially more versatile systems currently at the demonstration stage, such as flow batteries or compressed air energy storage (CAES) [16], and 3) those electrical battery systems which are able to comply with the LDES definition.

This diversity in technological readiness creates challenges for policy, since support for huge constructions such as the planned 'Fearna' 1.8 GW pumped hydro facility in Scotland [18] has different characteristics from the government's £69 million investment in an LDES demonstration programme for less mature technology [17]. The next section will examine specific policy mechanisms that the UK government has put in place and discuss how effective they might be in helping the UK to reach its Net Zero targets.

## *Cap and floor: compromises and uncertainty*

In October 2024, the UK government introduced an LDES cap and floor scheme, to be delivered by Ofgem [19]. Essentially, the scheme provides developers with a guaranteed minimum price for selling power into the grid (the 'floor'), in return for a capped maximum price (the 'cap'). This is therefore a trade-off between risk and reward; investors will have more confidence in the floor-backed business case for these emerging technologies, and as such can accept lower maximum returns, which benefits the government and consumers.

Although the majority, 54% of respondents, supported the scheme, it is useful to explore the pros and cons. Supporters believe that cap and floor will significantly de-risk capital expenditure (CAPEX), has been used successfully for electricity interconnectors, will provide protection to taxpayers and consumers, and will encourage assets to optimise [20]. Those opposing it noted that the mechanism could distort the market, benefit some technologies more than others and may be difficult to administer. Others felt it would not sufficiently de-risk investment or incentivise assets to optimise, and that the interconnector cap and floor scheme is not comparable, as storage assets can access a variety of revenue streams. Some suggested a reformed Capacity Market with longer-term contracts would be better suited to LDES, as this would be a more technology-neutral alternative, retaining competitive tension between different providers [20]. Whilst it is true that LDES and interconnectors are not directly comparable technologies, it is likely that the potential to significantly de-risk CAPEX is the key perceived advantage of cap and floor and hence why it has been chosen.

The scheme is split by technology readiness level (TRL: ranked from 1 - least mature, basic principles only - to 9 - most mature, fully operational and deployed), with a minimum capacity of 100 MW for technologies at TRL 9, and a minimum capacity of 50 MW at TRL 8 (likely to include technologies such as CAES). The majority of respondents felt that the minimum capacity for TRL 8 was too high, citing that a capacity of 1-20 MW was more suitable, and that 50 MW minimum would require significant CAPEX (circa £100m) and investment risk [20]. DESNZ noted this feedback and committed to reviewing this capacity; however, despite increasing the definition of LDES from 6 hours to 8 hours duration, they decided not to change their approach to the minimum project capacity [21]. Together, these policy decisions to increase minimum discharge time to 8 hrs at a minimum of 50 MW could significantly hinder the development of promising new TRL 8 technologies such as CAES, in which the UK could become a global leader if policies truly support their development. Therefore, this cap and floor scheme may appear to be more focussed on supporting mature technologies to deliver 2030 targets, than developing and scaling future technologies to achieve longer-term 2050 goals.

Compounding this, although LDES capacity targets of 4-6 GW by 2030 [19] have been set, no specific total UK-wide capacity target was identified for this cap and floor scheme, which was criticised during the consultation; many argued that a target would provide more confidence for investors. The government argues that it is too early to set targets, largely because other technologies like Carbon Capture, Usage and Storage (CCUS) may have a significant part to play in system flexibility. It is not clear whether this argument holds weight; CCUS does not generally provide the same grid-balancing function as energy storage. Further, it was identified that the cost benefit analysis (CBA) under a cap and floor would not consider the impact on other assets that exist or are in the pipeline. Respondents believed that a lack of policy alignment could also cause further risks; it is clear that policy alignment is needed in order to continue to accelerate the development of LDES.

## *Broader policy alignment*

So, how well does the scheme align with wider policy? In January 2024, Ofgem were 'minded-to' require projects to have valid planning consent and grid connection offers in order to apply for the cap and floor scheme [21]. However, stakeholders raised significant concerns about needing to have obtained full consent, a firm grid offer and a completed Front-End Engineering Design (FEED) study before even applying for the scheme. They have therefore relaxed their requirements; due to the National Energy System Operator's (NESO) ongoing grid connection reform process, only evidence of grid connection application is needed. Further, a FEED study is no longer required, and some planning consent flexibility has been granted for projects deliverable before 2030. These relaxed requirements are a positive step, however the outcomes of these policy frameworks remain to be seen, and it is unknown how many of these projects will secure a grid connection. The project assessment process will begin later this year, and in mid-2026, Ofgem expects to set out progress milestones which developers must meet to ensure timely delivery of their projects [21].

# Conclusion

Wind energy is an important driver for the UK's shift to renewable energy, which needs to be supported by energy storage solutions. The UK is already supporting the deployment of renewable energy technology with various policies, e.g., CfDs for wind energy or the LDES cap and floor scheme as well as systems aimed at increasing planning and permitting speed. However, both for wind energy and energy storage there is a long way to go to reach the targets set by the UK government.

Current projections for offshore wind in the UK for 2030 still fall short by 14.5 GW. While the key support mechanism, the CfD scheme has worked well in the past, reforms would enable the encouragement of more projects. This could be done through, for example, technology-specific auction pots, simplified bidding processes and the introduction of dynamic strike prices. A major challenge for the development of wind energy is permitting and planning. While reforms such as novel ways to filter grid connection requests and less strict eligibility criteria have been proposed to speed up the process, their effectiveness remains uncertain and requires ongoing evaluation. Furthermore, these policies need to be integrated into a holistic policy framework aimed at expanding wind energy capacity.

Targets to double LDES capacity by 2030 are ambitious, yet still small in comparison to the longer-term ideal of replacing gas which would make 2050 Net-Zero more feasible. Due to the novel nature of LDES technology, even the 2030 targets will require significant government support. The current approach of a cap and floor scheme to incentivise investment, combined with government-funded demonstration programmes, seems sensible, but the fact that the cap-and-floor scheme has no alignment with national targets reflects the huge uncertainty in this area. Generally, the government has been receptive to industry concerns about how the strict definition of LDES and difficulty of obtaining grid connections could impede the progress of this very immature technology, and has adapted policy accordingly. It is important that policy continues to balance developing emerging technologies which could help achieve longer term 2050 targets, whilst supporting technologies which can deliver to 2030 targets.

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# CLEAN POWER 2030: BUILDING A RESILIENT GRID

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# Summary

The UK's transition to a low-carbon energy system has reached a critical juncture, with ambitious government targets set to deliver 95% clean power by 2030 under the new Labour government. This report evaluates the current and proposed energy security policies through a detailed analysis of supply- and demand-side strategies, infrastructure upgrades, and system integration. We assess the feasibility of Labour's Clean Power 2030 target, considering technologies such as nuclear, wind, solar, and energy storage, alongside demand-side shifts like heat pump and EV implementation.

Our analysis includes energy mix projections, carbon savings modelling, cost-benefit comparisons, and grid demand forecasting to determine whether these policies can secure a stable, clean, and affordable energy future. We estimate that by 2030, wind and solar will comprise 55% of the UK energy mix, with nuclear at 20%. Our carbon savings model suggests that wind, solar, nuclear, heat pumps, and EVs together can deliver over 100 $MtCO_2e$ in emissions reductions by 2030. However, achieving this will require substantial infrastructure investment, grid upgrades, and stronger consumer incentives.

Despite the ambition, risks remain around storage scalability, nuclear investment gaps, and public uptake of new technologies. Our findings conclude that while the UK is directionally aligned with net-zero commitments, realising energy security alongside decarbonisation will demand coordinated policy, funding reform, and a systemic approach to energy demand management and grid resilience.

# Background

## *Energy Act*

The UK began significant focus on tackling climate change and national carbon emissions in 2008, with the lawful implementation of the Climate Change Act. This was significant as it was the world's first legally binding framework for reducing emissions, initially aiming for greenhouse gas emission reductions to 80% below 1990 levels, and a 2019 revision aiming for 100%. Importantly, the Climate Change Act required the setting of 5-year carbon budgets, which since have all been met, highlighting the success of the Act in its early stages. However, it may become increasingly difficult to manage the balance of greenhouse gas reduction with energy security plans[1].

## *Labour Plans*

The government have enacted many polices since 2008 but as a new government takes charge on Downing Street it is important to access their proposed plans and validate their feasibility and effectiveness in proving green, secure energy. The Labour government have changed the previous governments target to reach 'clean power' by 2030 instead of 2035. Clean power is defined as ‘In a typical weather year, the 2030 power system will see clean sources produce at least as much power as Great Britain consumes in total over the whole year, and at least 95% of Great Britain’s generation’[2]. This is an ambitious target and that will require the careful planning and implementation of government policy to be met. The Government plans to reach this target by continuing to invest in wind and solar, developing nuclear energy programmes, and creating the Great British Energy[2].

# Supply-side Plans

## *Nuclear*

The delivery of new and advanced nuclear power sits on the government’s Ten Point Plan for a Green Industrial Revolution[3], with the 2022 British Energy Security Strategy proposing an expansion of nuclear power from 15% of the energy share to 25% by 2050[4]. The creation of Great British Nuclear highlights the intention to increase the share of low-carbon nuclear energy to accompany renewables, leading to an effective energy transition with nuclear having the same carbon footprint as wind (lower than solar)[5], lower mineral requirements[6], and using 18 times less land per MWh energy than solar[7]. Nuclear is critical for security, the aforementioned lower mineral requirements reduce reliance on risky supply chains, especially where mineral extraction is constrained to only one or two countries worldwide. The supply chain for nuclear is lower risk than solar and wind power, and 93% of it is located within the UK[8], improving security and boosting the economy. The critical barrier to expanding nuclear is the high costs involved, though once the initial investment is made, prices and the energy itself are stable and reliable. The privatisation of the industry has led to reduced investment, as nuclear has long lead times and slim margins. Investment in nuclear needs to be made more desirable, for example by supporting the use of regulated asset base funding such as in Hinkley Point C. Further investment in a geological disposal facility would assert the UK as a leader of a nuclear shift, as we have already invested in building a HALEU facility. Finland demonstrated that this could not only have a positive impact on our energy but on the surrounding communities[9].

## *Storage*

With the UK’s plans to move to 95% clean power by 2030, the energy mix will become more intermittent [10]. This necessitates not only baseload energy but also storage for hourly, daily and seasonal fluctuations to guarantee energy supply [11]. Drawing from the Royal Society Report on Energy Storage Technologies, LAES, CAES, Pumped Hydro Storage and Hydrogen alongside Flow Batteries have been evaluated [12]. With increasing electrification and intermittency and considering different maturity levels of storage options, this paper recommends R&D incentives, subsidies and tariffs to incentivise development and deployment of storage technology by 2030. Focus should be put on pumped hydro, hydro and flow batteries, their management and grid integration to maximise round-trip efficiency and storage capacity throughout the UK. For this, the 2024 cap and floor system is relevant and should receive more support.

# Demand-side Plans

## *Heat pumps*

As of 2022, 20% of the UK's greenhouse gas emissions came from residential buildings, majority of which were attributed to oil and gas combustion for heating purposes[15], therefore decarbonisation of heating in homes has formed a significant part of recent energy policy. Especially as the UK plans to reduce reliance on gas, low-carbon technology advancements and replacements need to occur at a coherent pace to supply side transformation. Alongside the *Net Zero Strategy*, a *Heat and Buildings Strategy* was also released in 2021, which built on the messages of buildings decarbonisation from the *Clean Growth* Strategy and *Ten Point Plan.* This strategy set out key actions including, the phase out of new natural gas boiler installations from 2035, building a UK market which can deploy at least 600,000 heat pumps per year by 2028 and improving energy efficiency of homes, all while also committing to affordability through grant schemes like the Boiler Upgrade Scheme (BUS) and ensuring opportunities for jobs are created[16]. Although BUS applications seem to be increasing per year, according to the latest *CCC Progress Report to Parliament* the UK is not on track to meet to meet the installation target set for 2028[17]. By 2030, 10% of homes would need to be heated via heat pumps which is a large jump from the 1% currently, implying an evaluation of barriers to heat pump uptake is required to understand how an increased installation rate can be achieved.

The main barrier to heat pump uptake is the upfront cost associated with not only installations and equipment but also home insulation upgrades required to ensure effectiveness of heat pump operation. Air source heat pumps can cost up to £10,500 and ground source heat pumps can cost up to £45,000, not including the external upgrades. Even with the increased BUS grant amount of £7500, the extra cost a consumer would have to cover is still quite high. With many households struggling to cover energy bills, it is expected that consumers would prefer short-term fixes over long-term solutions; according to Citizens Advice only around 16% of homeowners are able to afford heat pumps without additional borrowing[18]. Running costs are a major concern amongst consumers. Though moving to an electric only home can save costs in terms of gas standing charges and operating costs, there are still concerns over the long-term cost effectiveness of heat pumps at high electricity prices. Even in ideal scenarios of houses with a suitable seasonal performance factor, a heat pump is 9% more expensive than an efficient gas boiler[19]. Alongside cost, little awareness and understanding of heat pump technology types as well as energy efficiency is another barrier to uptake.

The new Labour government has introduced the Warm Homes Plan which aims to support 300,000 households with upgrades and help households save money on energy bills[20]. An addition to previous BUS plans includes households not having to submit a planning application to install an air source heat pump which was a deterrent for many consumers previously. The plan also aims to boost UK heat pump manufacturing industry and support low-carbon jobs.

Although consumers are taking more advantage of current government schemes, uptake is still slow and the UK is falling behind compared to other European countries. Many myths exist regarding heat pump effectiveness during winter, therefore awareness of heat pumps needs to be improved and customers should be provided with more resources. Currently, even efficiently insulated households may not save a large amount by replacing an efficient gas boiler for a heat pump, therefore focus could be shifted towards those households with older gas or potentially oil powered systems. Upfront and operating costs are a major worry amongst consumers; in the long-term high power price is due to be combatted by supply side measures however in the short-term the government should further work with relevant companies to develop special heat pump tariffs as well as interest-free loan schemes to help households spread out upfront costs not covered by the grant. This is already available in Scotland[22].

### *EVs*

Transitioning to electric vehicles (EVs) is essential for decarbonising the UK's transport sector, among the largest carbon emissions sources[23]. Shifting to EVs powered by renewable energy bolsters the UK's net-zero goals and improves energy security by reducing dependence on unstable global oil markets[24]. Nevertheless, success in this transition depends on establishing a robust and widespread EV charging infrastructure. 59,670 Public EV charging devices were installed in the UK in April 2024, of which only 19.4% are fast chargers[25]. By the end of 2023, there were over 1,474,000 plug-in EVs in the UK[26]. This concludes that each charging device needs to serve more than 24 cars.

A widespread rollout of electric vehicles (EVs) will significantly increase electricity demand, necessitating a robust and flexible grid. Without proper charging infrastructure, grid stability may falter, especially during peak charging times. To address this, smart charging solutions should be utilised to shift demand when renewable energy generation is at its peak, reducing the reliance on fossil fuel backup power[27]. Additionally, vehicle-to-grid (V2G) technology can further improve grid flexibility by allowing EVs to serve as mobile storage units, supplying electricity back to the grid during high-demand periods[28].

Expanding the charging infrastructure is crucial for urban and rural regions to promote widespread EV adoption. Investment is needed in public fast-charging networks, charging points at workplaces and residences, alongside upgrades to grid capacity to avoid electricity distribution bottlenecks. Moreover, coupling charging stations with renewable energy sources like solar and wind will further reduce dependence on natural gas for electricity generation.

## Infrastructure

### *Public transport*

In the UK the domestic transportation sector accounts for the largest sector for emissions. This has been the trend for the last few years, which means efforts to decarbonize transport, and enhance public transport are crucial if the UK is the meet its net-zero commitments[29]. Recent policies in the UK such as the UK's Zero-Emissions Vehicle (ZEV) mandate, suggest the UK will see sustained growth in zero-emission vehicles each year on UK roads. The ZEV policy only focuses on private vehicles, but public transport vehicles are also undergoing the same transition[30].The UK currently has around 41 million registered vehicles with only 1 million of that number being zero-emission vehicles[31]. Current figures suggest that personal vehicle use in the UK has decreased by 5% on average over the past 10 years and this trend remains. Indicating that public transport services will be in strong demand. Transport for London has already confirmed that it will completely transition to EVs on its bus fleets by the end of 2034[32]. It is expected that this trend will continue till public transport services meet national 2050 Net-zero commitments. Various service vendors across the UK also confirmed their commitment to long-term electrification across their services. Rail electrification in the UK is currently only around 40%, with plans for the rail network to be 95% electrified by 2045[33].

As a result of these shifts, the UK is projected to see a surge in demand on the national grid in the coming years. This will impact both the UK's energy security and energy infrastructure. Currently, annual grid capacity in the UK produces between 300 – 360 TWh and National Grid estimates this transition will lead to extra demand of 100 TWh per year until 2050[35] to support the transition to Zero-emission technology. Without the necessary infrastructure upgrades, and grid solutions the UK would be left reliant on international energy imports. This could lead to power shortages, higher energy costs, and transportation delays across the country, threatening the UK's ability to maintain stability and resiliency.

# Conclusion

The UK's 2030 clean power target is achievable—but only through immediate, coordinated action that addresses current gaps in investment, infrastructure, and policy execution. Delivering 95% clean electricity and long-term energy security will require precise, systemic changes across every component of the energy system.

To ensure a reliable baseload as gas is phased out, the government must commit £30–50 billion to nuclear expansion over the next decade, using Regulated Asset Base (RAB) financing to de-risk investment. Without this, the UK risks falling short of its 25% nuclear capacity goal by 2050, undermining supply stability.

Simultaneously, a legally binding national storage strategy must be implemented by 2026, mandating minimum storage capacity for grid operators and offering tax incentives for technologies like flow batteries, pumped hydro, and green hydrogen and an expanded cap and floor system. This is essential to balance intermittent generation from wind and solar, which are projected to make up 55% of the grid mix by 2030.

On the demand side, the Boiler Upgrade Scheme (BUS) should be increased to £10,000 per household, paired with zero-interest loans for remaining installation costs. Current uptake rates are insufficient to meet the 600,000 annual heat pump installations needed by 2028. Heat electrification must be supported by both financial and regulatory tools, including targeted subsidies for low-income households and streamlined planning processes.

Electric vehicle (EV) adoption must be matched with robust infrastructure. We recommend a national mandate of 150,000 public EV chargers (including 50,000 fast chargers) by 2030, alongside upgrades to grid capacity in high-demand areas. Without smart charging integration and vehicle-to-grid systems, peak load spikes will further destabilize an already strained grid. To support decarbonisation in transport, the UK should electrify 60% of its rail network by 2035 and require all public bus fleets to transition to EVs by 2030, supported by matched Department for Transport funding. These shifts will reduce urban emissions and ease pressure from private vehicle reliance overall.

Finally, a National Grid Modernisation Taskforce should be established by 2025, with cross-department oversight and direct Treasury funding. The grid must handle a projected 545 TWh of annual demand by 2050, up from 330 TWh today. Without timely upgrades to substations, transmission networks, and digital grid management, clean power deployment will be severely constrained.

With available technologies and defined targets, the next step calls for bold action. By incorporating prior suggestions, the UK can meet its clean power targets, reduce reliance on volatile global energy markets, and deliver secure, affordable, and resilient energy for generations to come.

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# ASSESSING THE UK'S RTFO POLICY

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# Summary

This paper provides a thorough review of the United Kingdom's Renewable Transport Fuel Obligation (RTFO) policy, especially regarding worldwide best practices and future energy transition objectives. The RTFO, an essential legislative framework within the Department for Transport, promotes the adoption of low-carbon fuels via Renewable Transport Fuel Certificates (RTFCs), aiming to diminish greenhouse gas (GHG) emissions in the transport sector and attain the UK's Net Zero objectives by 2050. The research assesses the strengths and limitations of biofuel pathways by comparing worldwide projects in Brazil, the United States, and the European Union, with a special emphasis on the trade-offs between waste-derived and crop-based feedstocks, and the technical viability of waste-derived and land-intensive biofuels is evaluated using energy yield projections and lifecycle efficiency metrics. The analysis underscores the enhanced sustainability attributes of waste-derived biofuels, encompassing their compatibility with biogas systems, reduced land-use effect, and potential for technological advancement via breakthroughs like enzymatic degradation. The report, alongside technical evaluations, examines the economic, political, and communicative aspects of the RTFO, pinpointing essential success factors such as financial incentives (subsidies, RTFC trading, and double-counting mechanisms), strategic communication to harmonise with public and stakeholder interests, and countermeasures to political dissent from across the ideological spectrum. Case studies illustrate that policy consistency, market stability, and sustainable feedstock development are essential for international success, providing relevant insights for the UK. RTFO offers a scalable and adaptable framework for decarbonising UK transport; nevertheless, its efficacy depends on sustained research and development investment with a particular emphasis on utilising energy from agroforestry waste, and universal political endorsement.

# Case Studies:

## *The United Kingdom's Renewable Transport Fuel Obligation (RTFO) in Global Context.*

The transport industry continues to be one of the most emissions-intensive elements of the UK economy, representing over 25% of national greenhouse gas (GHG) emissions as of 2023. In this sector, road transport accounts for more than 90% of emissions, highlighting the pressing necessity for revolutionary measures to comply with the UK's constitutionally mandated Net Zero by 2050 objective and its obligations under the Paris Agreement. In addressing these difficulties, the Renewable Transport Fuel Obligation (RTFO) has become a fundamental element of the UK's policy to decarbonise transportation, improve energy security, and promote sustainable innovation. The RTFO, created by the Energy Act 2004 and enhanced via subsequent legislative revisions, requires fuel suppliers to gradually incorporate renewable fuels into the national transport fuel mix. The program establishes a mandatory objective of 21% renewable content by 2032, emphasising waste-derived and advanced biofuels—specifically those generated from spent cooking oil, agricultural wastes, and municipal waste—while enforcing a strict 2% limit on crop-based biofuels. This cap represents a calculated attempt to mitigate the negative environmental and social impacts identified in previous worldwide biofuel initiatives, such as deforestation, food-versus-fuel disputes, and indirect land-use change (ILUC). By prioritising non-food feedstocks, the RTFO corresponds with the UK's overarching circular economy goals and establishes the country as a global frontrunner in sustainable fuel policy. Worldwide, biofuel efforts have had varied results, providing essential insights for the UK's strategy. The Proálcool ethanol program in Brazil, the Renewable Fuel Standard (RFS) in the United States, and the Renewable Energy Directive (RED) in the European Union exemplify the advantages and challenges associated with extensive biofuel implementation. Although these policies have propelled technical progress and diminished reliance on fossil fuels, they also underscore dangers including agricultural displacement, resource-intensive feedstock cultivation, and market instability. The RTFO's design incorporates these insights, employing a precautionary yet progressive framework that harmonises ambition with environmental protections. It assesses the UK's strategy in comparison to international frameworks, evaluating its ability to attain scalable decarbonisation while preserving ecological integrity and social equality. The research offers practical insights to enhance the RTFO by examining successes, problems, and emerging innovations, ensuring its alignment with the UK's Net Zero trajectory.

## *Case Study 1: Brazil: Proálcool Ethanol Initiative Policy*

### Introduction:

The Proálcool Program (Programa Nacional do Álcool) was initiated in Brazil in 1975 by President Ernesto Geisel under the military administration, as a strategic measure to address the 1973 oil crisis and the increasing reliance on petroleum imports. At that time, Brazil imported about 80% of its oil, rendering it significantly vulnerable to fluctuations in global prices. The government, acknowledging the potential of its sugarcane sector and aspiring for energy independence, launched Proálcool to manufacture anhydrous ethanol as a petrol additive and subsequently hydrous ethanol as an independent fuel (Ninô de Carvalho, 2013; Stolf & de Oliveira, 2020). The program was governed by the state, featuring essential support measures such as: - Assured minimum prices for ethanol, adjusted for inflation; - Low-interest loans for constructing distilleries, sometimes situated beside sugar mills; - Tax exemptions for automobiles fuelled by ethanol; - Compulsory ethanol incorporation in petrol, peaking at 25% throughout the 1980s; - Government acquisitions of ethanol to bolster demand. Proálcool emerged as one of the most ambitious biofuel initiatives worldwide, establishing the groundwork for Brazil's evolution into a significant bioethanol economy. During the 1990s and early

2000s, Proálcool evolved into a deregulated ethanol market, characterised by diminished governmental oversight. In 2003, the launch of flex-fuel vehicles (FFVs), created through collaborations among the Brazilian government, research institutions like UNICAMP, and manufacturers such as Volkswagen, signified the onset of a new consumer-driven era. Flexible Fuel Vehicles (FFVs) facilitated effortless transitions between petrol and ethanol according to price and availability, significantly enhancing domestic ethanol usage (Ninô de Carvalho, 2013).

## Achievements

The Proálcool Program positioned Brazil as a global leader in biofuel production and technology. Its sugarcane ethanol is considered one of the most efficient and sustainable biofuels, boasting an energy return on investment (EROI) of 8:1, which is substantially greater than that of U.S. maize ethanol at 1.3:1. Lifecycle greenhouse gas emissions from sugarcane ethanol are 80–90% lower than those of petrol, rendering it a potent decarbonisation instrument for transportation (Goldemberg, Coelho, Nastari, & Lucon, 2008). By 2020, ethanol accounted for over 40% of Brazil's light vehicle fuel demand, with more than 80% of newly marketed vehicles being flex-fuel vehicles (FFVs). The program facilitated the displacement of over 1 billion barrels of oil from 1975 to 2015, resulting in substantial savings on fuel imports for the country. Brazil has emerged as a significant exporter of ethanol, serving markets in the United States, Europe, Japan, and South Korea. The sugarcane-ethanol sector economically sustains about 1.2 million jobs, especially in the states of São Paulo, Goiás, Minas Gerais, and Paraná. The sector has established integrated value chains connecting sugar producers, ethanol facilities, automobile manufacturers, and fuel distributors. The Centro de Tecnologia Canavieira (CTC) and Embrapa (the Brazilian Agricultural Research Corporation) have been instrumental in enhancing agronomic methods, resulting in a more efficient and mechanised sugarcane harvest. Brazil has consistently updated its policy approach. The RenovaBio policy, initiated in 2017, established a market-oriented framework of Decarbonisation Credits (CBIOs) to incentivise producers with minimal carbon intensity. This strategy matches Brazil's transport fuel policy with its Nationally Determined Contributions (NDCs) as stipulated in the Paris Agreement.

## Obstacles & Setbacks

Notwithstanding these considerable advancements, Brazil's ethanol initiative has also raised important environmental and social issues. Although the spread of sugarcane is technically prohibited in the Amazon rainforest, heightened demand has propelled production into the Cerrado, a biodiversity hotspot, the Pantanal, and has indirectly influenced land use in the Amazon basin. Research indicates that from 2000 to 2015, more than 2.5 million hectares were transformed into sugarcane cultivation, resulting in spillover impacts on pasture and soybean areas, hence contributing to indirect land-use change (ILUC) and forest fragmentation. The utilisation of water is a significant concern. The processing of ethanol is highly water-intensive, necessitating 15 to 20 litres of water for each litre of ethanol produced. Industrial-scale sugarcane cultivation use substantial quantities of fertilisers and pesticides, resulting in water pollution and eutrophication in rivers such as the Tietê and São Francisco. Socially, although the business generates employment, a significant portion has always been in low-wage, high-risk positions. The once prevalent manual harvesting of sugarcane has been associated with heat stress, inadequate living conditions, and exploitative labour practices. While the advancement of mechanisation in São Paulo has enhanced working conditions, analogous improvements have been delayed in northern regions. Brazil's Ministry of Labour and foreign NGOs have reported instances of forced labour and insufficient health protections in smaller plantations. Market volatility continues to be a concern. The prices of ethanol vary in relation to sugar prices, as they vie for the same feedstock. In times of elevated global sugar prices (e.g., 2010–2012), producers diverted from ethanol production, leading to diminished fuel supply and subsequent price surges for consumers. The execution of RenovaBio aims to enhance environmental governance via means of: - Carbon intensity metrics throughout the lifecycle for each producer; - A transparent CBIO market governed by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP); - Incentives for low-emission ethanol via enhanced agronomic and industrial practices.

Nonetheless, adoption has been inconsistent, and small producers frequently encounter difficulties in fulfilling certification criteria due to technical and budgetary limitations

## *Case Study 2: United States: Renewable Fuel Standard (RFS) Policy*

### Introduction

The Renewable Fuel Standard (RFS) was established by the Energy Policy Act of 2005 in response to increasing apprehensions regarding fluctuating oil prices and U.S. reliance on foreign energy supplies. The program significantly extended under the Energy Independence and Security Act (EISA) of 2007, raising the renewable fuel volume mandate from 7.5 billion gallons in 2012 to 36 billion gallons by 2022 (Bracmort, 2016).

The Renewable gasoline Standard (RFS), overseen by the Environmental Protection Agency (EPA) in collaboration with the Department of Energy (DOE) and the Department of Agriculture (USDA), mandates that transportation gasoline sold in the United States must include a minimum volume of renewable fuels (EPA, 2020). The policy delineates four categories of fuel:

1. Conventional biofuel - predominantly corn ethanol (limited to 15 billion gallons)

2. Advanced biofuel derived from non-corn starch feedstocks.

3.. Diesel derived from biomass, encompassing soy-based and regenerated oils

4. Cellulosic biofuel is derived from agricultural residues, grasses, and lignocellulosic biomass.

Every fuel type is required to satisfy GHG emissions reduction criteria relative to petroleum-based fuels, varying from 20% to 60% (Bracmort, 2016). Compliance is regulated using Renewable Identification Numbers (RINs), which monitor biofuel output and blending.

## Achievements

The RFS significantly transformed the U.S. biofuel sector, especially by enhancing corn ethanol output. In 2023, U.S. ethanol production surpassed 15 billion gallons per year, representing almost 10% of petrol usage (Bracmort, 2016; EPA, 2020).

The initiative enhanced rural economies throughout the Midwest. States such as Iowa, Nebraska, and Illinois currently allocate up to 40% of corn production to ethanol facilities, with the biofuel sector generating over $45 billion yearly for GDP and sustaining 300,000 jobs in agriculture, logistics, and fuel processing (Bracmort, 2016; Tyner, 2010). Ethanol facilities also promoted enhancements to infrastructure such as unit trains and blending terminals. The RFS improved energy security, decreasing net petroleum imports by more than 30% from 2008 to 2014, particularly during global oil price fluctuations (Bracmort, 2016). More than 200 ethanol refineries were established, decentralising domestic fuel production.

The program promoted innovation in advanced biofuels, facilitating research on algae-derived biodiesel, landfill biogas, and ethanol from switchgrass and maize stover via agencies such as ARPA-E (Tyner, 2010). Brazil serves as a comparative standard. The ethanol derived from sugarcane exhibits a higher Energy Return on Investment (EROI) of 8:1, in contrast to the 1.3:1 ratio of U.S. maize ethanol, and provides greenhouse gas reductions of 80–90% relative to petrol (Macedo, Seabra, & Silva, 2008).

## Obstacles & Setbacks:

Notwithstanding its advantages, the RFS has encountered significant criticism over market inefficiencies and environmental compromises.

The food vs fuel issue intensified as legislation redirected over 40% of U.S. corn to ethanol, aggravating the 2007–2008 global food crisis (Searchinger et al., 2008). This raised ethical questions regarding the utilisation of food crops for fuel purposes.

Emissions from land-use change diminish the climate advantages of maize ethanol. The transformation of grasslands or forests into agriculture can release substantial quantities of $CO_2$, hence nullifying any greenhouse gas reductions (Searchinger et al., 2008; National Research Council, 2011). The EPA's analysis anticipates a mere 20% reduction in greenhouse gas emissions from corn ethanol, significantly lower than that of cellulosic alternatives (Bracmort, 2016).

Further environmental issues encompass water consumption—approximately 3 gallons of water for each gallon of ethanol—and fertiliser runoff, which leads to hypoxic zones such as the Gulf of Mexico and adversely affects local ecosystems (National Research Council, 2011).

The cellulosic biofuel industry, once projected to produce 16 billion gallons by 2022, significantly underachieved. By that year, production had fallen below 20 million gallons. Financial and technical challenges resulted in the failure of commercial plants such as Project LIBERTY and DuPont's Nevada facility (Bracmort, 2016; Tyner, 2010).

Political obstacles also hindered policy execution. The EPA's yearly Renewable Volume Obligations (RVOs) experienced delays, legal disputes, and small refinery exclusions from 2016 to 2020, destabilising the RIN market and deterring corporate investment (EPA, 2020).

Infrastructure and vehicle compatibility challenges, referred to as the "blend wall," further limit ethanol penetration beyond the E10 threshold. The adoption of higher blends like as E15 or E85 is constrained by antiquated fuelling infrastructure and older engine designs (National Research Council, 2011).

## *Case Study 3: European Union: Renewable Energy Directive (RED)*

### Policy Introduction:

The Renewable Energy Directive (RED) was enacted in 2009 as a component of the EU's Climate and Energy Package, aiming for a 20% decrease in greenhouse gas (GHG) emissions, a 20% contribution of renewable energy, and a 20% enhancement in energy efficiency by 2020—referred to as the "20-20-20 targets" (DieselNet, 2023; House of Commons Energy and Climate Change Committee, 2016; European Commission, 2009).

In the transport industry, the Renewable Energy Directive mandated that 10% of transport energy originate from renewable sources by 2020. The primary focus was on first-generation biofuels, including biodiesel derived from rapeseed, palm oil, and soy, as well as ethanol produced from wheat, maize, and sugar beetroot. The program incorporated double-counting incentives for waste-derived biofuels and established sustainability measures to mitigate environmental damage (Scarlat & Dallemand, 2011).

In response to apprehensions regarding indirect land-use change (ILUC), RED II was enacted in 2018, establishing a 14% renewable energy target for transport by 2030, which includes a 7% limit on crop-based biofuels and a minimum requirement of 3.5% for advanced biofuels (European Parliament & Council, 2018). High ILUC-risk feedstocks, such as palm oil, are slated for elimination by 2030. RED II introduced rigorous greenhouse gas reduction criteria and strengthened certification processes for traceability and sustainability (Ecofys, 2016).

## Achievements:

The EU has established itself as a global leader in the regulation and promotion of renewable transport fuels via a cohesive legal framework. RED urged the majority of Member States to adopt biofuel blending standards, including 7% biodiesel in diesel in Germany and 10% ethanol in petrol in France (Transport & Environment, 2019).

The EU allocated in excess of €1 billion under Horizon 2020 to promote second-generation biofuels, encompassing: 1. Lignocellulosic ethanol derived from straw and wood, such as Clariant's Sunliquid facility in Romania. 2. Algae-derived fuels (e.g., SPLASH and BIOFAT initiatives); 3. Gasification-to-liquid (GTL) fuels derived from municipal trash; 4 Hydrotreated vegetable oils (HVO) derived from waste oils, marketed by Neste (Finland) and Eni (Italy) (European Commission, 2020).

RED II improved environmental governance by mandating life-cycle GHG accounting and stipulating that biofuels must achieve a minimum of 50%–60% GHG reductions relative to fossil fuels (Directive (EU) 2018/2001).

Furthermore, the EU has spearheaded initiatives in sustainability certification, endorsing voluntary programs such as ISCC-EU and RSB, which ensure that biofuels are not sourced from deforested or socially contentious regions (Lamers et al., 2011). These solutions enhanced supply chain transparency and enabled market differentiation between low-ILUC and high-ILUC feedstocks.

## Obstacles & Setbacks:

Notwithstanding policy advancements, the RED framework has encountered structural and environmental obstacles. From 2009 to 2018, under RED I, the EU was significantly dependent on palm oil-derived biodiesel, a feedstock linked to deforestation and peatland drainage in Southeast Asia. Research indicates that palm oil biodiesel possesses a greenhouse gas footprint three times greater than that of fossil diesel, attributable to indirect land use change emissions (Transport & Environment, 2016; Valin et al., 2015).

Between 2008 and 2018, the EU purchased in excess of 46 million tonnes of palm oil, over 50% of which was utilised for biofuels, resulting in an estimated 1.4 million hectares of deforestation (European Commission, 2019). RED II classified palm oil as a high ILUC-risk feedstock, requiring its elimination by 2030, albeit with exceptions for certified low-ILUC providers, a provision critics argue undermines the regulation (WWF, 2020).

The biodiesel market exhibited considerable volatility in economic terms. Inexpensive biodiesel imports from Argentina and Indonesia, frequently bolstered by government subsidies or devalued currencies, undermine EU manufacturers, resulting in the closure of facilities in nations like as Germany and Spain. The EU implemented anti-dumping measures; nevertheless, WTO challenges curtailed their effectiveness (OECD/FAO, 2022).

Policy volatility also deterred private investment. Frequent modifications to the definitions of "advanced biofuels," postponements in delegated acts, and alterations in sustainability standards generated uncertainty (Scarlat et al., 2015). Numerous second-generation programs encountered scalability issues owing to ambiguous eligibility requirements and inconsistent incentive structures.

The implementation among Member States has been inconsistent. Sweden and Finland surpassed RED targets through the use of advanced fuels and sustainable procurement, whilst Poland and Hungary fell short, frequently depending on first-generation imports (IEA, 2022). This has hindered compliance tracking across the EU and undermined unified greenhouse gas reduction initiatives.

## *Comparative Lessons and Probable Futures for the UK's RTFO Policy*

The examination of global biofuel policies—Brazil's Proálcool Program, the United States' Renewable Fuel Standard (RFS), and the European Union's Renewable Energy Directive (RED)—provides essential insights for the ongoing development of the United Kingdom's Renewable Transport Fuel Obligation (RTFO). The UK seeks to achieve its 21% renewable transport fuel target by 2032 while balancing environmental integrity, economic feasibility, and technological scalability (Department for Transport, 2021). The UK can learn from Brazil the importance of sustained policy consistency and technological innovation, shown by Brazil's strategic investments in sugarcane ethanol and flex-fuel vehicles, which established the nation as a global leader in biofuels (Goldemberg et al., 2008). Brazil's experience exemplifies the ecological repercussions of agricultural expansion, notably deforestation in the Amazon and Cerrado biomes (Macedo et al., 2008; WWF, 2020). The UK's 2% limit on crop-based biofuels serves as a precautionary measure; but, with an increasing dependence on imported feedstocks, enhanced environmental regulation will be essential to mitigate analogous land-use constraints (Scarlat & Dallemand, 2011). The U.S. Renewable Fuel Standard illustrates how the swift growth of a biofuels market can promote rural development and improve energy security (Bracmort, 2016; Tyner, 2010). However, its significant reliance on first-generation maize ethanol revealed sustainability constraints and resulted in land-use change emissions, excessive water consumption, and minimal greenhouse gas reductions (Searchinger et al., 2008; National Research Council, 2011). The subpar performance of cellulosic ethanol serves as a warning regarding the risks of overcommitting to nascent technologies lacking dependable commercial avenues or investor assurance (Bracmort, 2016; EPA, 2020). The United Kingdom ought to endorse advanced biofuels, contingent upon pragmatic deadlines, substantial research and development financing, and explicit regulatory frameworks. The UK acquires knowledge from the EU about the incorporation of GHG accounting, certification frameworks, and advanced biofuel sub-targets into national policy (European Parliament & Council, 2018; Transport & Environment, 2019). The evolution of RED II demonstrates the advantages of traceability and lifetime sustainability; nonetheless, the EU has faced challenges related to policy instability, import reliance, and inconsistent national implementation (Scarlat et al., 2015; Valin et al., 2015). The UK's unified policy structure provides an advantage in preventing regulatory fragmentation and fostering a stable investment environment.

## *Future Outlook: Probable Trajectories for the RTFO*

The RTFO is anticipated to develop according to essential pathways shaped by national objectives and global best practices. There will be a pronounced focus on the advancement of domestic feedstock, encompassing waste oils, agricultural leftovers, and municipal biowaste, in accordance with circular economy ideas (IEA, 2022). Collaborations among municipalities, private trash processors, and research and development centres might bolster supply resilience and diminish reliance on imports. The investment environment for advanced biofuels is expected to enhance. To mitigate finance problems observed in the U.S. and EU, the UK may implement green bonds, carbon contracts-for-difference, or tax relief initiatives to reduce the risk of early investment (OECD/FAO, 2022). These techniques would facilitate the scalability of nascent technologies such as lignocellulosic ethanol, algae-derived fuels, and gasification-to-liquid processes. The RTFO will progressively assist transport sectors that are challenging to electrify, including aviation, maritime, and long-haul freight. Subsequent iterations of the RTFO may implement sector-specific quotas or credit multipliers to promote investment in sustainable aviation fuels (SAFs) and renewable marine fuels (IEA, 2022; European Commission, 2020).

Stricter criteria for sustainability certification of imported fuels are anticipated to uphold environmental and ethical integrity. In accordance with RED II, the UK may require adherence to third-party schemes such as ISCC-EU or RSB for waste-derived biofuels, guaranteeing comprehensive lifecycle compliance and conformity with Net Zero 2050 objectives (Lamers et al., 2011; WWF, 2020). Regulatory flexibility will be essential; however, it must be structured to ensure clarity. Periodic RTFO review cycles, potentially every 3 to 5 years, might facilitate adaptive policymaking while maintaining investor trust. In contrast to the EU's erratic updates, the UK can provide consistent, evidence-based modifications aligned with technical and market advancements (Scarlat et al., 2015). Global cooperation will be imperative. Forming strategic alliances with Brazil (ethanol proficiency), Finland (HVO advancements), and the United States (biogas and algae research and development) may establish the UK as a frontrunner in biofuel technology transfer, collaborative enterprises, and international sustainability benchmarks (Goldemberg et al., 2008; European Commission, 2020; Tyner, 2010).

## *Conclusion:*

In conclusion, the UK's RTFO is poised to emerge as a widely acknowledged paradigm of innovation-driven, environmentally sustainable biofuel policy. By analysing Brazil's environmental trade-offs, the U.S.'s technological overreach, and the EU's regulatory fragmentation, the UK may devise a more astute strategy. Through robust governance, stable investment frameworks, and international collaborations, the RTFO can advance national climate objectives, promote a flourishing bioeconomy, and establish new global standards for sustainable transport decarbonisation.

# An Analysis of the Technical Opportunity Provided by RTFO

With a working understanding of similar policies around the globe and their respective advantages and drawbacks, it is key to see where real change can be made on a domestic level in the UK. As of the 2025 compliance guidance set out by the Department for Transport (Department for Transport [DfT], 2023), the following low-carbon fuels are eligible for Renewable Transport Fuel Credits (RTFCs) which serve as financial incentives for industry to proliferate their use:

- Biofuel
- Renewable fuels of a non-biological origin (RFNBOs)
- Recycled carbon fuels (RCFs)
- The eligible portion of any partially eligible fuel

Given historical successes in Brazil, the United States and the EU, this analysis will primarily focus on biofuels in particular and their potential in the UK.

## *Waste or Crops?*

Biofuels can typically be sourced either from waste or from crops, so it is key to understand which of these is a better option for the UK to best inform policy.

It has been estimated (Arshad et al., 2022) that there is around 2.7 MHa of marginal land in the UK. This is used in this context as a relative term; land which is defined by a set of criteria to be 'marginal' for one purpose which could be productive for another purpose. To that end, land which may be considered marginal in relation to pastoral farming may be better used to grow biofuel crops.

The same report outlines that around two-thirds of this land is already in use for food production, leaving around 1 MHa for the potential growth of biofuel crops which is around 4% of the country by land area.

Usage of biofuel crops can, however, have unintended consequences. For one, in Borneo, a rapid increase in demand for these biofuel-producing crops, has resulted in the destruction of ecosystems via deforestation to allow for sufficient space to plant the crops in the first place.

Moreover, the UK already produces 16 million tons of waste which can be used for biofuels annually (Royal Academy of Engineering, 2017) This same report suggests increasing the level of biofuels required under RTFO, which could provide a means by which British capability in this sector can be improved resulting in an increase in the fraction of this waste being used for useful biofuel production.

One question this prompts is how easy it would be to turn this waste into viable biofuels. This is an active area of scientific research, and enzymes from wood-eating gribble (M. Kern et al., 2013) have been discovered which can catalyse this process. It can therefore be reasonably expected that the efficiency of these processes will also continue to increase with time, and the UK should be a frontrunner in pioneering this development if it wants to maintain its position as a global leader in the green revolution.

Given that waste treatment centres are typically kept away from areas with rich ecosystems, biofuels from waste clearly offer the most potential whilst minimizing potentially unwanted harm.

## *Advantages of Biogas Systems*

One way of realising this vision is through the implementation of biogas systems. These have several key advantages:

- Waste that goes to biogas systems skips landfill
- Chemicals associated with landfill are no longer released
- It composts using an anaerobic digester

It must also be noted, however, that this only works for biodegradable materials. This should prompt further government incentive to replace plastics with more sustainable options wherever possible.

## *Potential Annual Energy Generation from Biogas Systems*

A figure for the annual mass of waste that can be used for biofuel generation in the UK yearly has been outlined. By taking the product of this, the amount of energy that can be expected to be obtained per unit mass of various biofuels and the efficiency of the biogas system itself, a first order estimation for the annual amount of energy generated by using biofuels from waste can be found as shown below.

$$Energy\ From\ Biofuel\ Waste = GCV\ \times PEIO\ Ratio\ \times Mass\ of\ Available\ Biowaste \quad (1)$$

The gross calorific value (GCV) of agroforestry species from which the majority of the suitable waste will be made ranged from around 14.3 – 25.4 MJ/kg (Gravalos et al., 2016). To contextualise this, petrol is typically estimated to have a GCV of 44 - 46 MJ/kg, dry firewood around 16 MJ/kg and hard black coal under the International Energy Agency has a GCV over 25.9 MJ/kg (World Nuclear

Association, 2020). Whilst this energy density is crucial for weight-sensitive industries such as aviation, here it is necessary only to obtain enough energy to justify using it for fuel. Given that the energy density of agroforestry is expected to be comparable to firewood and lower quality coal, it is certainly a viable option for a fuel looking to the future.

Primary energy input to output ratio, which is a measure of efficiency for these systems, corresponds to 10.5 - 64.0% and 34.1 - 55.0% for single feedstock digestion and feedstock co-digestion respectively (Pöschl et al., 2010). Again, by comparison, coal has a thermal efficiency of around 36% (MacLeay, 2016).

This gives an estimate of between 24 TJ and 260 TJ for the amount of energy which can reasonably be obtained annually from waste using biofuels. Here, the efficiency of energy production can plausibly be compared to that of coal, thus demonstrating that biofuels are a viable option for clean energy production.

Looking to the future, it can reasonably be expected that scientific development will continue to extract more energy per unit mass from waste, so when considering government policy, biofuels from waste is a technology which should undoubtedly be incentivised. It is future proof since waste will almost inevitably be a byproduct of civilisation; it is environmentally sustainable since greenhouse gas emissions are reduced significantly in comparison with existing energy sources such as coil, oil and natural gas; and the UK is already poised to make good use of this opportunity.

# Politics and Broader Considerations

## *If the RTFO is to succeed, what do the government need to do?*

From a broader standpoint, it is obvious that if the RTFO is to succeed, (we will quantify "succeed"), then it must make political and financial sense, both to fuel suppliers and to the government, first off. But also, to consumers of the eventual fuel products at the end of the supply line. When we say "succeed", what we essentially mean, qualitatively, is that we just want to reduce the UK's consumption of dirty fossil fuels, but to quantify this, the government states that by 2035, each fuel supplier which qualifies, will be obligated to supply at least 17.4% of its total fuel supply in the form of RTFO accepted fuel types, shown in the graph below.

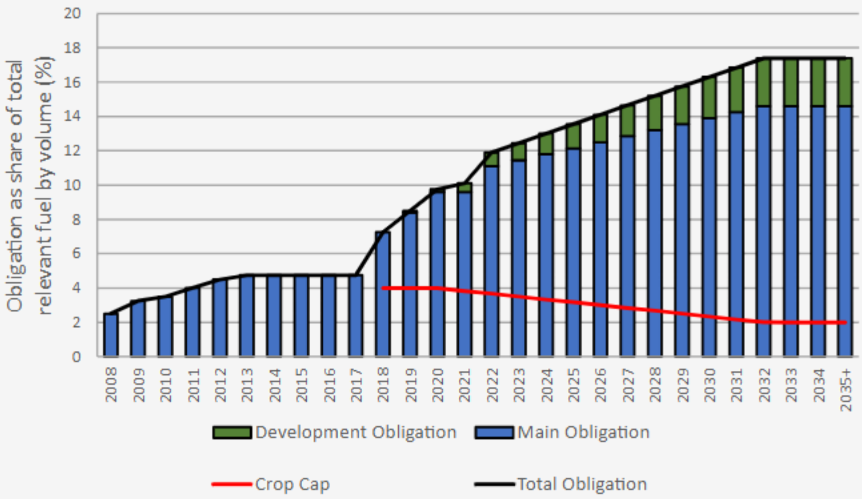


Figure 1: RTFO Obligations and Crop Cap over Time (Statutory review, UK Gov, 2024)

From a communications standpoint, what the government may say about the success of this scheme, is that they want to use it to show the voters and stakeholders that they are concerned about the environment and are doing something about it. Which brings us onto the topic of this section – to analyse the 3 main things the government should focus on if the RTFO is to succeed.

Most policy weaknesses, potential improvements and success factors, can be placed broadly under one of the 3 following considerations – Incentives, Communication or Political Objection.

## *Incentives: How can uptake of this scheme by suppliers be achieved?*

From the government's perspective, the primary way to increase the uptake of renewable fuel supply by corporations, is by utilising financial incentives.

Firstly, and most simply, are subsidies. Subsidies are direct cash handouts given to suppliers which they can then use to invest in new infrastructure. This can allow them to expand current facilities and therefore expand the capacity to achieve their obligations for second-generation and waste-based biofuels. Subsidies tend to be the most standard incentive from government, and for valid reason, because they are generally quite successful at helping increase the capacity of the economy, but they can also cause political problems. Because subsidies are widely used in many industries, they are not just exclusive to the RTFO scheme, meaning conflicts of interest can arise as voters may say "You give money to the RTFO, but why don't you give money to the defence industry?" – for example. As a result of this non-exclusivity to the RTFO, it essentially comes up to the party in power to decide whether the RTFO scheme gets the money or not, and so it is therefore not guaranteed that this money will continue flowing for long enough into the future for it to make positive headway towards its objective. Therefore, with the impeding threat of opposition parties in government such as the "anti-net-zero" Reform Party and an ever more right-ward shifted Conversative Party, it is not guaranteed that RTFO subsidies wouldn't be cut immediately after the next general election in 2028.

Our suggestion to the government on this topic then would be to – yes, hand out RTFO subsidies to suppliers to assist them in uptake, but crucially, balance this with the fact that subsidy money isn't always guaranteed for the future, and so by using other incentives, it is important to ensure that suppliers are not totally reliant on subsidies, and can make progression even without them.

Subsidies are one option – a government intervention option, but for reasons just mentioned, this cannot be the reliant factor, therefore market-based solutions may also be considered. We now talk about RTFC's – Renewable Transport Fuel Certificates. These are credits/certificates earned by suppliers for every unit of renewable fuel they supply to the market. These essentially work in the same way (but in a reverse fashion), as carbon credits, where if one company over-emits on their allowance, they can buy additional credits from other companies, to afford them to emit more carbon. The RTFC part of this scheme assigns each supplier an obligation certificate target for the supply of renewable fuel; for each unit they supply, they earn certificates. If by the end of the year, they supply more than they were obligated to, then they essentially have "spare certificates". These spare certificates can then be sold on at a market driven price, to other companies who undersupplied. This is positive for both companies as the seller earns money for their extra certificates, and the buyer is "let off the hook" for not supplying enough. If, however, a company undersupplies and doesn't buy additional certificates to make up its obligation, it will be fined by the government. In 2024, BP overproduced on its obligation and offered up between 2 and 5 million "non-crop RTFC's" at 21.5p per certificate for transfer on the market in March 2025.

However, as well as incentivising overproduction with the ability to earn from additional credits, the RTFC scheme also offers a "buy-out" route for companies who undersupply, essentially allowing them to ignore their obligations, to an extent, and just buy the required obligation of certificates back at the end of the year or take the hit of the fine. This is then seen by those companies as just a "fee" or "tax" for operation in the industry.

RTFC's are more of a pull incentive than a push incentive, as they pull suppliers towards the supply of more renewable fuels, rather than obligating them to supply fewer fossil fuels.

Another incentive the government can use is an idea called "double counting" (RTFO, UK Gov, 2023), where certain "eligible fuels" can be counted with double weight toward the supplier's obligation. So, if they earn just one certificate for the supply of one unit of Recycled Carbon Fuel (RCF), they may earn two certificates by supplying one unit of RFNBO – Renewable Fuel from Non-Biological Origin. Fuels eligible for double counting are generally much more carbon saving than regular biofuels and so are encouraged more strongly. This ability to earn double the certificates can incentivise suppliers to focus more of their resources on these cleaner biofuel types rather than alternatives which may only earn them one credit per supply unit.

## *Communication: How should the government talk about the RTFO?*

For the RTFO to be politically favourable, the reasoning behind its implementation and an explanation of its positive impacts must be unambiguously communicated to stakeholders and to the public. It is also typically said that climate policies are more politically favourable if they are communicated alongside other benefits and explanations, rather than purely as a scheme to tackle climate related issues. This is because, although very important, climate change and the environment are not always, and quite often not at all a high priority on the agenda of voters. An ongoing survey from YouGov – below (YouGov, 2025) shows that when asked to pick up to 3 options, only 15% of voters picked "The Environment" as one of the top 3 most important issues facing the UK. With the economy, immigration, crime, defence & security and health all placing higher on the list.

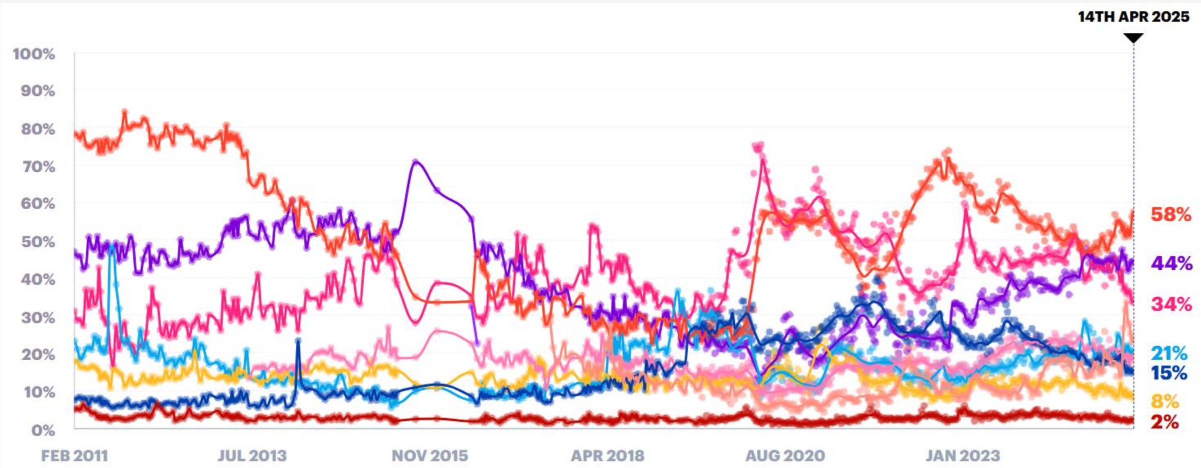


Figure 2: YouGov – The most important issues facing the country

A technique the government can do when communicating the RTFO to the public is to explain its positive side effects. The main one being that biofuels can be used as a direct substitute for fossil fuels, and so any developments in biofuels from the private transport industry, can be applied elsewhere in the economy and in other industries as a source of energy. We suggest that the government puts emphasis on the fact that biofuel development in the private transport sector, is not just an advancement for one industry, but an advancement for the entire energy system in the country. This will emphasise the significance of biofuels to the public and may influence them in their political views regarding the RTFO.

Within communication, the government must also tackle the large portion of the public who – vouch for a clean energy transition, but are sceptical about which path we should take, and how much it will affect their daily lives. Much like with the last point about explaining the positive side effects, the answer to this dilemma lies in the fact that biofuels are a direct substitute for currently used fossil fuels.

Because of this, it can be said that the uptake of renewable fuels will be met with much less infrastructural resistance than the uptake of vehicle electrification for example. Investment in new pipelines, fuel storage facilities and vehicle re-design may be kept to a minimum as these are the same types of infrastructure already in use for fossil fuels. To communicate this effectively, the government must emphasise that biofuels are not too much of a jump from the current system and won't change much about how people generally live their lives.

## *Political Objection: How should the government deal with disagreement?*

A recent "Call for evidence" (Call for evidence, UK Gov, 2024) by the government stated that "Despite incentives (such as double-counting), investment I development fuels has not met expectations, with most suppliers opting for the buy-out route". This again strengthens the observation that many suppliers in the fuel industry don't see the RTFO as a positive scheme, they see it as an additional "tax or "fee" for operation in the industry – which from a business perspective, is valid, but this causes problems for the government and most importantly for the environment of future generations.

Any policy that relates to any form of "tax" or "fee" will inevitably come under scrutiny from right leaning political supporters who see this as a handicap on industry and economic growth. Right-leaning political supporters typically opt for a hands-off approach to industry, with less government intervention, less regulation and more freedom for the market to do its thing and believe that that alone is what provides economic growth and prosperity. However, with pressing issues such as costs of living and climate change, this must not be the only answer, and economic fairness, environmental factors and social justice must also be observed. So, to counter this inevitable right-wing opposition, the government must look for reasons why the RTFO may be favourable for them, as well as just for people who are climate conscious. This may come in the form of communication about energy security, as homegrown feedstocks and biofuel development can help to reduce our dependence on other countries for fuel and energy supply.

Further, to counter the idea that many suppliers see this as a "tax or "fee" for industry operation, the government must seek ways to make the full supply of the fuel obligation the most profitable business route for suppliers. Because at the end of the day, private business will only uptake something if it benefits them financially. The government could look to do this by installing a minimum selling price for RTF Certificates on the market, placing a more attractive financial reward at the end of the year for companies who stick to their obligations.

Another point of political objection may come from left-leaning political supporters, who are generally more environmentally focussed when it comes to voting. Despite this general support, the RTFO can still come under attack from environmentalists, who will look very closely at adverse side effects discussed in other sections of this document, such as biodiversity impact and conflicts of interest with crop-loss. These attacks may slow down the process of further advancements of the RTFO scheme but coming from environmentalists – people who naturally want to support a policy to reduce carbon emissions – the attacks are more likely to come in a constructive and critical feedback type of manner, than a destructive manner with the intent of completely derailing the scheme.

Therefore, to counter objection from both sides, the government must look for the correct balance between positive environmental impact and political favourability, and, given the size of the biofuels market in the EU, Brexit appears to have resulted in an opportunity missed for the UK.

# Greenhouse Gas Savings and Compliance costs

The main goal of the RTFO is to cut greenhouse gas (GHG) emissions from the UK's transport sector by encouraging the use of renewable fuels. This section outlines the trends in GHG savings achieved over time through the scheme, along with the related costs, to assess effectiveness of the policy thus far. The analysis is based primarily on statistical data published alongside the RTFO annual reports.

In 2023, renewable fuels accounted for 7.5% of total transport fuel in the UK, reflecting a clear positive trend in the integration of renewables into the sector. While this increase can be linked to broader factors such as technological advancements driving costs down, it also closely aligns with the progressively rising targets set under the RTFO over the years. Figure 3a illustrates the $CO_2$ savings calculated based on the RTFCs awarded since the policy's inception. As shown, there was a 77% increase in $CO_2$ emission savings since the introduction of the scheme. The net positive trajectory of these savings suggests that the RTFO has been effective in achieving its primary objective of reducing emissions within the transport sector.

In the early years of the RTFO, overall GHG savings were lower due to the high use of crop-based feedstocks, which had a significant indirect land use impact. Since then, various incentives have been introduced to promote waste-based and development fuels, which have a lower carbon footprint. However, this shift has also led to higher overall implementation costs for the policy as these newer technologies remain in early stages of development and are often more expensive to produce.

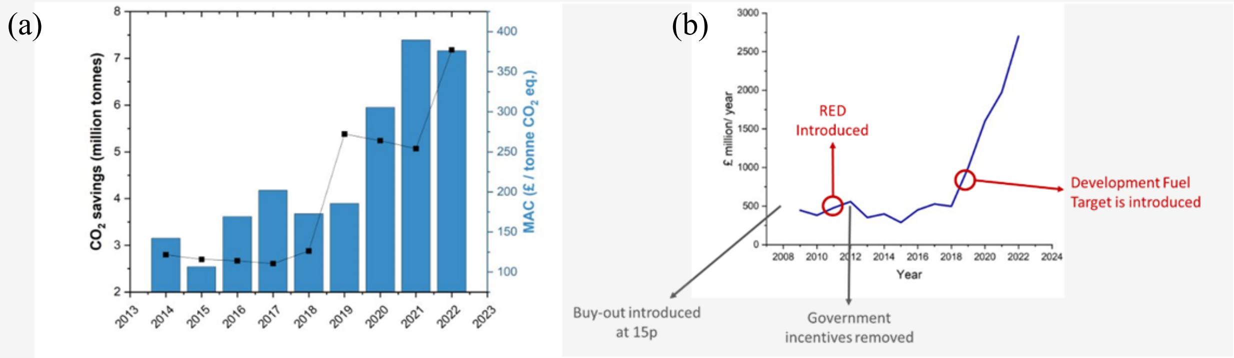


Figure 3. (a) illustrates the $CO_2$ savings (including ILUC) and marginal abatement costs (MAC) of replacing fossil-based fuels with renewables since the introduction of the RTFO. (b) compliance costs of the RTFO and key schemes introduced over the years.

The rising annual compliance costs of the RTFO can be attributed to several factors, including increasing fuel demand and supply year on year, as well as the widening price gap between fossil fuels and renewable fuels. As shown in Figure 3b, these costs began to rise significantly after 2018. A notable development during this period was the introduction of the development fuel obligation in 2019, which aimed to reduce dependence on biofuels derived from limited feedstocks - a resource expected to face growing constraints as demand increases. Development fuels offer the advantage of being compatible with existing vehicle infrastructure, avoiding the need for costly system adaptations. However, they currently have significantly higher production costs and remain in limited supply due to a lack of mature, efficient production technologies. This likely contributed to the rising compliance costs under the RTFO, as evidenced by the increasing development fuel buy-outs, which accounted for 8% of total compliance costs in 2021, rising to 10% in 2022.

## *Overall effectiveness of the policy - quantification of policy success*

To determine how successful this policy has been in the past, and quantify its success in future years, there are a selection of ratios and models which can be used to quantify the progression made towards the objective of the RTFO of increasing the uptake of renewable fuels, and further, decreasing carbon emissions from the private transport sector. Below contains a list of methods by which the success of a policy such as this can be judged:

**Shadow Pricing:** A method of quantitatively assigning monetary values to non-market impacts, such as carbon emissions, biodiversity, or ecosystem services. Shadow pricing intuitively assigns a monetary value to something which doesn't inherently have a monetary value. The downside of shadow pricing is that although we end up with quantitative data at the end of it, it is partially based on subjective information. The idea of shadow pricing forms a basis for which a number of the quantification methods below are based on.

**CBA (Cost Benefit Analysis):** Compares the total cost of implementing a policy against the monetised value of its benefits. (Does not account for climate/environmental benefits)

$$Benefit\ Cost\ Ratio\ (BCR)\ =\ \frac{Total\ Benefits}{Total\ Costs}$$

**MAC (Marginal Abatement Cost):** Calculates the cost of reducing one unit of GHG emissions (eg: £/tonne $CO_2$e). Ranks policies of technologies based on their cost effectiveness in achieving emissions reductions. Eg: In the use case of EV's it can be used to rank the "£/tonne $CO_2$e avoided" for a particular model of car, or for a particular policy aiming to increase the uptake of EV's.

**SROI (Social Return on Investment):** Evaluates the social, environmental and economic value created for every £1 invested in a policy or project.

$$SROI\ Ratio\ =\ \frac{Monetised\ Social\ Benefits}{Investment\ Costs}$$

**Monetised Social Benefit:** Can be monetarily quantified by looking at tangible **financial** increases/decreases in energy savings, job creation, economic activity, healthcare costs.

**Environmental Benefits:** such as the social cost of carbon (SCC, the estimated economic damage avoided by reducing emissions), using proxies like the market value of ecosystem services restored or protected (e.g. assigning a relative monetary value to river cleanliness particulate matter measurements, etc ...). **Social benefits** include assigning monetary benefits to things like time saved by an individual, stress reduction or better personal/mental health.

**Green GDP Contribution:** Assesses the policy's contribution to environmentally adjusted GDP, which subtracts environmental degradation costs from traditional GDP metrics. Combined measurement of economic and environmental performance. Again, this will take into account "shadow pricing" as you need to quantitatively assign a monetary value to "environmental degradation".

$$Green\ GDP\ Change\ =\ Monetary\ GDP\ Change\ -\ Environmental\ Degradation\ Cost$$

Impact assessments indicate that although renewable fuels have environmental advantages, they rank as some of the costlier carbon abatement alternatives compared to other mitigation measures. This is especially apparent when comparing their MAC - the expense of diminishing one additional unit of $CO_2$ - with alternatives like energy efficiency enhancements or electrification. In an effort to mitigate these high costs, the government has introduced several incentives, including amendments to the RED. While such measures can improve the cost-effectiveness of emission reductions (in terms of £ per tonne of $CO_2$), the cost per unit of energy (£/MWh) remains high. This is largely due to the low energy efficiency of many renewable fuels. This is reflected in the steadily rising overall cost of the RTFO in recent years.

One approach to reducing compliance costs is to prioritise fuels with higher energy density, which would help lower total fuel consumption and, in turn, reduce RTFO-related costs. Furthermore, only around 9% of renewable fuel used under the scheme is currently sourced from UK feedstocks, with the vast majority being imported. This not only increases costs but also adds to the carbon footprint of the scheme due to emissions from transportation and international supply chains.

Another potential solution is to integrate more RFNBOs (Renewable Fuels of Non-Biological Origin) into the energy mix. These fuels not only offer higher energy density but can also be produced domestically without additional land-use, leading to an increase in the supply of available development fuels leading to lower buy-outs. However, as already discussed the current high production costs of RFNBOs remain a major barrier, as efficient and scalable production methods have yet to be developed.

In response, the UK government has implemented various incentives, such as subsidy programs and modifications to the Renewable Energy Directive (RED), to improve cost-efficiency measured in £ per tonne of $CO_2$ mitigated. Nonetheless, these sometimes lead to a heightened cost per unit of energy (e.g., £/MWh), attributable to the comparatively low energy conversion efficiency of numerous biofuels. The trade-off is apparent in the increasing compliance expenses associated with the RTFO program in recent years.

A more sophisticated method for assessing the efficacy of the RTFO is to implement Shadow Pricing, utilising the social cost of carbon to measure the external advantages of emission reductions. This facilitates the incorporation of non-market environmental advantages, including less air pollution and climate harm, into economic assessments. Incorporating shadow prices reveals the greater societal worth of renewable fuel utilisation, particularly in policies that advocate for circular economy activities via waste-derived biofuels.

The Social Return on Investment (SROI) framework assesses the efficacy of the RTFO in converting public or private investments into beneficial results, in relation to economic and social returns. The SROI ratio for RTFO-funded projects remains undisclosed; nonetheless, significant potential social benefits encompass rural employment in feedstock production, enhancements in air quality, and technological innovation spillovers into related sectors such as agriculture and waste management. When effectively monetised, these non-financial advantages may enhance the overall Social Return on Investment (SROI) ratio of measures tied to the Renewable Transport Fuel Obligation (RTFO).

Furthermore, the Green GDP Contribution indicator can offer a macroeconomic perspective to evaluate the RTFO's extensive influence. Green GDP incorporates traditional economic output while deducting costs associated with environmental deterioration and including climate-related social savings. Traditional GDP may inadequately reflect the advantages of sustainable transport fuels; nevertheless, Green GDP modifications could indicate that domestic production of RFNBOs or biogas favourably impacts by decreasing dependence on high-carbon imports and alleviating environmental damage.

A notable shortcoming of the existing RTFO plan is that merely 9% of renewable fuel is sourced domestically, indicating that the UK remains significantly reliant on imported feedstocks, which escalates costs and diminishes carbon efficiency due to embedded emissions from transportation. Addressing this necessitates a planned transition towards the development of domestic feedstocks, including agricultural waste and municipal biowaste, and the expansion of indigenous production of RFNBOs, which can be generated without imposing further land-use pressures.

## *Quantification recommendation for government*

Looking at each of the above methods for quantification, our recommendation to government would be to more deeply explore the use of **SROI** as a basis for the evaluation of performance of the RTFO scheme. This ratio takes in data for several of the most important considerations – cost, environmental degradation, payback and social benefits, and with thoroughly determined shadow pricing to monetarily define the cost of subjective things like river health, job creation and mental health benefits, the SROI can act as a highly significant piece of evaluation data for the scheme. Obviously, there must be more than one model used to quantify success of such a large policy framework, but even for just a starting point, the SROI may tell the government that the policy is clearly or clearly not working properly, and that changes need to be made. Then once a decision has been made that changes need to occur, other quantification methods can be used to determine more niche performance factors that include a smaller subset of considerations, such as Green GDP Change which only measures financial and environmental concerns.

While our current analysis provides a foundational understanding of the policy's impact, there are additional quantification methods the government could pursue to more comprehensively evaluate its effectiveness. These approaches remain unexplored in our study primarily due to the lack of available data. We recommend that the government prioritize the collection of relevant data to enable deeper, more nuanced analysis moving forward.

An effective method for assessing the efficacy of the RTFO is to implement Shadow Pricing, utilising the social cost of carbon to measure the external advantages of emission reductions. This facilitates the incorporation of non-market environmental advantages, including less air pollution and climate harm, into economic assessments. Incorporating shadow prices reveals the greater societal worth of renewable fuel utilisation, particularly in policies that advocate for circular economy activities via waste-derived biofuels. The Social Return on Investment (SROI) framework assesses the efficacy of the RTFO in converting public or private investments into beneficial results, in relation to economic and social returns. The SROI ratio for RTFO-funded projects remains undisclosed; nonetheless, significant potential social benefits encompass rural employment in feedstock production, enhancements in air quality, and technological innovation spillovers into related sectors such as agriculture and waste management. When effectively monetised, these non-financial advantages may enhance the overall Social Return on Investment (SROI) ratio of measures tied to the RTFO.

Furthermore, the Green GDP Contribution indicator provides a macroeconomic lens to assess the broader impact of the RTFO. By adjusting traditional GDP to account for environmental degradation and climate-related social savings, Green GDP offers a more comprehensive view of whether the net benefits of adopting renewable fuels justify their economic costs.

# Conclusions and Recommendations

Across the key foci for analysis in this report, we have identified some actionable findings which we recommend the UK Government consider in order to optimise the use of the RTFO policy in the context of its Net Zero ambitions by 2050.

From research into similar policies in Brazil, the United States, and the European Union, policy consistency, market stability, and sustainable feedstock development stand out as major drivers for successful implementation of government policy. Strategic investments in sugarcane ethanol and flex-fuel vehicles as part of the Proálcool program has established Brazil as a global leader in biofuels exemplifying the importance of policy consistency and targeted investments – a lesson we recommend Government learns from to maximise the efficacy of RTFO policy. Similarly, the U.S. Renewable Fuels Standard has shown that a shift towards biofuels can increase energy security which is vital in the modern age as shown by the ongoing conflict in Ukraine, and a strategic benefit such as this may help the policy gain political support from shareholders and the public. Moreover, while market stability can only be controlled on a domestic level, a stable economy at home is of course ideal when looking to stimulate technological development and incentivise the use of sustainable fuels.

It is also clear from the technical analysis that biofuel from waste remains a key opportunity on which this policy should aim to capitalise. Efficiency metrics show that there is potential for the 16 million tons of suitable annual waste in the UK to be made into a fuel comparable to coal in its GCV and PEIO with the crucial advantage of emitting at most 40 – 50% of the GHG emissions of regular fuels. It is also clear that there is active research aiming to use enzymes to ensure that as close to all the available waste can be made into a viable fuel as possible. Government should therefore invest in further academic research developing these technologies and incentivise the use of biofuels through the RTFO via methods such as double counting to stimulate growth in this market sector, while remaining mindful of sectors such as aviation which are dependent on using fuels with the highest energy densities.

When evaluating the success of the scheme, we recommend that Government use metrics such as the SROI Ratio as a starting point for quantifying the success of the policy framework. Evidently, the nature of an overarching policy such as this means it cannot be simplified down to one number, and nuance must be applied where necessary, but a single figure to show positive social, economic and environmental impact can be used to draw support across the political spectrum – something which will be key in the bid to solve the climate crisis.

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# APPENDICES

# ENERGY GENERATION

# Appendix A

## Appendix A1: Production

Corn and wheat are the most widely used feedstocks of biofuels supply in the UK. Corn is composed of 72 % starch, 9.5% fiber, 9.5% protein and 4.3% oils [21]. Not only because of corn's high starch content, corn is a popular feedstock because it can be used to produce a wide range of products such as corn syrup for food industry and polylactic acid polymers. On the other hand, the wheat used by Ensus is sourced in the UK and Europe [19]. Feed wheat has high yield. Due to its low quality, it is not used for human food production but mainly as animal feed. Therefore, it is utilized as a bioethanol feedstock .

On the other hand, algae cultivation follows techniques like flocculation, centrifugation, or filtering for harvesting in either closed photobioreactors or open ponds. These systems encourage quick algae growth by using nutrients, carbon dioxide, and sunlight. Several businesses have led the way in this field, including Solazyme (now TerraVia), Sapphire Energy, and Algenol [22]. After being extracted from the algae using mechanical methods or chemical solvents, the lipids (oils) undergo transesterification to produce biofuels, like biofuels produced from waste cooking oils, which the UK has already started utilizing, according to the Department for Environment, Food C Rural Affairs (DEFRA). Other conversion processes include pyrolysis to produce bio-oil and anaerobic digestion for biogas production [24].

### *Bioethanol*

Bioethanol is produced through fermentation through four main stages: bioethanol production, liquefaction and saccharification, fermentation, distillation and dehydration based on Figure 4 [6][19].

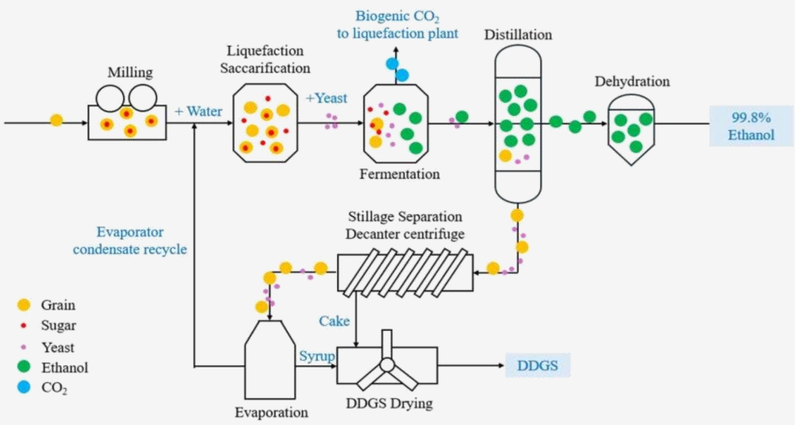


Figure 4: Schematic Diagram of Bioethanol Production [1S]

During liquefaction and saccharification, Water and enzymes are added into a mixing tank and form a mixture called mash. Here, starch from milling is liquified. Enzymes convert the starch into simpler sugars. Then, yeast converts the sugar to produce a beer solution and carbon dioxide, the latter used for drinks, food production and industrial purposes. Next, in the distillation tank, the beer is separated into ethanol and stillage. Ethanol undergoes dehydration whereas stillage is used to produce protein feedstuff for feedstock, DDGS. Finally, the ethanol with high water content is passed through a molecular sieve and dehydrated to become 200 proof ethanol which is theoretically 100% ethanol [18]. However, it is impossible to produce 100% pure ethanol. Therefore, here it means the highest possible purity of ethanol that can be produced through molecular sieve, which is 99.80% anhydrous ethanol. Purity will decrease because ethanol will absorb moisture in the air [11].

The bioethanol production process produces by-products carbon dioxide and DDGS which are both fully utilized, minimizing the waste of the system.

### *Biodiesel*

For biodiesel, crops from generation 1 biofuels are pressed to extract the oil in it and treated with methanol [11]. This process utilizes waste cooking oil (WCO) and consists of 3 main steps to biodiesel production: filtered, then treated with catalysts in a chemical reaction known as transesterification. A mixture of biodiesel and other byproducts are produced hence purification is required for the biodiesel to be obtained. Nanoparticles added such as cerium oxide and zinc oxide act as catalyst to increase efficiency, better engine performance, and reduce emissions. Biodiesel made from used oils are also known as Fatty Acid Methyl Ester (FAME), a renewable biofuel made from vegetable oils, animal fats, and recycled cooking oil [23].

# Appendix A2: Biofuel Producing Companies

### *Shell*

As a trader and a prestigious global biofuel blender, Shell has important operations through its joint venture, Raizen, in Brazil. In 2022, Shell incorporated approximately 9.5 billion liters of biofuels into its global supply of petrol and diesel which increased to 9.7 billion liters in 2023. Among these numbers, Raizen contributed 3.4 billion liters, an increase compared to last year's 3 billion. This is indicative of Shell’s increased integration of biofuel in the energy transition strategy.

### *Ensus UK Ltd*

As a subsidiary of CropEnergies AG since 2013, Ensus UK Ltd has been a major manufacturer of first- generation bioethanol. The company preprocesses various feedstocks at its bioethanol plant located in the Northeast England, which is one of the largest in the country, yielding 400 million liters of bioethanol, 350 thousand tons of Distillers' Dried Grains with Solubles (DDGS) and 250 thousand tons of carbon dioxide each year. According to a report from 2023, the Renewable Fuel Statistics stated that Ensus has also been ranked among the top 10 suppliers of renewable fuels proving its contribution to the decrease of emissions in transport by the UK Department of Transport [3].

## *Vivergo Fuels*

Vivergo Fuels, founded in 2007, remains a leading producer of bioethanol in the UK. The company produces about 420 million liters of bioethanol every year, which is one-third of the UK's total demand. Alongside bioethanol, in the aftermath of the RTFO, Vivergo also produces 400,000 tons of high protein animal feed from the processing of approximately one million tons of wheat sourced annually [28]. A significant portion of the wheat is from Yorkshire and Lincolnshire farmers, which ensure a strong domestic supply chain integration [27]. During bioethanol production, starch is extracted for fuel, and the remaining protein and fiber are fed to livestock. Vivergo Fuels also meets around 20% of the protein requirements of the UK's dairy cattle, which highlighting the company's contribution to the agricultural sector according to DEFRA reports from 2023.

## *Greenergy*

Unlike competitors, Greenergy emphasizes biofuel production from waste oils like used frying oils sourced from restaurants and food companies. This process enhances circular economy practices by transforming waste into high-value energy sources Greenergy (2023). The company has three biodiesel production plants in Immingham (UK), Teesside (UK) and Amsterdam (Netherlands) with modern business processing technologies.

Greenergy has put in place traceability systems to prevent the illegal handling waste oil feedstocks. Furthermore, the company remains invested in expanding the capacity of its Amsterdam plant to accept a wider variety of waste-derived feedstocks. The company is one of the major providers of low carbon transport fuels to independent retailers in the UK, Ireland, and Canada supporting the decarbonization of the transport sector.

## *Argent Energy Ltd*

Argent Energy is a leading producer of waste-based biodiesel, having a combined annual production capacity of 195,000 tons of biodiesel, of which 95,000 tons are produced in the UK [36]. Argent specializes in converting waste fats and used cooking oils into biodiesel, thereby reducing dependence on virgin crop-based feedstocks. This alternative through waste valorisation is consistent with the UK government's Renewable Transport Fuel Obligation (RTFO). Argent Energy presence is evident through its involvement with Transport for London (TfL), which utilizes the firm's B20 biodiesel (20% biodiesel blend) to power its public transportation fleets. Interestingly, one-third of London's buses currently operate on B20 biodiesel, demonstrating the application of Argent's renewable fuel technology in real life.

# Appendix A3: Advantages and Disadvantages of types of biofuels

## *Generation 1: Crops Biofuels*

### *Advantages*

#### Greenhouse gas emissions reduction

Crop-based bioethanol contributes to more than 65% of greenhouse gas (GHG) reductions compared to conventional petrol. This translates to the removal of nearly 260,000 petrol automobiles from UK roads.

#### Compatibility with existing infrastructure

One of the major advantages of Generation 1 biofuels is their easy integration with existing fuel infrastructure. Unlike electric or hydrogen vehicles, biofuels do not require extensive upgrades to their current transport systems, hence adopting them is more cost-effective and practical. Biofuels can be blended with conventional fuels (e.g., E10 petrol and B7 diesel) for gradual implementation without major infrastructural modifications [4].

#### Fuel customization and supply chain efficiency

First-generation biofuels can also be tailored depending on transport system needs. For instance, bioethanol and biodiesel formulations can be tailored to suit different engine requirements so that fuel usage and emissions are kept to a minimum. Existing logistics networks for fossil fuels can also be used to handle the distribution of biofuels, with minimal cost in altering supply chains.

### *Disadvantages*

#### Competition with Food Production

One major issue with first-generation biofuels is that they compete with the supply chain of food- based feedstocks. Instead of feeding people, crops like corn and wheat are being used to make fuel. This ultimately brought up a debate of using feedstock for biofuels against food security as approximately 2% of land for agricultural purposes is used for the purpose of biofuel production when it can be used instead to cultivate food [2]. In the UK alone, nearly 8,800 hectares of land are used to grow wheat for biofuels, which could otherwise produce about 15 million loaves of bread every day [13]. Globally, this shift in agricultural use drives up food prices and can contribute to food shortages, contradicting the UN's Sustainable Development Goals.

**Ecological and environmental Impact**

Farming crops for biofuels isn't always eco-friendly. These crops require large amounts of water and fertilizer, leading to water shortages and pollution. The carbon footprint from corn ethanol had been underestimated due to the higher use of fertilizer and water in practice. Some studies even show that producing biofuels like corn ethanol generates 24% more carbon emissions than regular petrol [4]. Deforestation for biofuel farming also destroys ecosystems and can introduce invasive species that further disrupt biodiversity [2].

**Difficult to take advantage of economies of scale**

There simply isn't enough land to produce biofuels at the scale needed to replace fossil fuels. It is estimated that 5% of European farmland is used for biofuel production. If the EU wanted to replace just 6.5% of its crude oil imports with biofuels, that number would have to double. Replacing all crude oil with biofuels would require a staggering 70% of EU farmland, making large-scale adoption exceedingly difficult and production cost and supply of biofuels stagnant.

**High cost for consumers**

Due to the novelty of biofuels, challenges in mass-production will increase its implementation cost. Ultimately, those costs are passed on to consumers. UK drivers have already spent an extra £2 billion due to biofuel mandates, and this figure could reach £23 billion in the future [4]. On top of that, the Department of Transport has indicated that the cost of reducing carbon emissions with biofuels is estimated at £165-£170 per tonne—far more than the £59 per tonne cost of switching to electric vehicles, which doesn't even consider the subsidies provided by the government.

## *Generation 2: Waste-based Biofuels*

### *Advantages*

**Higher environmental benefits**

Generation 2 biofuels gave a greater environmental impact compared to its predecessor. As of 2021, 4.9% of the total road fuel supplied in the UK comprises biofuels. Some common examples are petrol blended with 10% bioethanol (known as E10), while diesel is blended with 7-10%

biodiesel (B7-B10).

For the period 2017-18 biofuels in the UK saved approximately two million tons of GHG emissions, equivalent to removing more than one million cars from the road.

**Waste utilization and cost-effectiveness**

Seeing that the most common feedstock used in the production of biodiesel is Waste Cooking Oil (WCO), WCO provides an economical and environmentally friendly option as these waste oils would be disposed of if not converted to biodiesel. Restaurants, supermarkets, industrial and commercial kitchens are popular options for obtaining WCO at a cheap rate. According to BioUKFuels, WCO with heavy contamination can be bought at around £5 per 100 liter while uncontaminated WCO only costs £15 per 100 liters.

**Engine compatibility and efficiency**

The typical blend of biodiesel used in the UK is B7 as most modern engines can make this transition from normal diesel without any modifications. Hence, engines do not require modifications to utilize biofuels in accordance with European Union standards. Most manufacturers of heavy goods vehicles permit the use of higher blends such as B20, B30 and some up to B100. However, higher blend such as B100 require modifications including different materials in the fuel delivery system, heated fuel lines, and insulated fuel tanks. Hence, higher blends of biodiesel are not available for conventional transportation but only used by commercial fleets in bunkered fuel supplies.

According to Argent Energy, biofuels produced from waste oils are more sustainable and environmentally friendly as the highest level of biodiesel available (B100) is reduced to 90% CO2 emission in comparison to normal diesel. This is mainly because the use of these biofuels increases vehicle performance while acting as a detergent that maintains vehicle and storage cleanliness which is less toxic that the generation 1 biofuels.

## *Disadvantages*

**Storage and performance issues**

Biodiesel, a common second-generation biofuel, can be tricky to store and use due to its low gel point. It thickens in cold weather, becoming a waxy solid hence, less reliable for vehicles operating in colder climates [36]. This renders the fuel ineffective as it cannot be pumped into the engine for combustion. In general, biodiesel will gel at 30F higher than that of normal diesel.

Additionally, it absorbs water easily, which can lead to microbial growth if stored for months. Biocides, being non-toxic in nature, will further promote this growth and biodiesel must be implemented to prevent this. Hence, second-generation biofuels require frequent fuel quality testing.

#### Higher maintenance costs

Switching to biodiesel isn't as simple as filling up a regular diesel engine. Vehicles need modifications, which can cost up to £4,000 per engine, as seen is the B100, depending on the concentration of biodiesel blend used [36]. As the concentration of the biodiesel blend used increases, the cost increases as well.

Annual maintenance costs, including tank cleaning and fuel sampling, can add another £1,000 per vehicle, making it an expensive transition. On the other hand, (Fatty Acid Methyl Ester) FAME biodiesel, a more water absorbent variation, requires more fuel management such as fuel filters and oil inspections compared to regular diesel.

Table 3: Additional annual maintenance cost comparison between B20 and Normal diesel [31]

| Cost Item | Biodiesel (B20) | Diesel |
|---|---|---|
| **Annual service** | £200- £250 | £115- £315 |
| **Tank cleaning** | £750 | £0 |
| **Fuel sampling** | £0- £240 | £0 |
| **Total additional cost annually** | £950- £1240 | £0 |

## *Generation 3: Algae-based Biofuels*

### *Advantages*

#### Year-round production

Compared to conventional and alternative biofuel sources, algae biofuels offer many benefits. Unlike seasonal crops, algae may be grown year-round and grow rapidly, providing sustainability. Macro algae typically yield from 7 to 30 tons per hectare per year, compared to maize at 10-15 tons per hectare annually [20]. Other biofuel crops, such as soybeans and rapeseed, do substantially less well, yielding just about 2.8 and 3 tons per hectare, respectively according to the FAO [30]. Given this comparison, algae have much higher biomass productivity, indicating its potential as a more efficient and scalable biofuel source.

#### Carbon neutrality potential

Furthermore, when combined with carbon capture technologies, they have the potential to make carbon-neutral production by capturing carbon dioxide throughout expansion. Algae can capture approximately 1.8 kg of $CO_2$ per kilogram of algal biomass produced, making it a valuable option for reducing greenhouse gases, aligning with UK's sustainability goals [29].

**High oil yield and versatility**

Freshwater resources and cultivable land can also be preserved by growing algae in wastewater, eliminating the need for fertile agricultural land; a significant advantage in the UK, where freshwater resources are increasingly under pressure. This reduces the demand for freshwater by up to 90% compared to traditional biofuel crops like corn or soybeans [23].

Finally, algae are very effective in producing fuel because they produce more oil per hectare than crops like corn or soybeans. Algae can produce up to 2,500–5,000 gallons of biofuel per acre per year, compared to 18 gallons per acre for corn and 48 gallons per acre for soybeans [8]. For example, the biodiesel production of microalgae significantly overperforms that of corn as in Table 4 [5].

Table 4 Yield of algae and other biodiesel crops [5]

| Crop | Oil Yield (L/ha/year) | Biodiesel Productivity (kg/ha/year) | Crop | Oil Yield (L/ha/year) | Biodiesel Productivity (kg/ha/year) |
|---|---|---|---|---|---|
| Rapeseed | 1190 | 862 | Sunflower | 952 | 946 |
| Oil palm | 5950 | 4747 | Jatropha | 1892 | 656 |
| Corn | 172 | 152 | Microalgae * | 58,700 | 51,927 |
| Soybean | 446 | 562 | Microalgae ** | 136,900 | 121,104 |

* 30% oil (L/wt) in algae biomass, ** 70% oil (L/wt) in algae biomass.

Similarly, bioethanol production is also much greater with microalgae [33]

Table 5 Yield of algae and other bioethanol crops [33]

| Source | Ethanol yield (gal/acre) | Ethanol yield (L/ha) |
|---|---|---|
| Corn stover | 112–150 | 1,050–1,400 |
| Wheat | 277 | 2,590 |
| Cassava | 354 | 3,310 |
| Sweet sorghum | 326–435 | 3,050–4,070 |
| Corn | 370–430 | 3,460–4,020 |
| Sugar beet | 536–714 | 5,010–6,680 |
| Switch grass | 1,150 | 10,760 |
| Microalgae | 5,000–15,000 | 46,760–140,290 |

Compared to other biofuels, algae biofuels have unique advantages that position them as a superior option for the future. Algae can produce up to 10 to 100 times more fuel per hectare than traditional crops like soybeans or corn due to their rapid growth rate and high lipid content [24]. Furthermore, algae do not compete with food crops for arable land, thereby not impacting food prices, a significant concern in the UK [17]. They are also water-efficient, growing in brackish water, seawater, or even wastewater, unlike corn or sugarcane, which require significant freshwater inputs [29]. Algae can produce various biofuels, including biodiesel, bioethanol, biogas, and even aviation fuels, making them more versatile than other biofuel sources [8]. Their ability to grow and be harvested year-round ensures a consistent and scalable production cycle, unlike traditional crops that are seasonal.

### *Disadvantages*

**High production costs**

Algae-based biofuels are promising but incredibly costly. Producing bioethanol from algae can cost between $10.00 and $20.00 per litre—far more than traditional bioethanol, which costs between

$0.30 and $0.53 per litre [10]. Similarly, algae-based biodiesel costs around $11 per gallon, compared to just $3.48 for soybean-based biodiesel according to e-education data [32]. This cost disparity presents a challenge for the UK, where energy costs are already high.

**Technological and Infrastructure Challenges**

Scaling up algae biofuel production are still being refined, making industrial-scale production difficult to achieve. ExxonMobil and Synthetic Genomics invested over $300 million into algae biofuel research but ultimately scaled back their efforts due to technological challenges [24]. Additionally, while ethanol and biodiesel have over 230,000 fuelling stations, algae-based fuels still lack the infrastructure needed for widespread use, limiting market penetration [23].

**High energy demands**

Algae biofuel production is energy-intensive, which reduces its environmental benefits. Harvesting and drying algae can account for up to 50% of total energy input, making the energy balance less favourable than expected [23]. However, ongoing research and government support, such as the U.S. DOE's $258 million investment in algae biofuel research since 2010 through its Bioenergy Technologies Office (BETO), may eventually improve its viability [23].

# Appendix A4: Biofuels initiatives outside the UK

Biofuel research hasn't just expanded in the UK, countries around Europe and the United States of America has demonstrated interest in biofuel implementation, including algae biofuels. Algae biofuels, especially biodiesel, are very adaptive for current automobiles because they can be utilized in diesel engines with little to no modification. According to the U.S. Department of Energy (n.d.), algae biodiesel has a cetane number of 50–60, which is higher than petroleum diesel (40–52) [23]. The cetane number is a measure of ignition quality of diesel fuel. A higher cetane number means diesel ignites more efficiently and burns more completely, resulting in reduced emissions of carbon monoxide (CO), hydrocarbons (HC), and particulates. Thus, they are a viable choice for long-distance transportation and heavy-duty vehicles due to their high energy density [29].

Several companies, including Algenol and Sapphire Energy, have collaborated with automotive manufacturers like Audi and Toyota to test algal biofuels in fleet vehicles [24]. However, rather than being widely used in commerce, algal fuels are now primarily in the research or experimental stages due to production limitations. Furthermore, as production costs decline and technology advances, regulations that favor cleaner fuels could accelerate their adoption. Depending on the $CO_2$ sourcing, the emissions could range from 48 to -57 $gCO_2e/MJ$ [12], which means it can have negative emissions, an attractive feature for the UK aiming to achieve net-zero emissions by 2050 [34].

# Appendix A5: Challenges in the implementation of biofuels

## *Ecological Challenges*

While biofuels are marketed as sustainable, their production can exacerbate environmental degradation. The Environmental Sustainability of Biofuels: A Review states that there are potential ecological impacts from the aspect of global warming, energy use, water use, biodiversity and many more when accounting for farming of crops for production of biofuels. These environmental impacts could bring forth potential greenwashing claims due to unresolved ecological impacts of scaled-up biofuel production.

Crop sources needed for biofuel production are also unreliable as biofuel feedstock are vulnerable to climate variability. Extreme weather conditions, such as the 2018 European heatwaves, demonstrated uncertainty in crop production due to unpredictable nature patterns, causing significant crop yield losses. Vivergo Fuels expressed this concern, suffering UK wheat shortages due to extreme weather which affected their bioethanol production. Greenergy has implemented measures to mitigate physical risks, such as flood defense systems, and regularly updates its emergency management plans to ensure operational resilience.

## *Logistical and Market Challenges*

**Feedstock competition**

Greenergy faced an increasing global demand for waste-derived feedstocks, without a proportional increase in supply which is driving up costs and creating supply chain constraints. Hence, to address this, Greenergy is diversifying its supply chains by sourcing waste oils globally, establishing long-term partnerships with collectors, and investing in technologies to process a wider range of feed stocks. This includes recent upgrades at its Teesside and Amsterdam plants to expand their pre-treatment capabilities [7].

**Shifting demand dynamics**

The transition to zero-emission vehicles, the rise of electric vehicles (EVs) and improved fuel efficiency are expected to reduce long-term demand for biofuels, which could impact Greenergy's market position and revenues. To combat this, Greenergy is focusing on expanding its portfolio of renewable fuels and aligning its business with the evolving energy transition. This includes developing advanced biofuels and supporting the decarbonization efforts of its customers through lower-carbon products. On the other hand, Argent Energy is also diversifying the implementation of other forms of biofuel blends.

**Policy delays**

Delays in the implementation of the Renewable Transport Fuel Obligation (RTFO) have an impact on bioethanol consumption. However, the UK government's decision to introduce E10 petrol, which contains up to 10% bioethanol, resurrected the business. The RTFO requires that 9.6% of total fuel supplied be renewable in 2022, with intentions to increase this aim to 12.4% by 2032. This strategy has played an important role in increasing the use of biofuels in the UK [14]. Vivergo Fuels was affected by this delay. "While biofuel consumption has increased, obstacles such as changing market conditions and competition from alternative renewable energy sources persist," reported Vivergo Fuels.

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# Appendix B

## Appendix B1: Development of total energy supply

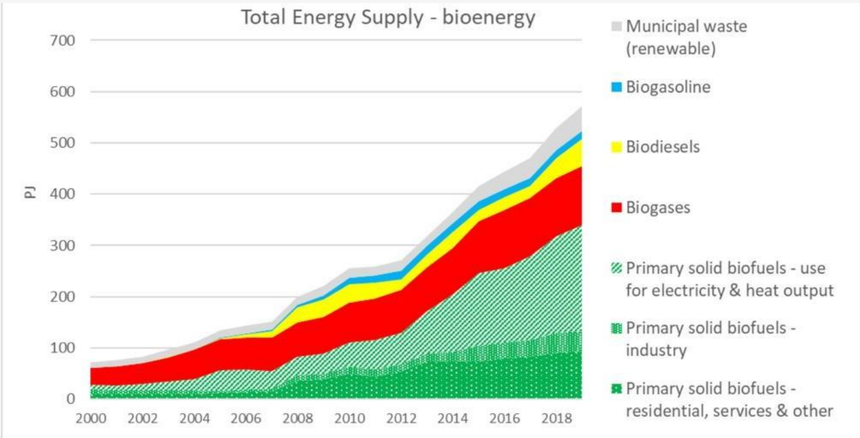


*Figure 1: Development of total energy supply from bioenergy in the United Kingdom 2000 - 2019 (Source: IEA (2021) World Energy Balances and Renewable Information)*

## Appendix B2: Hydrolysis

At this initial stage, hydrolytic bacteria break insoluble organic polymers such as carbohydrates into soluble derivatives. This step is crucial for making complex organic compounds available for further degradation [22]. A generic equation for hydrolysis is as shown [23]:

$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2$ (Eq. 1)

### Acidogenesis

At this stage, acidogenic bacteria convert hydrolysis products to various substances, including short-chain volatile fatty acid (VFA), alcohols, ketones, carbon dioxide, hydrogen, ammonia, etc. This stage is generally rapid, with acidogenic bacteria having a regeneration time of less than 36 hours [22]. The chemical reactions in this stage are [23]:

$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$ (Eq. 2)

$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ (Eq. 3)

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \text{ (Eq. 4)}$$

**Acetogenesis**

At this stage, acetogenic bacteria transform the previous products and some long-chain fatty acids into acetate, carbon dioxide, and hydrogen. This stage is thermodynamically feasible only when the partial pressure of $H_2$ is lower than $10^{-4}$ atm, maintained by methanogenic bacteria consuming the produced $H_2$ [4]. The reactions in this stage are [23]:

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+HCO_3^- + 3H_2 \text{ (Eq. 5)}$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \text{ (Eq. 6)}$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+ \text{ (Eq. 7)}$$

**Methanogenesis**

This final stage involves converting ethanol and hydrogen from the previous stages into methane, carbon dioxide, and water by methanogenic bacteria [22]. The primary reactions in this stage are [23]:

$$CH_3COOH \rightarrow CH_4 + CO_2 \text{ (Eq. 8)}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \text{ (Eq. 9)}$$

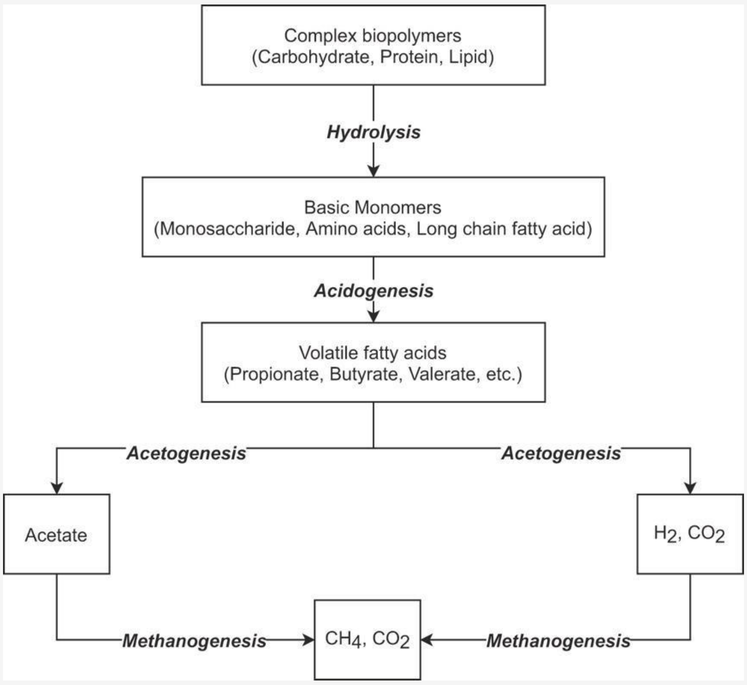


*Figure 2. Anaerobic Digestion decomposition stages and key compounds [4]*

At the same time, mechanically, the system has been designed to optimize the anaerobic digestion process. As shown in Figure 3, feedstock would first be transferred into the digester tank through an influent pipe after being processed from a reaction pit. While inside the tank, there are mechanical mixers to ensure a uniform distribution of solids and maintain consistent temperature conditions for microbial activity. There are also heat exchangers integrated to regulate the temperature, providing an optimal temperature for efficient digestion. The biogas produced would be stored in a rigid cover at the top of the tank, while the digested material, or effluent, exits through an outlet pipe for further processing or application [24].

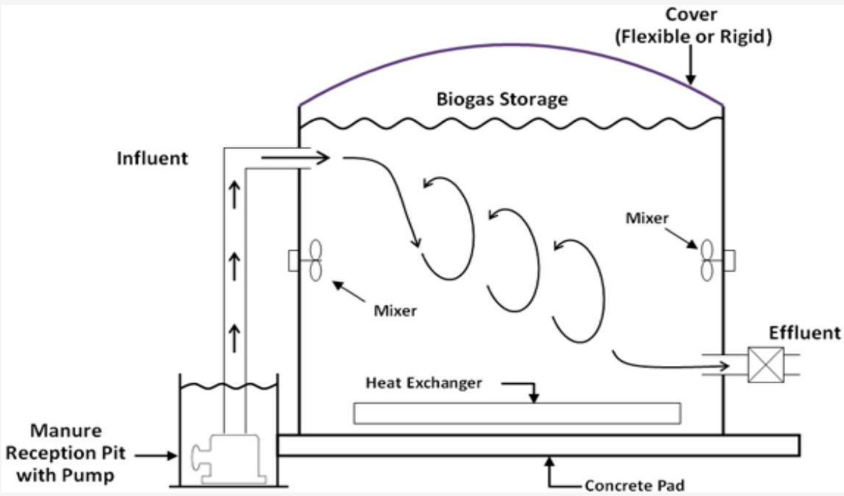


*Figure 3 Mechanical Design of an Anaerobic Digester [24]*

# Appendix B3: Producer gas composition of various biomass

| Biomass | Gas composition (% by volume) | | | | | Calorific value ($MJ/m^3$) | Cold efficiency (%) |
|---|---|---|---|---|---|---|---|
| | CO | $H_2$ | $CH_4$ | $CO_2$ | $N_2$ | | |
| Charcoal | 28–31 | 5–10 | 1–2 | 1–2 | 55–60 | 5.65 | – |
| Wood | 17–22 | 16–20 | 2–3 | 10–15 | 55–50 | 5.86 | – |
| Sawdust | 19.48 | 18.89 | 3.96 | – | – | 6.32 | 62.5 |
| Wood chips | 26.5 | 7.0 | 2.0 | – | – | 5.06 | 48.7 |
| Coconut shells | 19–24 | 10–15 | – | 11–15 | – | 7.20 | – |
| Rubber wood | 20.2 | 18.3 | 1.1 | – | – | – | – |
| Corn cobs | 18.6 | 16.5 | 6.4 | – | – | 6.29 | – |
| Rice hulls pelleted | 16.1 | 9.6 | 0.95 | – | – | 3.25 | – |
| Pine wood blocks | 25.53 | 28.93 | 6.82 | – | – | 4.76 | – |
| Hazelnut shells | 16.8 | 14.12 | 1.70 | – | – | 4.55 | 51.53 |

*Figure 4: Producer gas composition of various biomass [8]*

Instead of complete combustion with excess oxygen, the process occurs in a controlled environment with limited oxygen, allowing partial oxidation to produce syngas.

The process consists of four key stages: dehydration, pyrolysis, combustion, and gasification. In the first stage, biomass is heated to around 100°C to evaporate the moisture content, while the steam could participate in subsequent reactions. The pyrolysis heats the biomass at even higher temperatures at over 550 °C to release volatile gases, tars, and a carbon-rich residue (char) [25].

At the combustion stage, the volatile products and char react with oxygen to form mainly $CO_2$ and CO with the following general equation, with C representing any organic compound.

$C + O_2 \rightarrow CO_2$ (Eq. 10)

$2C + O_2 \rightarrow 2CO$ (Eq. 11)

The final gasification stage involves the key reactions, where syngas is produced [26]. This includes:

The water gas reaction: $C + H_2O \leftrightarrow CO + H_2$ (Eq. 12) The Boudouard

reaction: $C + CO_2 \leftrightarrow 2CO$ (Eq. 13) The

Methanation reaction: $C + 2H_2 \leftrightarrow CH_4$ (Eq. 14) The water gas

shift reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$ (Eq. 15)

These reactions are influenced by factors like temperature, pressure, and the choice of gasifying agent, which can affect the composition and yield of syngas.

# Appendix B4: Transesterification

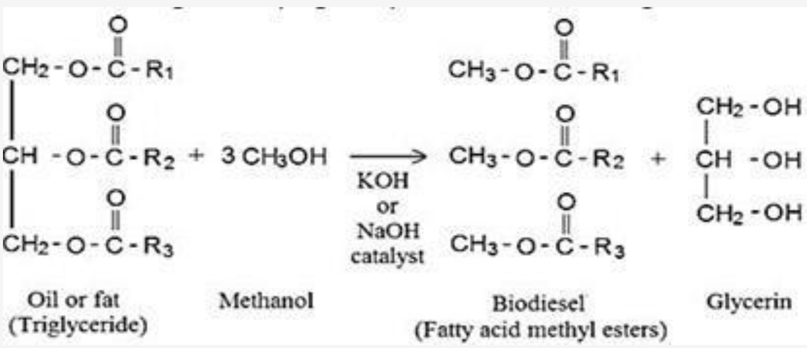


*Figure 5: Transesterification process [12]*

As a result of recent emphasis on renewable energy and mitigating the looming global warming disaster, biodiesel has become a viable alternative to fossil fuels. The $CO_2$ released from the combustion of biodiesel is offset by the $CO_2$ absorbed when cultivating the biomass. However, a notable challenge faced is the limited availability of oil feedstock. Increasing the use of vegetable oils provides issues of its own; heightened vegetable oil demand can cause an increase in global food prices [12], which especially impacts developing countries.

# Appendix B5: Breakdown of life cycle greenhouse gas emissions

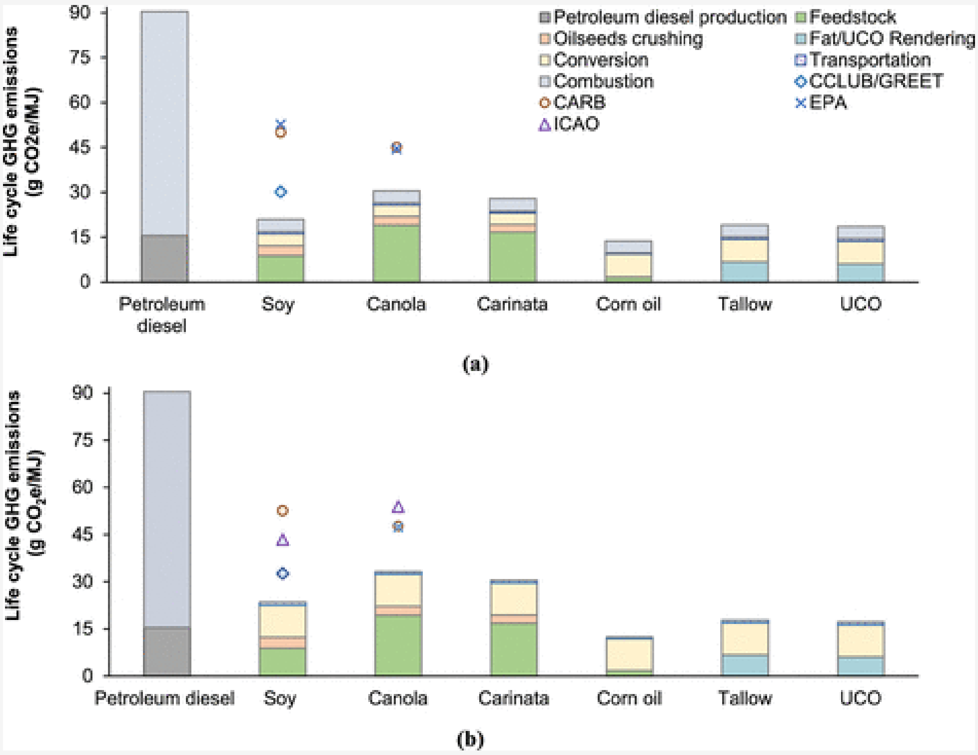


*Figure c: Breakdown of life cycle greenhouse gas emissions of (a) oilseed production and (b) biofuel conversion processes.*

A comparative lifecycle analysis [27] of biodiesel, renewable diesel, and petroleum diesel reveals substantial differences in greenhouse gas emissions across various feedstocks and production pathways. Figures 6  [27] illustrate the well-to-wake (WTW) greenhouse gas emissions, meaning the complete life cycle emissions of fuel, for biodiesel and renewable diesel pathways, respectively, highlighting contributions from feedstock production, oilseed processing, fuel conversion, transportation, and combustion.

Without accounting for land use change (LUC) emissions, the WTW emissions of soybean, canola, and carinata oils to biodiesel range from 21 to 31 g $CO_2e$/MJ [27], with soybean biodiesel presenting the lowest emission. In comparison, the corresponding renewable diesel pathways emit approximately 8–10% more greenhouse gases, ranging from 23 to 34 g $CO_2$e/MJ [27], primarily due to higher conversion emissions during hydroprocessing.

When land use change emissions are included, WTW emissions for soybean and canola-based fuels increase significantly. Depending on the estimation method, total emissions can reach up to 53 g $CO_2$e/MJ [27]. However, land use change estimations vary widely among sources, reflecting uncertainties in modelling land use impacts.

Feedstock production and fuel conversion are the dominant stages contributing to greenhouse gas emissions in both biodiesel and renewable diesel pathways, together accounting for 61% to 88% of total emissions [27]. For biodiesel, significant contributors within the feedstock stage include nitrous oxide emissions from fertiliser application, fertiliser production, and on-farm energy use. In the renewable diesel pathway, conversion emissions are 6.3 g $CO_2$e/MJ

[27] higher than those of biodiesel due to the energy-intensive hydrogen input used in hydroprocessing. Hydrogen accounts for 73% of renewable diesel conversion emissions, whereas methanol and natural gas dominate biodiesel conversion emissions. Methanol-associated emissions are 83% lower than those from hydrogen, making biodiesel relatively more efficient in the conversion stage [27].

To conclude, both biodiesel and renewable diesel pathways offer significant greenhouse gas emission reductions compared to petroleum diesel, with the greatest benefits observed in pathways utilising waste-derived feedstocks. However, the overall climate benefit of crop-based biodiesel and renewable diesel is sensitive to land use change assumptions and fuel processing methods, which must be carefully considered in policy and sustainability assessments. Compared to renewable diesel, biodiesel generally has lower conversion emissions due to its less energy-intensive production process, though renewable diesel can sometimes achieve slightly lower overall emissions depending on the feedstock and allocation method. Overall, biodiesel remains a strong low-carbon alternative to petroleum diesel, particularly when the sustainability of feedstock sourcing is prioritized.

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# Appendix C

Geothermal heat provided 0.3% of the annual heat demand in the UK in 2021, including ground-source heat pumps (GSHPs), one deep geothermal well and mine water heat networks (Government Office for Science).

## *Eden Geothermal Energy Project*

The Eden Geothermal Energy Project, located at the Eden Project in Cornwall, UK, is an initiative to decarbonise heat supply to the Biomes, greenhouses and other facilities. The £22 million project was funded by the European Union through the European Regional Development Fund, Cornwall Council and Gravis Capital Management. It aims to decarbonise the heat supply to the Biomes and greenhouses, but is primarily an industrial research project for the University of Exeter to improve our understanding of deep geothermal, especially in the Cornwall region which has been shown to have particular potential.

EG-1 is the UK's longest deep geothermal well, drilled to a vertical depth of 4,871. Drilling began in May 2021 and was completed in October 2021, taking a total of 162 days. Energy is supplied through a single well heat-exchanger system, illustrated in Figure 1. A vacuum-insulated tube runs to a depth of 3,850m in the centre of the well for pumped hot water. At the surface, a plate heat exchanger extracts heat from well water at 85°C, and newly cooled water travels back down the annulus of the well. The system operates in continuous circulation. The geothermal well heat exchanger then transfers water to the various heat exchangers around the site, as shown in Figure 2.

The system will reduce energy bills by approximately 40% and produce around 1.4MW of energy. The project is not without its challenges: there are future plans to use the well to generate electricity, however the grid connection is only scheduled for December 2036. The well drilling was also difficult due to the hard granite rock, and additional costs were incurred due to Covid (Hook).

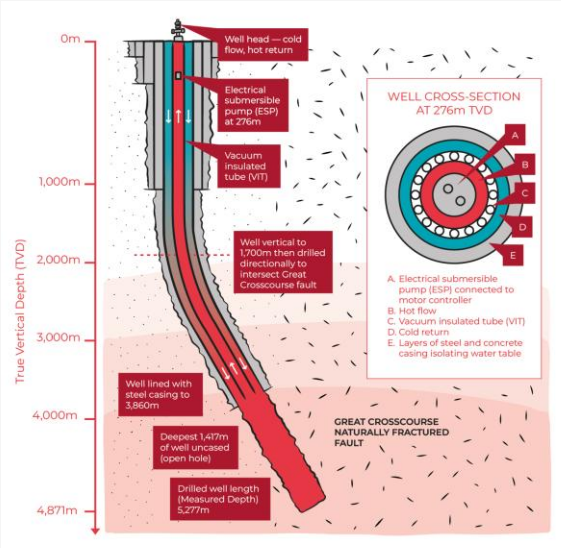


*Figure 2b: Schematic of Eden project*

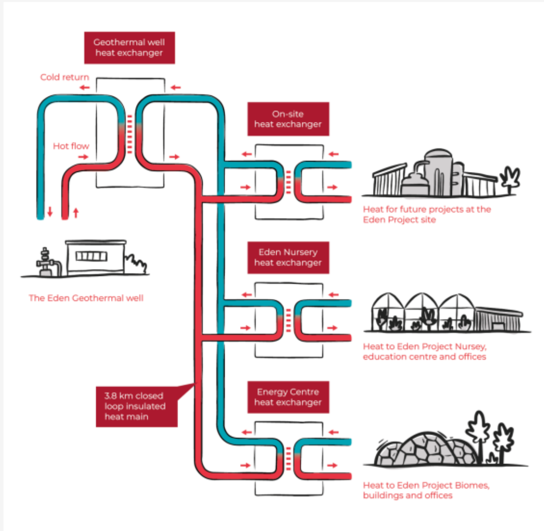


*Figure 2b: Schematic of heat pump*

## *Current regulation*

In the UK, geothermal energy is not recognised as a natural resource, and is controlled by numerous regulations, planning permission granted by Local Planning Authorities, Coal Authority Planning, and health and safety laws (Government Office for Science). This presents several challenges - multiple geothermal operations extracting from one heat source have the potential to impact one another and reduce efficiency, yet there is no regulation to balance the interests of different users. Although closed-loop GSHPs are subject to General Binding Rules as of October 2023, these primarily cover the environmental impacts of the scheme.

## *EU Geothermal Energy*

Geothermal energy is one of 8 strategic technologies included in the EU's Net-Zero Industry Act (European Commission), which aims to create better conditions and market access for clean tech in the EU. By simplifying the regulatory and licensing framework, this will help increase the competitiveness of technologies. The Act proposes to identify Net-zero Strategic Projects and prioritise these, and attract investment through the Net-Zero Europe Platform and European Hydrogen Bank. Moreover, skill enhancement through Net-Zero Industry Academies could also be particularly valuable to train and educate workers on net-zero technologies. Many of the skills required in the geothermal sector can be transferred from the oil and gas industries, which could provide a knowledgeable and high quality workforce.

The EU has funded a number of geothermal energy projects (CORDIS), including the DEEPEGS project which was successfully undertaken drilling tests and Iceland. The GeoWell project developed and tested new reliable, economic and environmentally safe technologies for the design, completion and monitoring of high-temperature geothermal wells. By directing funding into geothermal energy research projects, the UK could help to stimulate research in this area and improve the feasibility of technologies.

The Netherlands is an important case study for geothermal energy in Europe, given the government's clear commitment to developing the technology. Following a 2018 masterplan for geothermal energy developed by industry partners, government departments and the geothermal regulator, this has enabled the setting of clear targets and policy support measures. These include ongoing updates to regulation by the Ministry of Economic Affairs and Climate, as the technology develops. The government introduced a guarantee scheme on drilling risks in 2010 and the Stimulation Sustainable Energy production scheme in 2012.

## *Geothermal energy aquifers in the UK and its maximum geothermal energy output*

A full report by Durham University identifies council areas of major geothermal sources in the UK (Jefferies et al.). Most of these sources are insufficient for electricity generation; generally, medium-temperature and high-temperature sources of 100-150°C and >150°C ("3.6 Geothermal Energy Production"), respectively, are required for electricity generation as recommended by IRENA ("Geothermal energy"). This only leaves areas including Cheshire East, York, Shropshire, Carlisle, Newcastle upon Tyne, Allerdale, Ribble Valley, and Harrogate, as listed in Table 1 below, as suitable candidates.

*Table 1: Suitable areas for geothermal electricity generation, using data retrieved from* (Jefferies et al.).

| **Council area** | **Average geothermal gradient (ºC/km)** | **Estimated aquifer temperature at 4km (ºC)** | **Population density ($km^{-2}$)** |
|---|---|---|---|
| **Cheshire East** | 22 | 99 | 326 |
| **York** | 26 | 115 | 772 |
| **Shropshire** | 24 | 107 | 100 |
| **Newcastle upon Tyne*** | 24 | 107 | 2646 |
| **Allerdale** | 24 | 107 | 79 |
| **Ribble Valley*** | 28 | 123 | 103 |

| | | | |
|---|---|---|---|
| **Harrogate*** | 23 | 103 | 123 |

Obviously, geothermal electricity requires specialised power plants placed strategically at specific locations. The following plots in the Durham University study identifies specific regional hotspots in the UK where the geothermal thermal gradient is sufficiently high to generate medium- and high-temperature resources at depths of between 2-4 km below the surface.

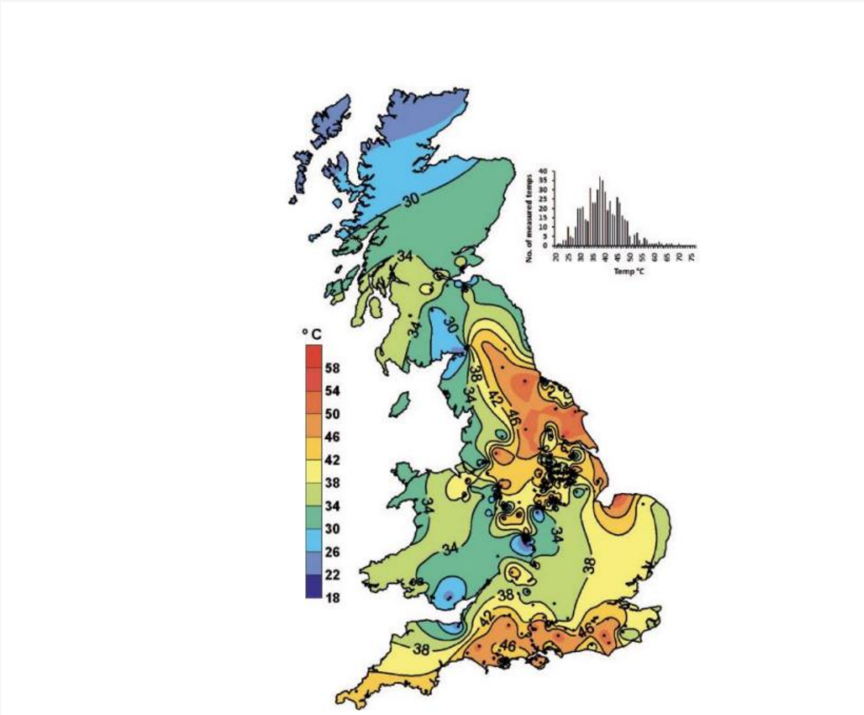


*Figure 3. Measured temperature at 1 km below ground level, retrieved from* (Jefferies et al.)

Geothermal temperature is not the only heat-related factor that determines the viability of GEG; heat flow is equally important.

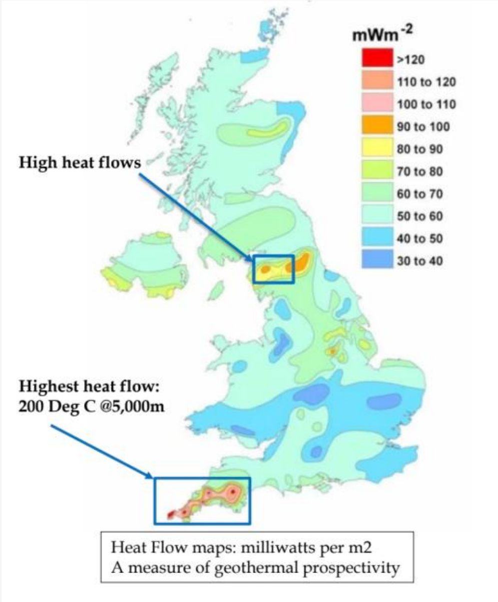


*Figure 4. Heat flow map across the UK, retrieved from* (Busby).

As shown in the above plot, very large heat flows are found around the Cornubian and North Pennine. These hot granite batholiths can theoretically supply up to 200% of the UK's electricity needs with surplus district heating (Aghahosseini and Breyer). In practice, estimates suggest that up to 20% of the UK’s electricity needs can be satisfied using contemporary technology of geothermal energy extraction (Merino-Garcia et al.).

**Geothermal energy under the CfD Scheme in the UK**

At the time of writing, there is no governmental support for deep geothermal projects in the UK (Merino-Garcia et al.). Projects like in Cornwall were only possible with support from local authority and the European Regional Development Fund (ERDF) (“United Downs Geothermal Project”); the latter is no longer possible after the UK has left the EU.

Officially, the UK government’s main channel of support for low-carbon electricity generation is through the Contracts for Difference (CfD) scheme (Merino-Garcia et al.), but the success of geothermal projects under CfD support is viewed unfavourably due to the strong competition of better developed technologies like offshore wind. Successful bids for geothermal energy projects are yet to be seen. Again, the lack of incentivisation sits at the root of the problem.

**Challenges facing GEG**

Governmental and logistical problems face GEG (Government Office for Science) in the UK, which are summarised below:

- Regulation gaps:
    - Geothermal energy is not regulated as a natural resource
    - Regulations on over-abstraction or even control of geothermal installation usage is missing
    - Local regulatory system depends on local authorities, environmental regulators, and the Health and Safety Executive, but remains little tested due to the lack of GEG systems.
    - Licensing systems are absent
- Underfunding
    - Lack of governmental support (as discussed above)
    - Lack of stakeholder confidence in sector (low maturity, high GEG project costs, high financial and geological risk, low governmental investment)
- Supply chain issues:
    - Manufacturing capacity and supply chains issues, including worries over
        - Capacity
        - Coordination
        - Maturity
        - International cooperation often required for equipment and/or skills
- Geothermal data:
    - Both availability and accessibility:
        - Further mapping work required
        - Data, including temperature, water chemistry, thermal conductivity, aquifer depth, permeability and transmissivity.
        - Lack of production testing, including of exploration wells
    - Affects stakeholders and regulators equally

- Technology
    - Though technology is evaluated by stakeholders as high in readiness, they remain expensive.
    - Technological innovation is critical, encompassing:
        - Drilling and electricity generation efficiency
        - Drilling and GEG station set-up speeds

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# Appendix D

## Appendix D1: Relevant Information

Shipping via maritime methods has been a long-standing industry, particularly when it comes to international travel. It has the ability to transport extremely large volumes of goods cheaply, with the only alternative being planes for most shipping which are not only more expensive but also would increase emissions. The main exporters in the world are the USA and China, both exporting around 3 trillion dollars worth of goods yearly (www.cia.gov, 2023), most of these being to another continent. Economic growth worldwide only points to an increase in this number with international goods production often being a cheaper alternative to local production. This leads to the only option being to directly decarbonise shipping, as the industry will only continue to grow.

The yearly consumption of petroleum fuels in shipping is almost double that of jet fuel and is among the largest of any sector (Tan et al., 2022). Combined with aviation, shipping contributes almost all sulfate emissions, half of the nitrate emissions and 36% of greenhouse gas emissions in the EU (Arias et al., 2024). Alongside this, petroleum is a non-renewable fuel source, and alternatives must be explored in order to maintain the growth in fuel consumption of shipping. The alternative fuel and energy industries are rapidly growing, and many options have been developed to use alongside of or instead of petroleum fuels. However, as these developments have been quite recent, acquiring a comprehensive understanding of the fuel alternatives has proved complex and unapproachable for most.

## Appendix D2: Hydrogen

### *Hydrogen storage*

Starting with a brief description of hydrogen storage, it can be classified into 4 types, namely type I, II, III and IV which type I is the earliest. A brief history of it would be the invention of type I hydrogen storage tank using only metal. Since hydrogen is not dense, it has to be compressed in order for the storage to be efficient, which metal is strong enough to withstand the pressure from gas inside. To create a lighter storage tank that could withstand higher pressure, type II and III storage tanks used a partial and full composite design respectively, with thick metal body. They are wrapped with cable or glass fiber-resin composite. Using aluminium as liner gives a higher capacity-to-weight ratio as it is around 70% lighter. Type IV uses polymeric liner instead which makes it significantly lighter and is able to withstand pressure up to 70MPa (Hy Responder, n.d.), which makes it the most used type of storage tank, especially in mobile applications like shipping industry.  It has highest storage density and has excellent fatigue resistance as well.

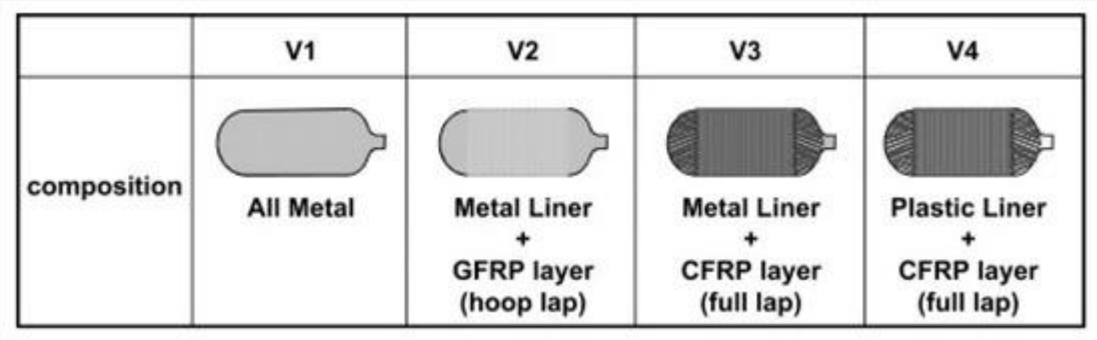



Fig 1. Types of Hydrogen Storage Tanks (Su et al., 2021)

While type IV storage is the most technological advanced method in the market, it has 2 main disadvantages, cost and hydrogen permeation. While no metal was used in the storage tank itself, with the only metal application being the shut-off valves, the complex manufacturing process makes it more expensive than the other types. Also, the hydrogen permeation is inevitable, despite the permeation rate is minimal with current technology, it is still a potential efficiency and safety concern especially at a high-pressure system, which the design for a hydrogen storage system has to consider material selection and design optimization, then conduct sufficient safety test before application. This may cause a hydrogen project to require more manpower and cost to ensure a safe operation.

## *Hydrogen Production*

Production is another key challenge for hydrogen to fulfil its potential, as the production of green hydrogen currently is low, which also causes the price to be high. With most hydrogen being produced by (strong methane reforming) SMR, which is grey hydrogen that is not sustainable and carbon emitting, this cheaper source of hydrogen is certainly not part of the future of energy generation. The most probable method for green hydrogen would be water electrolysis, which the method will be reviewed below.

The general reaction for water electrolysis would be

$$\mathrm{H_2O \rightarrow H_2 + \frac{1}{2} O_2}$$

, in which the process can be net-zero if renewable energy sources like solar or wind are used to supply the required voltage. Industrial scale of high purity hydrogen (up to 99.9999% (Nebi Yelegen et al., 2024)) can be produced with current technology, which the challenges would be the amount of renewable energy generated and cost.

Renewable energy sources are developing rapidly, since oil and gas are not sustainable, despite pollution can be minimized and carbon capture system is applied, it is still a limited resources that cannot be easily replenished. As the technology for hydrolysis has been well-established as it has been developing for more than a century, especially for alkaline water electrolysis. There are also other types of water electrolysis methods like solid oxide water electrolysis, anion exchange membrane (AEM) electrolysis and more under development. Since these types of technology are all net-zero with challenges mainly regarding the design and electrolyte used, this would not be further discussed in the report as it is slightly out of scope for application in the shipping industry. Currently, only 4% of hydrogen is produced by electrolysis, but with the worldwide green hydrogen research and manufacture ongoing, the price is likely to decrease soon. With more infrastructure and development in green energy sources in the future, hydrogen production should be a relatively small concern.

## *PEMFC Mechanism*

1. Basic flow(description) and material

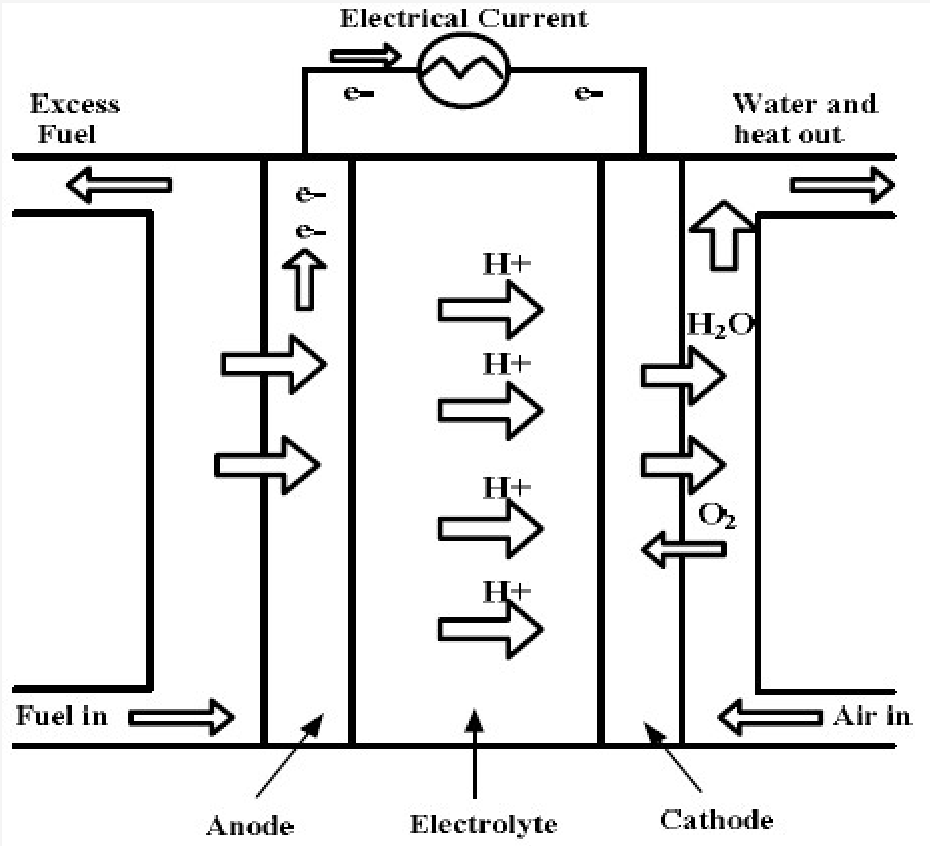



Fig 2. Schematic diagram of a PEM fuel cell (Fan et al., 2013)

In short, hydrogen fuel is fed into the anode side as oxidation reaction takes place to form protons, which travel through the membrane that is permeable to proton. Then the proton reacts with the oxygen fed from the cathode side, forming water and heat, with energy in the form of electricity produced in the process by hydrogen oxidation reaction in anode. More specific mechanisms will be discussed below, by explaining the function of each part of the cells alongside their corresponding material and design.

The PEM fuel cell has a few key components, a polymer membrane, porous electrodes and catalyst layer in between as shown in diagram above. The polymer membrane is usually made of perfluorocarbon-sulfonic acid ionomer (PSA). The function of membrane is acting as electrolyte, providing a medium for proton flow, whilst blocking species other than proton flowing through. The most commonly used membrane material, Nafion, has a hydrophobic chain with the ionic group, SO3-, absorbing large amounts of water, providing the medium for proton transfer mainly by Grotthuss mechanism.

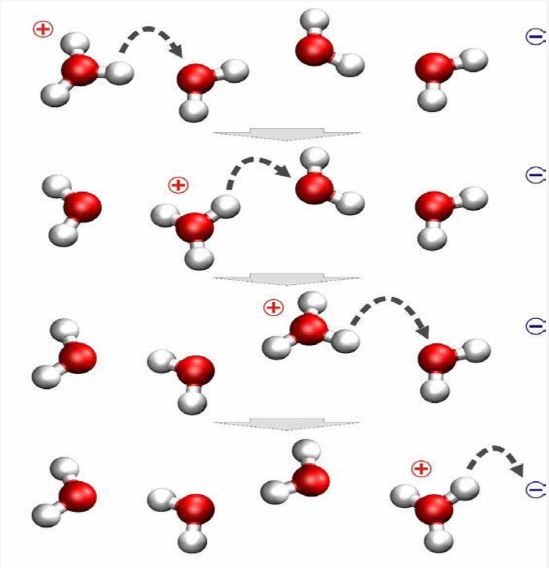


Fig 3. Schematic diagram for Grotthuss mechanism (Ilya Belevich, n.d.)

Grotthuss mechanism is a process for the diffusion of proton, through hydrogen bonding network. By this mechanism, protons travel from the anode to the reaction site, located in the layer between the membrane and the cathode. When the membrane is more hydrated, vehicle mechanism would be dominant, which protons are carried by water directly, with the movement of water molecules. While a more hydrated membrane increases the rate of proton transfer, too much water may cause flooding, which blocks ion transfer, which monitoring the level and temperature constantly is important.

The electrode must be solid and porous, as protons and gas are designed to travel through the electrode, then reaching the catalyst layer that is connected to the electrode. To fulfil the above properties, carbon paper, carbon cloth and carbon nanotube can be used as the electrode for PEMFC. Carbon paper has higher conductivity but is more fragile, and vice versa for carbon cloth. While the more advanced carbon nanotube is more suitable as it has both conductivity and strength, the price is significantly higher.

The catalyst layers are the reaction site for both hydrogen oxidation and oxygen reduction reaction (ORR), with the latter being the slower reaction hence the catalyst layer between membrane and cathode is more critical. The layers are designed to be very thin, as it decreases the rate of net proton transfer which a thick layer will lead to significant potential losses. Platinum or platinum-based alloy catalysts are mainly used for both catalyst layers, with carbon support in which Pt/C ratio is around 10-40%, to provide a reasonably large catalytic surface area, while reducing the use of platinum as it is expensive. There is non-precious metal catalyst under research currently, to reduce the use of platinum, which potential replacements are Transition Metal-Nitrogen-Carbon (M-N-C) Catalysts, metal oxides or biomimetic catalyst (East China University of Science and Technology, 2019), making it more sustainable.

2. Equations below for efficiency

In this part, performance of PEMFC will be investigated including calculation of theoretical maximum efficiency, voltage and overpotential.

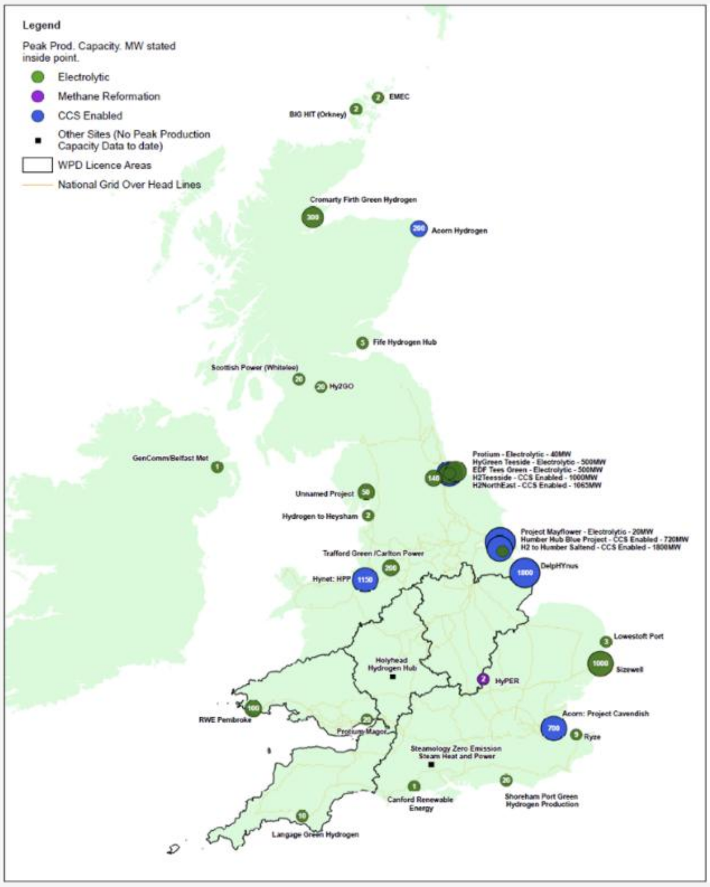
The overall reaction in the fuel cell can be expressed by

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

As thermal efficiency is defined as the ratio of Gibbs free energy to enthalpy change of reaction, using equation (1) and (2) (Mohammed et al., 2019) at standard conditions, which maximum theoretical efficiency for this reaction in PEMFC is calculated to be 83% by equation (Ohta, 2009). The actual efficiency in practical applications is lower than this, as there are other factors other than the inevitable heat loss, due to other factors like mass transport limitations and ohmic resistance, reducing to around 55% with current technology.

For electrochemical analysis, at standard conditions, the maximum theoretical voltage is calculated to be 1.23V with equation (3) and (4). Therefore, each PEMFC provides around a theoretical maximum value of 1.23V, which is around 0.8V in real life taking internal resistance and activation loss into account. With most applications requiring hundreds of volts, generally PEMFC stack is used rather than a single PEMFC unit, which they are connected in series to increase the voltage output to meet the requirement.

With the advantages of PEMFC as mentioned, including quick start-up time, long driving range and most importantly zero harmful emissions, it is shown to best the alternative to current internal combustion engines using traditional fuels. There is also research on regenerative PEMFC (Nebi Yelegen et al., 2024), which the fuel cell could be recharged by a power source which reverse the reaction, separating water into hydrogen and oxygen, instead of solely relying on refuelling hydrogen. The main challenge currently is the round-trip efficiency being too low to use, as green hydrogen is costly and infrastructure is limited currently. This also show the potential of PEMFC in the future as it could also work as electrolyser in the same fuel cell, which a hybrid PEMFC ship with stored power could travel further without refuelling.




In the UK, there are currently almost 3GW peak capacity for electrolytic green hydrogen production, which the number is expected to rise with few projects in near terms. combining with blue hydrogen as intermediate solution, it is expected to produce around 11.7GW of hydrogen, which has exceeded the UK's target of 10GW by 2030. (GHD, 2022) This figure show the feasibility of hydrogen energy in the future, with below map showing the locations of hydrogen are mainly in coastal area, making the transport of hydrogen easier.

Fig 4. Green and blue hydrogen production projects in UK (GHD, 2022)

# Appendix D3: Biofuel

## *Overview:*

Most biofuels produced at the moment are first generation (Arias et al., 2024), using either oil crops or grains as feedstock, which raises issues around the use of agricultural resources in a time where food production is arguably a better use for these. Alternatively, second generation biofuel production using waste cooking oil or forestry residues which can then utilise otherwise disposed of resources. The less consistent aspect of these biomass sources does mean that these aren't easily found commercially, and the potential scarcity of resources could lead to higher prices. Third generation biofuels are the most promising but also most underdeveloped of the three, with the ability to produce much larger volumes of biofuels for equivalent amounts of biomass. Algae is also a rapidly growing sector, being very simple to cultivate with a large diversity of commercial products that can be produced with them.

Production and Costs:

| Feedstock | Initial Processing | Precursor | Secondary Processing | Biofuel | Cost per ton ($/t) |
|---|---|---|---|---|---|
| Oil crops | Extraction | Vegetable oil | Esterification | Biodiesel (FAME) | 1 450 |

| | | | | | |
|---|---|---|---|---|---|
| | | | Hydroprocessed esters and fatty acids (HEFA) | Sustainable aviation fuel (SAF), renewable biodiesel | 1 350 |
| | | | - | Straight vegetable oil (SVO) | - |
| Waste oils and fats | Collection | - | Esterification | FAME | 495 |
| | | | HEFA | SAF, renewable biodiesel | 814 |
| Starch crops | Hydrolysis | Sugar | Fermentation | Ethanol, butanol | 213 |
| Lignocellulosic biomass | Hydrolysis | Sugar | Fermentation | Ethanol, n-butanol, isobutanol | 51 |
| | Hydrothermal liquefaction (HTL) | Bio-oil | Catalytic refining | Renewable diesel | 113 |
| | Fast pyrolysis | | Hydrotreating | Renewable diesel | 155 |
| | Catalytic fast pyrolysis | | Catalytic upgrading | Renewable diesel/gasoline | 145 |
| | Gasification | Syngas | Catalytic synthesis | High-octane gasoline (HOG1450), methanol, methane, DME | 102 |
| | | | Fischer-Tropsch | Renewable diesel/SAF | 91 |
| | | | Mobil oléfines to gasoline and distillates (MOGD) | Renewable gasoline | 165 |
| | | | C2 + alcohols + Geurbet reaction | Renewable diesel, SAF | 132 |
| | | | Oxygenates + carbon coupling | SAF | 147 |
| | | | C2 + alcohols + carbon coupling | SAF | 109 |

| | | | | | |
|---|---|---|---|---|---|
| | | | Catalytic synthesis + MTG | Gasoline | 81 |
| | | | Mixed alcohol synthesis | Ethanol | 93 |
| | | | Syngas fermentation + Geurbet reaction | Renewable diesel, SAF | 113 |
| Micro algae | Oil extraction | Green crude | Catalytic upgrading | Renewable diesel | 731 |
| Macro algae | Hydrolysis | Sugar | Fermentation | Ethanol, butanol | 173 |
| | Anaerobic digestion | - | - | Methane | 142 |
| Municipal solid waste (MSW) | Hydrothermal liquefaction (HTL) | Bio-crude | Catalytic refining | Upgraded bio-oil | 144 |
| | Anaerobic digestion | - | - | Methane | 34 |

Note the cost per ton column is the yearly operating cost divided by the daily biorefinery capacity (scaled to a year, minus 8 days for bank holidays). This table is a slightly modified version of table 3 in Tan et al., 2022, refer to original source for additional information.

The table found above summarises data for feedstock and their processing costs. The cost per ton uses the data for operating costs per year and the data for refinery capacity per day, this means the compiled information does not take into account feedstock cost or availability and is a generous estimate. Among the feedstock in the table, the least scalable are municipal solid waste and waste oils and fats as these come from a limited source, however algae and lignocellular biomass (woody biomass) are expected to scale well. The average processing cost per ton is 320$.

As seen in the table, most of the fuels produced in this paper are SAF, renewable diesel/gasoline, biodiesel, and ethanol. These can all be used interchangeably with existing fossil fuel systems, with ethanol actively being mixed into fuels for cars (US Department of Energy, n.d.).

## *Regulations and Data:*

The Internation Energy Association (IEA, 2023) predicted that biofuel demand would increase by 38 billion litres over 2023-2028, almost a 30% increase from the previous five years. In this prediction, renewable diesel and ethanol accounted for almost two thirds of the growth. Notably most of this demand comes from emerging economies, particularly from Brazil, Indonesia and India. Within advanced economies such as the EU, US, Canada and Japan there is limited growth due to high costs and technical limitations. The growth in emerging economies can largely be attributed to the abundant feedstock availability and lack of existing renewable infrastructure, along with a lower number of electric vehicles.

Policies pushing growth of biofuels in aviation and marine sectors are less common, with most policies focusing on overall fuel emission reduction. However, there are specific policies such as ReFuelEU Aviation and Maritime, which are adopted by participating countries in the EU and EEA. ReFuelEU Maritime (European Commision, 2023) has set goals to reduce greenhouse gas emmissions from ships by 80% by 2050 and plans to enforce use of either onshore power supple or alternative zero-emission technologies for moored passenger ships from 2030 onwards. The policy specifically seeks to avoid the use of crop-based biofuels as a replacement for fossil fuels, to prevent a shift of the fuel away from road transport (Europa.eu, 2023, section 28), and consider any crop-based biofuels as equivalent to fossil fuels in its regulation (section 10.1).

Within the UK the equivalent policy is found in the Renewable Transport Fuel Obligation (RTFO) scheme, established in 2008 and providing guidance on use of renewable fuel sources (GOV.UK, n.d.). It has also set targets to reduce crop-based biofuel use, with less value being placed on crop-based fuels than alternative sources. According to the RTFO data from 2023 (Department for Transport, 2024), 72% of renewable fuels in the UK are made from waste feedstock (with the main source being used cooking oil) with the other 28% only coming from crops and other non-waste sources. This proportion has been roughly steady for the past three years but is a significant increase of waste feedstock compared to 2013 (waste comprised of 40% of feedstock).

Another important policy being applied is the addition of maritime sectors into the UK Emissions Trading Scheme (ETS) by 2026 (Department for Energy Security & Net Zero, 2025). This policy aims to apply to ships with over 5000 gross tonnage, establishing stricter regulations for emissions and adjusting prices of fuels dependent on their GHG emissions.

Overall, regulations within the EU and UK are currently aimed primarily at road transport vehicles. These have a heavy focus on electric alternatives to fuelled cars, and don’t seek to increase biofuel production. Nevertheless, biofuel production will increase in coming years as emerging economies establish their own sectors. Policies are actively being implemented to increase the proportion of renewable fuels in both maritime and aviation sectors, with limitations on crop-based biofuels. Alternative sources of biofuels are currently well developed, with no significant expectations of growth in the UK from the data sets available.

# Appendix D4: Ammonia

## *Production of ammonia*

### *SMR-based Haber-Bosch (H-B) process*

Traditionally, ammonia is synthesised from nitrogen and hydrogen using an iron-based catalyst under high temperatures (400-450°C) and high pressures (15-20 MPa). This technology of producing ammonia is mature after continuous optimizations over the past century and is currently operating at the megaton scale.

$$N_2 + 3H_2 = 2NH_3$$

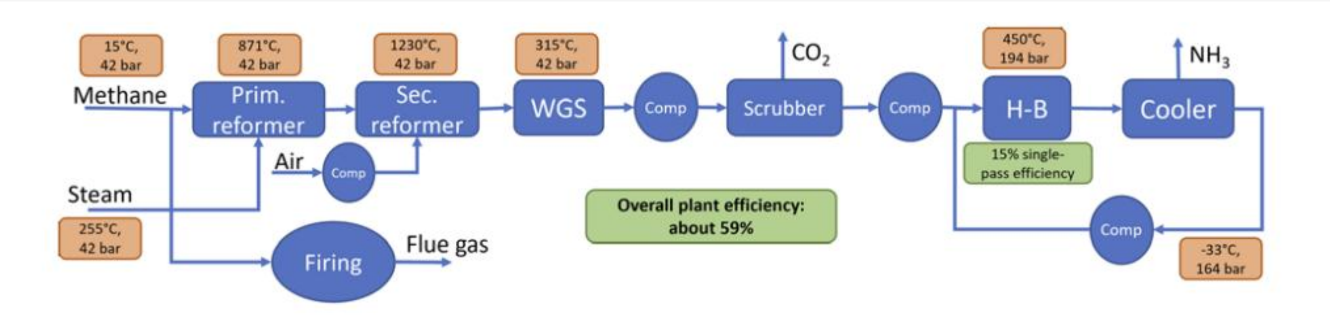



Fig (4) Simplified process flow diagram of the SMR-based H-B Process (without CCS)

The key to decarbonising the Haber-Bosch process is the hydrogen supply, as over 95% of the global hydrogen is produced via reforming of fossil sources with about half of that amount coming from steam reforming of natural or shale gas. First, steam reforming of

The H-B methane is carried out in an SMR to produce syngas containing mostly $H_2$, CO, and $CO_2$. In a secondary reformer, air is separated to provide the nitrogen for the process. Next, a water gas shift (WGS) reactor further reacts CO with steam to produce more $H_2$ and $CO_2$. $CO_2$ is then separated followed by methanation to hydrogenate CO and $CO_2$ to methane (to avoid poisoning of the H-B iron catalyst). Nitrogen and hydrogen are compressed and reacted in the H-B reactor to produce ammonia. This only has a single-pass conversion efficiency of about 15%, so cooling to -33°C and condensation are used to separate and recycle unreacted $H_2$ and $N_2$ while producing liquefied ammonia.

Since the process $CO_2$ is already being separated from the scrubber, instead of typically being vented, it should be stored underground to reduce emissions. This should not require significant changes to the process and will have lower capture costs as it is at a high partial pressure due to already being separated from the process stream during normal operation. The SMR reactor requires high temperatures, and it obtains its heat input from natural gas furnaces that contain a flue gas stream. The $CO_2$ emission from the flue gas stream must also be captured and stored for deep decarbonisation. However, this will incur higher costs as the partial pressure of the $CO_2$ is lower and an additional post combustion $CO_2$ carbon capture unit must be fitted in the flue gas stream. The flue gas capture system is a typical amine scrubber to capture $CO_2$ using chemical absorption. In an absorber column, the flue gas is contacted with a lean amine solution that absorbs the $CO_2$. This $CO_2$-rich amine solution then passes through a stripper column, where steam is used to regenerate the lean solvent. This leaves a stream of pure concentrated $CO_2$, which is compressed and pumped to a storage site.

## *ATR-based blue ammonia process*

An alternative to conventional SMRs is autothermal reformers (ATRs), which introduces pure oxygen in the reformer to partially oxidise the feed and provide heat, so no external natural gas furnaces need to be fired, thus also eliminating the flue gas stream from the conventional SMR process. An advantage of ATRs is that $CO_2$ is present in the process stream at higher partial pressures and concentrations and nitrogen is only introduced into the process later on, so the size of the carbon capture unit is smaller. ATRs use an air separation unit (ASU) to provide oxygen and nitrogen by separating air. Large-scale ATR-based ammonia production facilities are already commercially available, which can achieve up to 99% emissions reduction. [1]

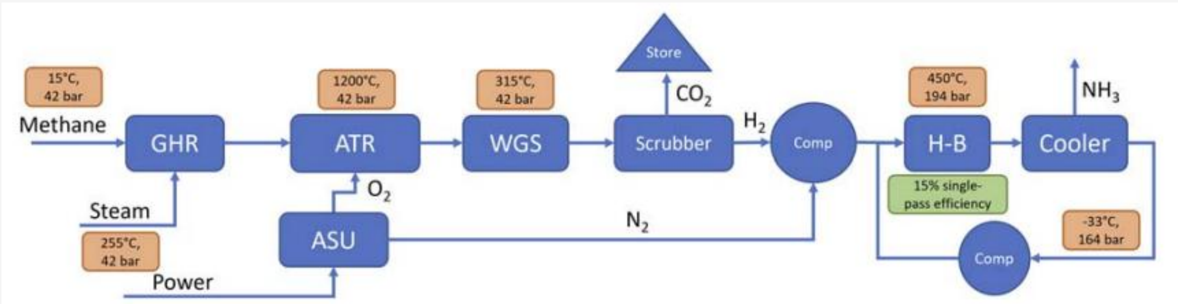



Fig (5) Simplified process flow diagram of ATR-based blue ammonia production

As emissions from the H-B process can be significantly reduced using carbon capture and storage (CCS), the upstream methane emissions to provide the hydrogen supply will dominate the total emissions and must be reduced as much as possible. If the US average upstream emissions are considered, blue ammonia plants with CCS are still about 90% less carbon intensive than the conventional ammonia plants. [2]

Alternatively, renewable energy used to split water in water electrolysis using alkaline electrolysers, solid oxide electrolysers, or polymer electrolyte membrane (PEM) electrolysers can produce green hydrogen and thus green ammonia. There are also other methods of producing green hydrogen such as biomass gasification to produce syngas, steam reforming of biogas from anaerobic digestion, photocatalysis, and thermochemical water splitting. Without subsidies and tax credits, these low-carbon ammonia production processes will always be more expensive than the conventional process. However, the cost competitiveness of these technologies is expected to increase due to increases in production of green ammonia and investment incentives such as tax credits, so the price of green ammonia will reduce.

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# Appendix E

## Appendix E1: Engineering backgrounds

➢ **Flash Steam Plants**:
Use high-temperature geothermal fluid (>180°C) to produce steam that drives turbines. Rare in the UK due to lower geothermal temperatures.

➢ **Binary Cycle Plants**:
Common for UK conditions, where geothermal temperatures are moderate (100–150°C). Heat from geothermal water vaporizes a secondary fluid with a lower boiling point, such as isobutane, which drives the turbine [8].

➢ **Combined Heat and Power (CHP)**:
Utilizes waste heat from electricity generation for heating applications, increasing overall efficiency.

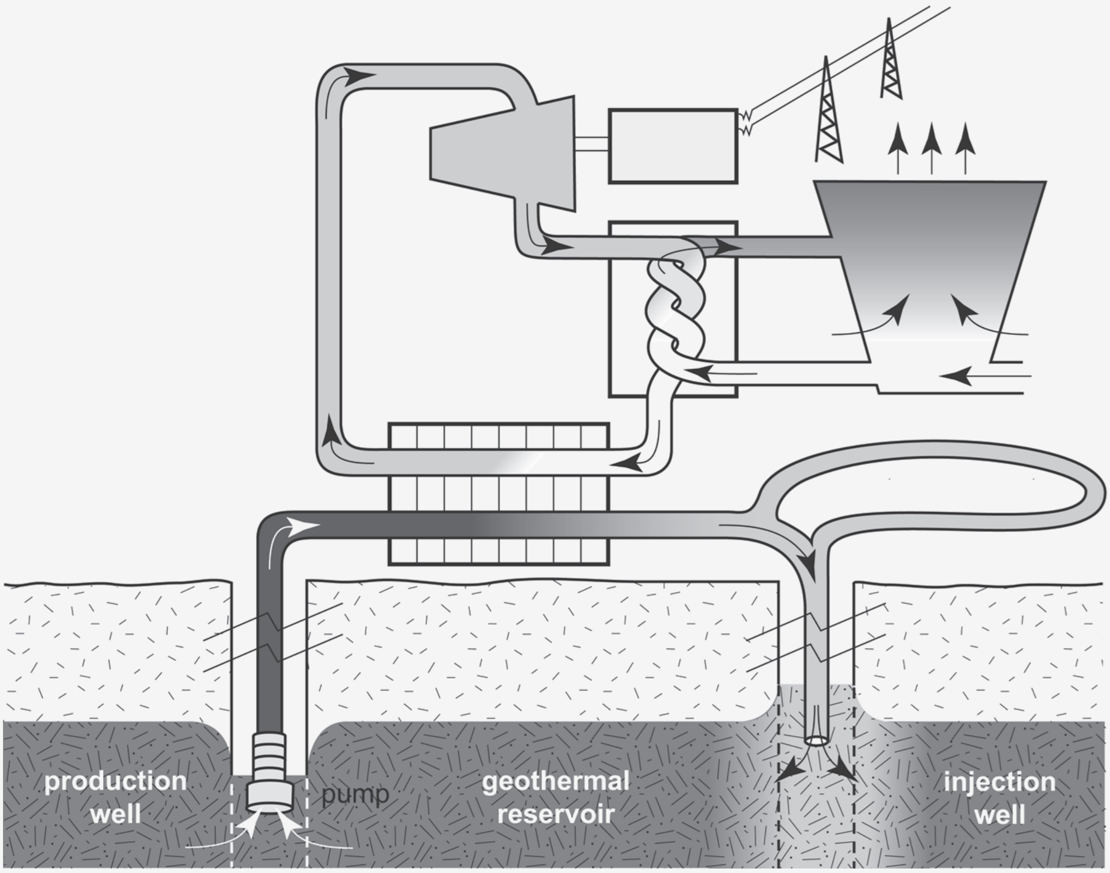


Figure 1: Simplified process flow diagram for a typical binary power plant of the type proposed to harness deep geothermal resources in the UK for power generation [3]

From an engineering perspective, the implementation of geothermal systems involves several key components. Drilled geothermal wells access hot water or steam reservoirs, while heat exchangers and pumps facilitate the transfer of heat to power generation systems or heating networks. In the UK's moderate geothermal conditions, binary cycle plants are often used; these systems utilize a secondary fluid with a lower boiling point to drive turbines, efficiently converting geothermal heat into electricity.

EGS projects incorporate advanced technologies and methodologies to overcome the inherent challenges of working with hot, dry rocks. Exploration and site selection rely on geophysics and geochemistry to pinpoint regions with high geothermal potential and geothermal gradient. Innovations in Enhanced Geothermal Systems (EGS) offer the potential to expand the resource base by artificially stimulating heat reservoirs in areas lacking natural water flow, while advancements in drilling technology and the use of corrosion-resistant materials help reduce maintenance costs and improve overall efficiency.

Deep wells, often drilled to depths of 3 to 10 km using directional and rotary drilling methods, provide access to hot rock formations. The creation of a permeable network is achieved through hydraulic stimulation, while continuous monitoring using seismic systems ensures that fracture creation does not trigger excessive seismicity. In operation, injection wells pump cold water into the reservoir, and production wells extract the heated fluid, which is then converted into electricity using binary cycle or flash steam technologies. The water then is redirected, creating an efficient loop of using water for heat extraction.

Mine water energy systems typically employ open-loop configurations, wherein water is extracted from the mine, passed through a heat exchanger or heat pump, and then re-injected into the ground [9].

To ensure environmental and operational safety. The engineering challenges include monitoring systems for precise drilling, efficient heat exchange design, and long-term maintenance of wells to prevent the overextraction of heat from these reservoirs depleteing these sources of energy. On another note the use of advanced geothermal reservoir simulation tools to design systems that maximize heat recovery is also a crucial advancement in technology and efficiency. Pipes and equipment are often made of stainless steel or specialized alloys to resist scaling and corrosion from mineral-laden geothermal fluids. Efficient thermal insultaion is essential for pipelines and heat exchangers to reduce energy losses. Development of closed-loop geothermal systems is also pivotal in future research as it minimizes environmental risks and scaling issues since there is no contact between groundwater and geothermal fluids. Mitigating seismic activity and the disturbance in the structural integrity of the geological environment is also essential in creating a safe source of green energy.

## *Benefits*

The environmental benefits of geothermal energy are considerable. Hydrothermal systems have a near-zero carbon footprint, which is essential for the UK's commitment to achieving net-zero emissions by 2050. Compared to fossil fuels, geothermal systems can reduce greenhouse gas emissions by up to 97% [3]. Furthermore, geothermal energy is a renewable and sustainable resource; the heat from the Earth's interior is continually replenished, ensuring a long-term stable energy supply while requiring minimal land use [10].

In addition to environmental advantages, geothermal energy contributes significantly to energy security and economic development. By harnessing domestic energy sources, the UK can reduce its reliance on imported fuels, thereby enhancing energy independence and protecting against global market volatility. Geothermal projects stimulate local economies through job creation in sectors such as exploration, drilling, construction, and maintenance. They also offer efficient heating and cooling solutions for a variety of applications, from district heating networks to industrial processes.

Mine water energy in addition provides a local source of energy, since the prevalence of abandoned mines ensures a localized and decentralized energy source, reducing transmission losses and transportation costs. By repurposing abandoned mines, these projects breathe new life into infrastructure that would otherwise remain unused [5].

Petrothermal geothermal systems and EGS are scalable and can be deployed in areas without natural geothermal reservoirs thereby utilizing non-conventional sites for energy generation and heating purposes.

EGS offers multiple benefits in terms of efficient land use and versatile applications. The system operates on a closed-loop basis, ensuring minimal environmental impact and negligible greenhouse gas emissions. Heat extracted from EGS can be transferred to water or another fluid and distributed via pipelines to residential and commercial buildings, thereby reducing reliance on natural gas for heating. In addition, small-scale Organic Rankine Cycle (ORC) units—tested in projects such as the MEET initiative—can efficiently generate electricity from low-temperature heat sources, making them particularly suitable for the UK's geothermal conditions.

In a social and community perpective, geothermal systems tend to be popular with the public, as they have lower visual and noise impacts compared to wind or solar energies. Projects in geothermal-rich areas can enhance local economies by fostering related industries and tourism (e.g., spa tourism in geothermal regions). They also provide a long-term and cheap spurce of heating and cooling. Gothermal energy can efficiently provide heating for residential, commercial, and industrial buildings, including district heating networks. These systems can offer cooling solutions, a feature that will become increasingly important as climate change causes hotter summers in the UK [11].

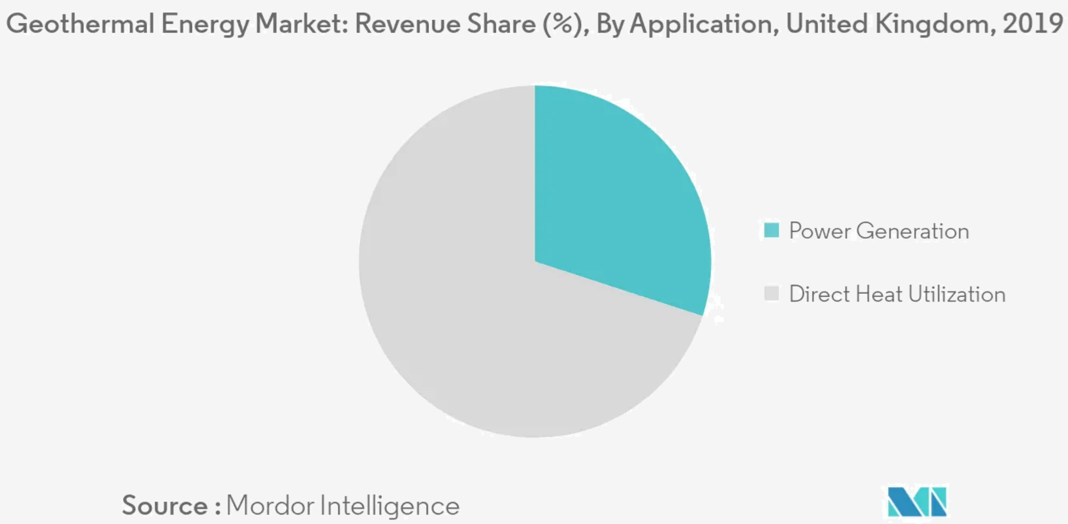


Figure 2: Utilisation of geothermal energy in the UK [26]

## *Downsides*

Despite its many advantages, geothermal energy is not without its challenges. High initial capital costs, coupled with long payback periods—often between five and fifteen years—can deter investment, particularly when compared with more immediately profitable renewable energy sources like wind and solar [12]. The UK government's current focus on wind and solar energy may overshadow investments and incentives for geothermal energy. Developers must navigate lengthy and complex planning and environmental permitting processes. For example, the UK's Environmental Permitting Regulations require extensive documentation, which can delay project timelines. Not to mention the fact that without government support, many projects would struggle to achieve financial viability, particularly during early stages.

Moreover, the geographical specificity of certain viable geothermal sites, largely confined to areas such as Cornwall, Weardale, and the Lake District, limits widespread adoption. Additionally, the UK's geological landscape, which is dominated by hard rock formations like granite and metamorphic rocks with low natural permeability, limits the availability of hot permeable rocks compared to volcanic regions such as Iceland. There are also technical and environmental risks, including induced seismicity, groundwater contamination, scaling, and corrosion of equipment, all of which necessitate careful regulatory oversight and advanced engineering solutions.

The challange of scaling and corrosion, as geothermal brines often contain high concentrations of dissolved minerals that can precipitate and form scale deposits, potentially blocking pipes and reducing plant efficiency. For district heating systems, heat loss during distribution over long distances can reduce overall efficiency. For petrothermal systems heat transfer through rocks is less efficient than direct access to hydrothermal reservoirs.

It requires specialised technical expertise as accurate drilling and engineering expertise are vital to prevent costly errors and ensure efficiency. As hydrothermal systems and shallow source geothermal energy sources require abundant water resources as large volumes of water are needed for injection and circulation, the contamination of groundwater sources and the subsidence risks of these areas have to be taken into account and sureveyed geologically.

## *Government policies*

Government policies play a crucial role in shaping the geothermal energy landscape in the UK [13]. While the country has established a general renewable energy framework—including mechanisms like Contracts for Difference and the Green Heat Network Fund—specific policies targeting geothermal energy remain under development. Contracts for Difference (CfD) is scheme providing price stability for renewable energy producers. It should be confirmed by government that geothermal energy is also applicable for this fund. Green Heat Network Fund (GHNF) has been established for the development of low-carbon heat networks, can be used for hydrothermal projects that supply heat to district heating systems. The absence of a dedicated regulatory framework creates uncertainty for investors and developers, even as international collaborations, such as the 2012 agreement with Iceland, foster knowledge exchange and innovation in geothermal technologies. The following are especially crucial in a well-organised regulatory framework:

- Groundwater Protection: Ensuring the safety and purity of surrounding aquifers.
- Worker and Resident Safety: Implementing strict safety protocols during construction and operation.
- Land Stability: Mitigating risks of subsidence due to drilling and other activities.
- Environmental Standards: Preventing contamination from residual chemicals or materials in abandoned mines.

## *Availability in the United Kingdom*

In the UK, several key projects underscore both the potential and the challenges of geothermal energy. The United Downs Deep Geothermal Project in Cornwall, for example, utilizes deep wells intersecting the Porthtowan Fault Zone at depths of 2.5 to 4.5 km to extract thermal energy for electricity generation. Cornwall has already demonstrated the feasibility of harnessing geothermal energy from granitic reservoirs, employing directional wells that tap into the Carnmenellis Granite and recording temperatures of up to 190°C [14].

Similarly, the longstanding Southampton District Energy Scheme extracts heat from the Triassic Sherwood Sandstone aquifer at a depth of about 1.8 km, providing district heating. These projects not only highlight the practical application of geothermal technology but also serve as important case studies in overcoming the financial and technical challenges inherent in geothermal development.

Approximately 25% of the UK population lives above abandoned coal mines, presenting significant potential for mine water geothermal energy [15]. Maps from the British Geological Survey highlight key regions where the resource is most viable, including the North East of England, Wales, and parts of Scotland. The widespread presence of flooded mines makes this resource a strategic asset for national energy planning [2] [14].

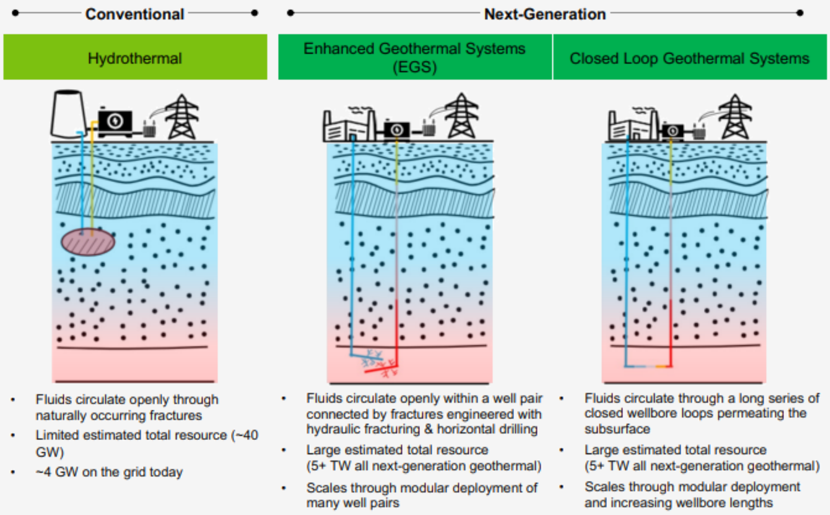


Figure 3: Geothermal technology overview across conventional (left) and next-generation (right) designs [22]

- **Gateshead Energy Company:** Located in the North East of England, this project integrates mine water heating into an existing district heating network. Feedback indicates high efficiency and customer satisfaction, with the scheme achieving significant cost savings compared to conventional heating methods [16].
- **Caerau, Bridgend:** A pioneering scheme in Wales utilizing mine water to heat homes. Supported by the Welsh Government, the project has been praised for its community impact and contribution to local decarbonisation goals. Initial feedback highlights its success in reducing heating costs for residents [17].
- **Bolsover District Council:** Based in Derbyshire, this initiative focuses on decarbonizing heat through mine water energy. Although in earlier stages, the project shows potential for replicability in other regions.

Hydrothermal resources thrive in regions where high subsurface heat combines with active water flow. In the UK, prime areas include Cornwall, Weardale in County Durham, and the Lake District—with Cornwall standing again out due to its granite formations that create strong geothermal gradients. Accelerating exploration in these promising areas requires robust support from both private and governmental funding.

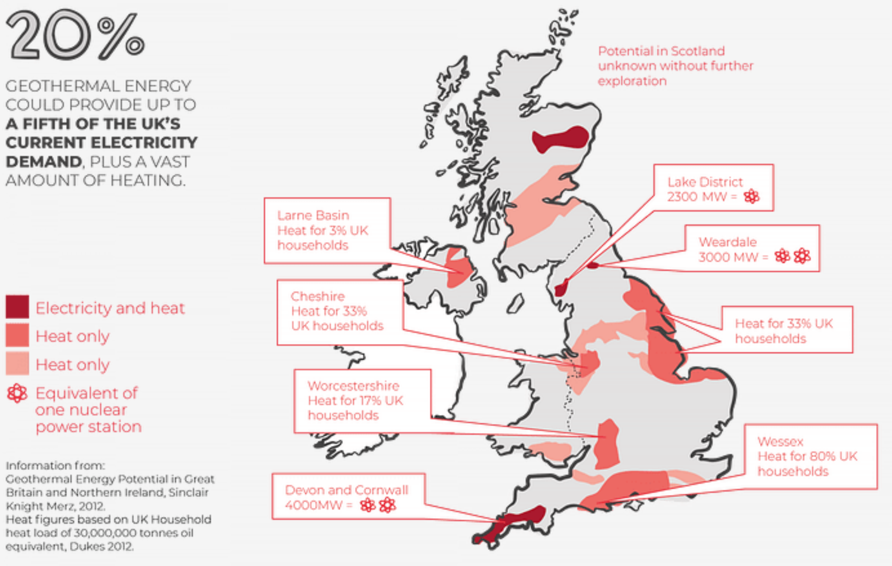


Figure 4: Map of potential places for geothermal energy in UK [1]

## *International examples*

Internationally, countries such as Iceland, Germany, Italy, and New Zealand have demonstrated the successful exploitation of geothermal energy for distric heating and cooling schemes, providing valuable insights and setting benchmarks for the UK [18]. Projections by the International Energy Agency suggest that geothermal electricity production could increase fivefold by 2040, significantly bolstering global decarbonization efforts and contributing to the targets set forth by the Paris Agreement.

The Mijnwater project in Heerlen, Netherlands utilizes abandoned mines for district heating and cooling. It serves over 200 buildings and incorporates an innovative energy exchange network that allows for seasonal energy storage. Positive feedback emphasizes its role as a model for similar projects globally [21].

A project is Lünen, Germany combines mine water heating with solar energy to optimize efficiency. It has demonstrated cost-effectiveness and sustainability, gaining international recognition for its innovative approach.

## *Prospects*

The water in flooded mines typically maintains a temperature between 10°C and 15°C, with deeper mines occasionally exceeding 20°C. While these temperatures are unsuitable for direct heating, heat pump systems can efficiently raise the temperature for domestic and industrial heating applications. This technology is ideal for district heating schemes, providing a sustainable alternative to traditional heating systems.

Mine water geothermal energy is primarily suited for heating rather than electricity generation due to the low temperatures involved. The energy is extracted using open-loop heat pump systems, which transfer heat from the water to a secondary medium for distribution [2]. This makes it a viable option for space heating, water heating, and cooling but not for electricity generation [2].

The future of mine water geothermal energy is promising, with several projects under development in the UK, including additional schemes in Gateshead and new initiatives in Nottinghamshire and Derbyshire [19]. Innovations in heat pump technology and drilling techniques are expected to reduce costs and improve efficiency. Enhanced policy support and funding could make smaller schemes viable, extending the technology's benefits to rural and less densely populated areas [14].

In industrial settings, geothermal energy offers medium-temperature heat (up to 200°C), which could be used in processes like food production, chemical plants, and greenhouses. This reduces the reliance on gas or oil heating, leading to increased sustainability in operations. Geothermal heat pumps also present an efficient solution for residential heating, providing not only warmth in colder months but also cooling during the summer. The technology can integrate seamlessly with underfloor heating systems or low-temperature radiators for improved efficiency. On the energy generation side, hydrothermal resources are capable of producing electricity using steam or hot water from subterranean reservoirs. Cornwall, with its favorable geology, is one of the prime potential sites for electricity generation [1]. Additionally, Combined Heat and Power (CHP) systems—systems that generate both heat and electricity from the same geothermal resource—offer the advantage of maximizing overall efficiency, making them a promising solution for energy needs across various sectors [8].

Enhanced Geothermal Systems present a promising opportunity to expand the UK's renewable energy portfolio by tapping into deep, hot rock formations that were previously inaccessible [11]. While challenges such as induced seismicity, scaling, high upfront costs, and geological limitations remain, ongoing technological advancements and targeted exploration in regions like Cornwall and parts of Scotland are paving the way for EGS to become a significant contributor to the UK's energy landscape [20]. With proper engineering practices, rigorous monitoring, and supportive policy frameworks, EGS could play a crucial role in achieving the nation's ambitious energy and carbon reduction targets [7].

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# Appendix F

## Appendix F1: Solar-powered Fuel

### *Mechanism Overview with Case Study: Synhelion*

Solar-powered fuel production leverages concentrated solar power (CSP) and thermochemistry to synthesize hydrocarbons. The process revolves around three main stages, each supported by experimental and industrial data:

Heliostat Field and Optical Concentration: Heliostat fields achieve flux densities >1,000 suns (1 MW/m²) with optical efficiencies of 60–70% after accounting for cosine losses, atmospheric attenuation (10–15% loss at 1 km air mass) [1], and mirror reflectivity (93–95% for silvered glass) [2]. Modern systems use stochastic optimization for canting, reducing spillage to <5% [3]. For scale, the SolarPACES guideline estimates 10,000 heliostats (10 m² each) for a 100 $MW_{th}$ plant [4].

High-Temperature Solar Receiver: Cavity receivers with Pyromark® coatings [5] achieve 50–60% thermal efficiency at 1,500°C [6]. Synhelion's spectrally selective quartz windows reduce re-radiation losses by 20% compared to standard designs [7]. Heat transfer fluids enable Brayton cycles with 45–50% exergy efficiency [8].

Fischer-Tropsch Synthesis: Fe/Co catalysts convert syngas ($H_2$:CO = 2:1) with chain-growth probability (α) of 0.9–0.95 for jet fuel [9]. Synhelion's Co-LTFT process operates at 220°C, yielding 0.7 kWh/L (LHV basis) [10], with methane selectivity <5% via zeolite promoters [11].

Synhelion has developed a high-efficiency solar receiver capable of reaching temperatures above 1500°C, enabling thermochemical reactions for solar fuel synthesis. Their solar tower in Jülich, Germany, built with the German Aerospace Center (DLR) and Aachen University, uses a 1,500 m² heliostat field delivering up to 600 kW solar input power [12]. Precision tracking is enhanced using AI-calibrated drones.

The system uses concentrated solar heat to drive the gasification of $CO_2$ and $H_2O$ into syngas (CO + $H_2$). This syngas is then processed via the Fischer-Tropsch (FT) synthesis to produce liquid hydrocarbons such as synthetic diesel, gasoline, or jet fuel. The process is entirely solar-driven, with captured $CO_2$ from industrial sources or direct air capture (DAC), making the fuel carbon-neutral. Synhelion uses redox materials identified via quantum-chemical simulations in collaboration with ExoMatter, exploring over 45,000 materials with 50 million CPU-hours of computation [13].

## *Advantages*

Solar-powered fuels offer several key benefits, making them a promising alternative to conventional fossil fuels. One major advantage is carbon neutrality, as the process utilizes $CO_2$ sourced from industrial emissions or direct air capture, potentially reducing net emissions by up to 100%. Additionally, these fuels are fully compatible with existing engines and fuel infrastructure, eliminating the need for costly modifications. Another significant benefit is their high energy density, which is 60 to 100 times greater than that of lithium-ion batteries, making them particularly suitable for long-haul shipping and aviation. The technology also demonstrates strong scalability, with the potential to meet up to 50 times the current global jet fuel demand if sufficient solar infrastructure is deployed. Furthermore, production costs are expected to decline over time, with short-term estimates at EUR 1–2 per liter and long-term projections as low as EUR 0.5–1 per liter by 2030.

## *Operational Considerations*

Several operational factors must be addressed to ensure the viability of solar-powered fuel production. One challenge is intermittency, as fuel synthesis relies on sunlight availability, necessitating thermal energy storage or hybrid systems to maintain continuous Fischer-Tropsch (FT) synthesis. Another consideration is land use, given that large mirror arrays—spanning 5 to 10 $km^2$ for a 1,000-barrel-per-day plant—require deployment in regions with high solar irradiance, such as deserts. Logistics also play a critical role, as transporting solar fuels from production sites to end-users (e.g., ports) involves pipelines or tankers, with costs comparable to those of conventional fuel distribution networks.

## *Technical Feasibility*

To assess technical feasibility, we estimate how much solar energy is needed to produce synthetic liquid fuel (e.g., diesel or kerosene) using solar thermochemistry [14]. Synhelion's process involves two main steps:

1. Solar-thermal gasification (splitting $CO_2$ and $H_2O$ into syngas using concentrated solar heat)
2. Fischer–Tropsch (FT) synthesis (converting syngas into hydrocarbons)

$$\text{A liter of diesel contains} \approx 9.5 \text{ kWh (LHV)}$$

**Step 1: FT Conversion Efficiency**

The FT synthesis step is not 100% efficient. Based on available data, assume:

- FT synthesis efficiency = 50% (i.e., syngas must supply 2× the output energy)

Therefore, to make 1 liter of fuel (9.5 kWh), the required syngas input is:

$$9.5 \text{ kWh}/0.5 = 19 \text{ kWh}$$

**Step 2: Solar-to-syngas efficiency**

Solar thermal gasification isn't perfect either. Use 50% efficiency as a working value:

- Solar energy required to produce 19 kWh of syngas:

$$19 \text{ kWh}/0.5 = 38 \text{ kWh}$$

**Final result:**

So to produce 1 liter of solar diesel, you need ≈38 kWh of concentrated solar energy

In a best-case scenario with higher efficiencies (60% for both steps):

$$9.5/(0.6 \times 0.6) = 26.4 \text{ kWh}$$

So solar input per liter is somewhere between 26–38 kWh.

**Land Area Estimation**

Suppose we want to produce 1,000 barrels per day (≈ 159,000 liters/day). Using a conservative energy input estimate:

$$159{,}000 \text{ L/day} \times 38 \text{ kWh/L} = 6.04 \text{ GWh/day}$$

Annually:

$$6.04 \text{ GWh/day} \times 365 \approx 2.2 \text{ TWh/year}$$

If we have solar flux of 2,000 kWh/m²/year, the required land area is:

$$2.2 \times 10^9 \text{ kWh} / 2000 \text{ kWh/m}^2\text{/year} = 1.1 \times 106 \text{ m}^2 = 1.1 \text{ km}^2$$

So Synhelion's claim of 0.5–1 km² per 100 barrels/day seems accurate.

## *Economic Feasibility*

**Capital Cost of the System**

Synhelion estimates a target price of €1/liter (≈ $1.10). To calculate if this makes sense:

- Assume most of the cost is upfront capital investment
- Suppose total CAPEX per daily barrel is $10,000

- 1,000 barrels/day = \$10M CAPEX
- Amortized for over 20 years, full operation (365 days), total production is:

$$1{,}000 \text{ bbl/day} \times 365 \times 20 = 7.3 \text{ million barrels} \approx 1.16 \text{ billion litres}$$

CAPEX per liter:

$$\$10{,}000{,}000 / (1.16 \times 10^{9} \text{ L}) \approx \$0.009/\text{L}$$

This is just capital. Now factor in:

- O&M, staff, consumables: ~\$0.20–0.30/L
- $CO_2$ feedstock and water processing: ~\$0.20/L
- Total cost target is therefore:

$$\$1.00\text{–}\$1.10/\text{L}$$

**Comparison to Fossil Fuel**

$$\text{Current diesel/kerosene cost} \approx \$0.30\text{–}\$0.40/\text{L}$$

So solar fuel is 2.5–3× more expensive without $CO_2$ pricing.

**Carbon Credit Incentive**

If a carbon tax is applied (\$100/tonne $CO_2$), we can credit solar fuel with avoided emissions.

- $CO_2$ avoided per liter ≈ 2.68 kg
- Monetary value of avoided $CO_2$:

$$2.68 \text{ kg} \times (100/1000) = \$0.27/\text{L}$$

New effective cost:

$$\$1.10 - 0.27 = \$0.83/\text{L}$$

Getting closer to parity with fossil fuels.

## *Conclusion*

Solar-powered fuels represent a drop-in solution for decarbonizing sectors with limited alternatives, such as aviation and maritime transport, where electrification is impractical due to energy density constraints [15]. These synthetic hydrocarbons are chemically identical to conventional fossil-derived fuels, ensuring full compatibility with existing engines, storage systems, and global distribution infrastructure without requiring modifications.

While current production costs remain higher than fossil fuels, ongoing advancements in heliostat field optimization, high-temperature thermal storage, and $CO_2$ capture efficiency are projected to narrow this gap. Under carbon pricing scenarios (e.g., ≥$100/ton $CO_2$), solar fuels could reach cost parity with conventional jet fuel and marine diesel by 2030 [16]. Strategic deployment in high-irradiance regions, coupled with policy support (e.g., mandates for sustainable aviation fuel [SAF] blends), would accelerate adoption.

The technology's scalability—potentially meeting 50 times global jet fuel demand—and net-zero emissions profile position it as a critical tool for achieving deep decarbonization in hard-to-abate sectors. By leveraging existing fuel logistics and combustion infrastructure, solar-powered fuels offer a pragmatic pathway to reduce fossil dependence while avoiding the systemic costs of entirely new energy systems.

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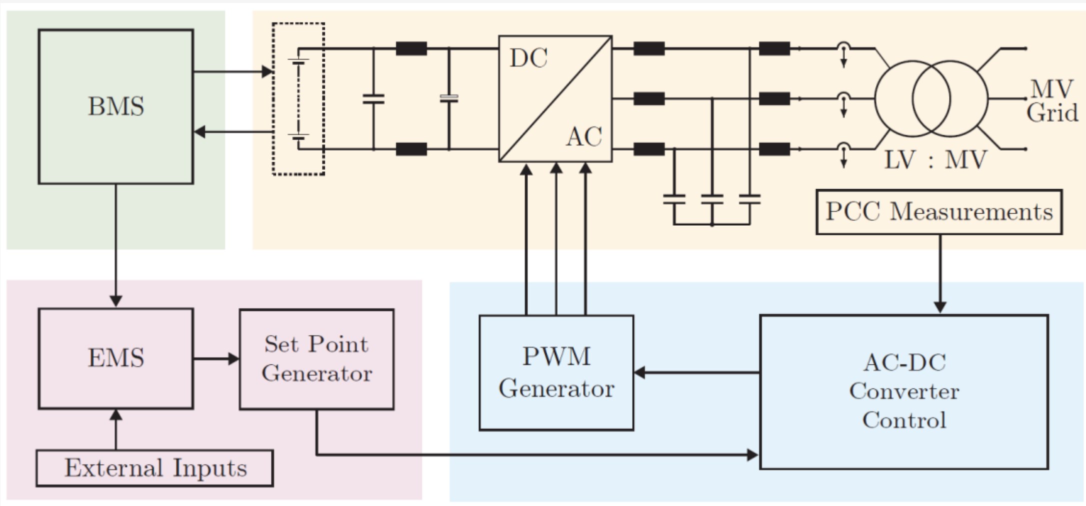
# Appendix F2: Battery Energy Storage Systems

## *Mechanism Overview with Case Study: Energy Observer*

Ships equipped with photovoltaic (PV) panels, battery energy storage systems (BESS), and hydrogen fuel cells utilize a sophisticated hybrid energy system to enable efficient and sustainable propulsion. PV panels capture solar energy and convert it into electricity, which can be used directly to power the ship's propulsion and onboard systems. Any surplus electricity is stored in batteries, ensuring a continuous power supply during periods of low solar energy availability, such as nighttime or cloudy conditions. Batteries act as a short-term storage solution, providing immediate energy when needed. Additionally, excess electricity can be directed toward electrolysis, a process that splits water into hydrogen ($H_2$) and oxygen ($O_2$), allowing the hydrogen to be stored in specialized tanks for later use. When required, hydrogen fuel cells convert stored hydrogen back into electricity through an electrochemical reaction, producing only water vapor as a byproduct. This multi-layered system ensures energy reliability, reduces dependency on fossil fuels, and contributes to zero-emission maritime transport. By integrating solar energy generation, battery storage, and hydrogen fuel cells, ships can optimize energy usage, reduce environmental impact, and enhance operational efficiency, making this a viable solution for sustainable shipping and off-grid energy applications.




A Battery Energy Storage System (BESS) stores and manages energy, typically using lithium-ion batteries due to their high energy density and efficiency [6]. These batteries work through the movement of lithium ions between the cathode and anode via an electrolyte. During charging, lithium ions move from the cathode to the anode; during discharging, they flow back to the cathode, releasing energy as electrons travel through an external circuit.

In systems integrated with hydrogen production, excess electricity powers an electrolyser that splits water into hydrogen and oxygen. The key reactions in electrolysis are [7]:

- **Cathode (reduction):** $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
- **Anode (oxidation, acidic):** $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
  In seawater, the presence of chloride can also lead to:
- **$2Cl^- \rightarrow Cl_2 + 2e^-$**

Hydrogen is stored under pressure and later used in a fuel cell to generate electricity when needed. The fuel cell reverses the process [8]:

- **Anode ($H_2$):** $H_2 \rightarrow 2H^+ + 2e^-$
- **Cathode ($O_2$):** $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Supporting components include a Battery Management System (BMS) to ensure safe battery operation, a Power Conversion System (PCS) for DC–AC conversion, and systems like HVAC, fire suppression, SCADA, and EMS for control, monitoring, and optimization. Together, these components enable flexible, safe, and efficient energy storage and use.

In the Energy Observer, 202 $m^2$ of PV panels with 22% efficiency provide up to 28 kW of peak solar power. This energy is stored in a 106 kWh battery and used for both direct propulsion and electrolysis. The electrolyser produces up to 8.2 kg of hydrogen daily, which is stored at 350 bar. A 100 kW PEM fuel cell converts hydrogen to electricity and heat. The vessel is also equipped with wind turbines and hydrokinetic recovery systems, enhancing off-grid autonomy. This layered system ensures resilience against solar intermittency and allows for continuous operation without fossil fuels.

## *Advantages*

The combination of PV, BESS, and hydrogen systems allows for flexible, emission-free operation. Batteries offer rapid-response storage and peak load coverage, while hydrogen enables long-term energy buffering. This enables vessels to operate with low noise and zero emissions, particularly beneficial in sensitive marine environments or protected areas. The modular nature of the system also allows for future scaling and hybrid integration with other renewable sources like wind or wave power.

## *Operational Considerations*

System complexity is a major factor. Integrating multiple energy systems—each with specific operating conditions, maintenance needs, and safety protocols—demands sophisticated control infrastructure (e.g., SCADA, EMS, BMS). Hydrogen requires careful handling, as its low volumetric energy density necessitates high-pressure or cryogenic storage. Solar intermittency and battery degradation impose reliability limits. Maintenance and crew training for high-voltage and hydrogen systems are also non-trivial.

## *Technical Feasibility*

Let's explore how much battery capacity is required to store meaningful energy for ship operations.

**Typical Energy Demand on a Vessel**

Let's start with an example vessel (e.g., Energy Observer-sized or similar small expedition vessel):

- Continuous propulsion requirement ≈ 50–100 kW for slow cruising
- Assume 80 kW average load, running 12 hours/day →

$$E_{daily} = 80\ kW \times 12\ hours = 960\ kWh/day$$

Let's round that up for hotel loads (navigation, HVAC, etc.):

$$E_{daily}\ total \approx 1{,}000\ kWh/day$$

**Battery Capacity**

Suppose we install a 1 MWh battery system (e.g., 1,000 kWh). This could power the ship for:

$$1{,}000\ kWh/80\ kW \approx 12.5\ hours$$

So this battery can provide half a day of propulsion at cruise speed, or a full day at reduced power.

**Battery Mass and Volume**

Li-ion energy density:

Gravimetric: ~150 Wh/kg
→ 1 MWh battery weighs:

$$1{,}000{,}000\ Wh/150\ Wh/kg \approx 6{,}700\ kg$$

Volumetric: ~250 Wh/L
→ Volume =

$$1{,}000{,}000\ Wh/250\ Wh/L = 4{,}000\ L = 4\ m^3$$

So for 1 MWh:

Mass = ~6.7 tonnes

Volume = ~4 $m^3$

This is manageable for smaller vessels. For large ships, you'd need 10–100× more**,** which becomes prohibitively heavy and voluminous for full propulsion over long distances.

**Charging Time and Power Requirements**

Suppose we want to fully charge a 1 MWh battery in 8 hours (overnight):

Required charging power:

$$1{,}000 \text{ kWh}/8 \text{ hours}=125 \text{ kW}$$

For fast charging in 2 hours:

$$1{,}000 \text{ kWh}/2=500 \text{ kW}$$

This requires heavy port infrastructure or dedicated onboard solar/wind, hydrogen backup (as in Energy Observer).

**Round-Trip Efficiency**

Battery round-trip efficiency (Li-ion): ~90%

So to get 1 MWh of usable energy from solar or shore power, you need:

$$1{,}000 \text{ kWh}/0.9\approx1{,}111 \text{ kWh input}$$

## *Economic Feasibility*

**Capital Cost of Batteries**

Battery prices (2024) [9]: ~$150–200/kWh (installed marine-grade system)

For a 1 MWh system:

$$1{,}000 \text{ kWh}\times\$200=\$200{,}000$$

**Lifetime and Cycle Count**

Li-ion batteries last ~3,000–5,000 full cycles.

Suppose we get 4,000 cycles out of the system:

- Total energy over life =

$$1{,}000\ \text{kWh} \times 4{,}000 = 4\ \text{GWh}$$

- Levelized cost of storage (LCOS):

$$\$200{,}000\ /\ 4{,}000{,}000\ \text{kWh} = \$0.05/\text{kWh}$$

**Comparison to Diesel [10]**

Diesel generator efficiency ≈ 0.25 L/kWh
Diesel cost: $1.00/L
So cost per kWh from diesel:

$0.25\ \text{L/kWh} \times \$1.00 = \$0.25/\text{kWh}$

Battery energy is 5× cheaper per kWh (ignoring generation cost), assuming you charge with low-cost solar or shore power.

**$CO_2$ Savings**

Diesel generator emissions ≈ 0.7 kg $CO_2$/kWh

1 MWh/day of battery use avoids:

$$1{,}000\ \text{kWh/day} \times 0.7 = 700\ \text{kg}\ CO_2/\text{day}$$

Annually (300 days):

$$700 \times 300 = 210\ \text{tonnes}\ CO_2/\text{year}$$

At a carbon price of $100/tonne, the avoided cost is:

$$210 \times \$100 = \$21{,}000/\text{year}$$

# Conclusion

Direct solar-hydrogen-battery propulsion systems, exemplified by the Energy Observer, demonstrate a technically feasible model for zero-emission maritime transport at small scales. However, their broader applicability is constrained by solar intermittency, limited power density, and the cost and complexity of hydrogen storage. While they are not yet viable for large-scale cargo shipping, such systems offer powerful demonstrators and testbeds for future decarbonization strategies. Continued advances in solar efficiency, electrolyser performance, and hydrogen infrastructure will be critical to moving from niche demonstration to mainstream application.

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# Appendix F3: Direct Solar Propulsion

## *Mechanism Overview with Case Study: PlanetSolar*

Direct solar propulsion uses photovoltaic (PV) panels to convert sunlight into electricity, which powers the ship's motors for propulsion. The core mechanism behind this is solar panels composed of semiconductor materials (such as silicon) that absorb sunlight. The energy from sunlight excites electrons within the material, creating an electrical current that is captured and stored in batteries. This electrical energy is then supplied to motors, which drive the ship's propulsion system.

Solar efficiency typically ranges from 15% to 25%, having increased significantly over the past decades, and the system's performance depends on factors like panel orientation, shading, and cloud cover. While this technology allows for fuel-free navigation, the need for large panel areas and reliance on consistent sunlight currently limits its use to smaller vessels or as a supplementary power source.

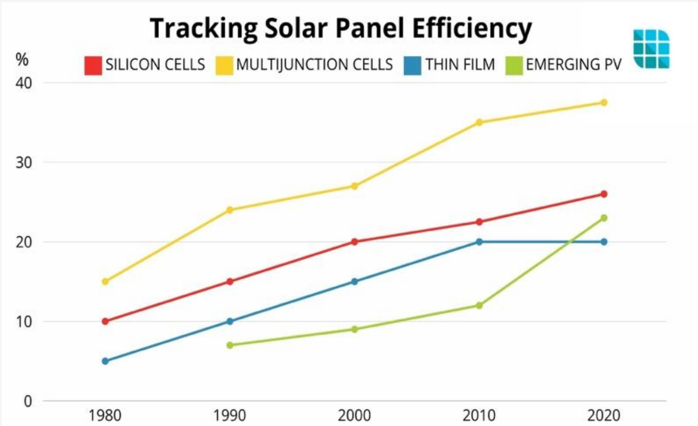

**Figure 1: How solar panel efficiency has changed over time [6]**

For instance, the PlanetSolar vessel, which is one of the largest solar-powered boats, operates on 537 m² of photovoltaic panels generating 93 kW of peak power. The vessel uses 8.5 tonnes of lithium-ion batteries with a total capacity of 1,140 kWh, enabling it to store energy for later use. It is propelled by two 20 kW permanent magnet motors, providing a total propulsion power of 40 kW. The vessel cruises at an average speed of 5 knots (9.3 km/h), with a maximum speed of 14 knots (26 km/h), and it operates fully on solar energy with no backup fuel systems. Under average operating conditions, the system provides about 480 kWh per day of energy, which is sufficient for the vessel's energy needs, with the batteries allowing for about 2.5 days of autonomy in low-sunlight conditions.

However, the scalability of this design for larger vessels is a significant challenge. For example, a standard 50,000-tonne cargo ship would require around 10 MW of propulsion power, necessitating an impractically large solar array of approximately 200,000 m². This highlights the limitations of relying solely on solar power for large-scale commercial maritime operations.

## *Advantages*

PlanetSolar demonstrated the potential for entirely fuel-free, emission-free maritime travel. It proved that with proper optimization of solar panel surface area and energy storage, solar energy could sustain small-scale long-distance voyages without fossil fuel reliance. Benefits included near-zero operational emissions, silent motor function, and reduced mechanical complexity due to the absence of combustion engines. As an early demonstrator, it also laid foundational insights for future development in solar-based marine engineering.

## *Operational Considerations*

While PlanetSolar demonstrated the feasibility of direct solar propulsion, several operational limitations restrict its broader application. Solar panels offer low power density, and even with high-efficiency modules, the energy output is insufficient for larger vessels—scaling up to meet the 10 MW demand of a cargo ship would require an impractically large surface area of over 200,000 $m^2$. Solar energy is also intermittent, varying with weather, time of day, and location, which necessitates large battery systems to ensure reliable operation. PlanetSolar's 1,140 kWh battery system added significant weight and volume, which would scale further for higher energy demands. The vessel's average cruising speed of 5 knots highlights another key limitation—solar propulsion alone cannot match the performance of conventional engines in terms of speed or range. Additionally, marine conditions degrade panel efficiency through salt exposure, biofouling, and mechanical wear, requiring frequent maintenance. The large surface area devoted to PV arrays also limits space for cargo or hybrid systems, and the absence of backup power reduces operational flexibility during prolonged low-insolation periods. These factors collectively constrain the viability of direct solar propulsion for anything beyond small-scale or demonstrator vessels.

## *Technical Feasibility*

Direct solar ship propulsion operates by converting sunlight into electricity through photovoltaic (PV) panels, which then power electric motors either directly or via battery storage. The technical feasibility of such systems depends heavily on available surface area for solar arrays, system efficiency, and propulsion power requirements.

**Solar Energy Availability at Sea:** At sea, average solar irradiance under optimal daylight conditions is approximately 200 W/$m^2$ [1], with real-world conditions leading to an average usable output of ~20% panel efficiency. Therefore, per square metre of solar panels:

$$\text{Power Output} = 200\ \text{W/m}^2 \times 20\% = 40\ \text{W/m}^2$$

**Required Power for Propulsion:** A typical small electric vessel may require around 20–40 kW to maintain a cruising speed of 5 knots [2]. Scaling this up:

To produce 40 kW with 20% efficient solar panels:

$$240\text{kW}/40\text{W/m}^2 = 1000\text{m}^2$$

For large ships, the requirement becomes more extreme. A typical 50,000-tonne cargo ship may need approximately 10 MW for continuous cruising at standard speeds [3]:

$$210\text{MW}/40\text{W/m}^2=250{,}000\text{m}^2$$

This is far beyond the deck area available on most ships (~5,000–10,000 m²), illustrating the limitations of direct solar propulsion as a primary means of powering large commercial vessels.

**Energy Storage:** Assuming 10 hours of solar energy production per day and 24-hour operation, storage is essential. For a ship requiring 40 kW for continuous propulsion:

$$14\text{hrs}\times40\text{kW}=560\text{kWh battery capacity needed}$$

Advanced lithium-ion batteries provide around 150 Wh/kg, so:

$$560\text{kWh}/0.15\text{kWh/kg}=3733\text{kg}\approx3.7\text{tonnes}$$

These figures reflect the moderate-scale feasibility for small or slow-moving vessels but show severe constraints for large, high-speed ships.

## *Economic Feasibility*

The economics of direct solar propulsion are shaped by the capital cost of PV systems, battery storage, and the absence of fuel costs over the vessel's operational life.

**Capital Costs:** Assuming $1.50/W for marine-grade solar PV (including installation) [4]:

$$40\text{kW}\times\$1.50/\text{W}=\$60{,}000$$

Battery storage costs average around $150/kWh for maritime applications [5]:

$$560\text{kWh}\times\$150/\text{kWh}=\$84{,}000$$

Total system cost (PV + storage) **≈** $144,000 for a small vessel.

**Operational Savings:** If a traditional ship burns heavy fuel oil (HFO) at 150 tonnes/day at $600/tonne, that's $90,000/day. If solar replaces even **1%** of total propulsion energy:

$$\$90{,}000\times0.01=\$900\text{ saved per day}$$

Payback period:

$$\$144{,}000/\$900\approx160\text{ days of operation}$$

For small vessels with lower fuel use, the payback may extend to several years, depending on use patterns and fuel prices.

## Conclusion

Direct solar propulsion offers a promising but currently limited pathway to low-emission marine transport. While technologies such as photovoltaic systems and solar sails show potential—particularly for small, low-speed vessels—current limitations in solar power density, energy storage, and scalability make them impractical for large-scale commercial use. The PlanetSolar case study underscores both the technical feasibility and the economic challenges of full solar propulsion. However, continued improvements in photovoltaic efficiency, battery technology, and hybrid integration could gradually unlock broader applications in sustainable shipping.

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# Appendix F4: Supplementary Solar PV System

## *Mechanism Overview with Case Study Auriga Leader*

Supplementary solar photovoltaic (PV) systems on ships operate by converting incident solar radiation into electrical energy, which is then integrated into the ship's power grid to support non-propulsion (auxiliary) loads or reduce the demand on diesel generators. This system relies on the photovoltaic effect, wherein semiconducting materials—commonly crystalline silicon—absorb photons, resulting in the excitation of electrons and the creation of electron-hole pairs. These charge carriers are separated by a built-in electric field within the solar cell, generating direct current (DC) electricity.

In the case of the *Auriga Leader*, developed by NYK Line and Mitsubishi Heavy Industries, approximately 328 solar panels were installed with a total peak capacity of 40 kW [1]. These panels are integrated into a hybrid power system that includes both solar energy and traditional diesel-electric propulsion [1]. The solar energy generated is routed through maximum power point tracking (MPPT) controllers, which optimise the panel output under varying irradiance and temperature conditions [2]. The regulated DC power is then converted to alternating current (AC) using inverters, allowing synchronisation with the ship's internal electrical network.

To manage intermittency—caused by cloud cover, shading, and diurnal cycles—the system employs nickel-hydrogen (NiMH) Gigacell batteries. These serve as an energy buffer, stabilising voltage levels and ensuring continuous power delivery to essential auxiliary systems, such as lighting, communication equipment, ventilation, and navigation systems. Unlike propulsion systems, these loads are lower in power demand and are well-suited for intermittent, supplementary energy sources like solar.

In terms of control architecture, the hybrid system on *Auriga Leader* includes an energy management system (EMS)that dynamically allocates power between solar PV, stored battery energy, and diesel generators based on load requirements and solar input [2]. Real-time monitoring allows for efficient peak shaving—reducing the load on diesel generators during times of high solar generation—and load levelling, which ensures smoother power profiles and improved generator efficiency.

Despite the relatively small contribution (around 0.3% of total ship energy demand in *Auriga Leader*'s case), the integration of solar PV serves two critical functions: (1) it reduces fuel consumption and greenhouse gas emissions, and (2) it acts as a proof-of-concept for scaling renewable systems in maritime applications [1]. The project also highlighted technical limitations such as panel degradation from salt corrosion, mechanical vibrations, and variable power output due to the ship's orientation and weather patterns [3].

## *Advantages*

Integrating solar panels into maritime vessels offers several notable benefits [4]. Primarily, solar panels provide a renewable energy source that can supplement traditional diesel generators, thereby reducing fuel consumption and associated greenhouse gas emissions. This not only contributes to environmental sustainability but also leads to potential cost savings over time. Solar panels can generate electricity both at sea and while docked, provided there is sufficient sunlight, thus offering flexibility in energy production. Additionally, the decreasing cost of solar modules—currently estimated at approximately $0.60 per watt—makes this technology increasingly accessible for maritime applications [5]. While the overall system installation costs range from $2.80 to $3.40 per watt, these expenses are expected to decline as technology advances and adoption becomes more widespread [5].

## ***Operational Considerations***

The effective implementation of solar PV systems on ships depends on multiple operational factors. Adequate deck space is essential but often limited on cargo-prioritised vessels. In marine environments, harsher conditions such as saltwater exposure, humidity, and shading reduce solar panel efficiency, which typically ranges from 10% to 30% [2]. Actual energy output is further affected by suboptimal panel angles, temperature fluctuations, and cloud cover. To ensure reliable performance, robust marine-grade panels and mounting structures—usually 20–30% more expensive than standard systems—are required. Additionally, integration demands inverters and energy management systems to balance real-time load and coordinate between solar and main power sources [2]. These hybrid systems require careful sizing based on operational profiles and auxiliary demand patterns. Economically, high initial costs—including approximately $1.50/W for marine-grade panels plus ~30% installation premiums—must be weighed against long-term savings from reduced diesel use and minimal maintenance [2]. As solar power contributes intermittently, it remains a supplementary source rather than a standalone solution.

## *Technical Feasibility*

In terms of technical feasibility, the solar potential of marine vessels depends largely on the available surface area [6]. Large cargo ships often have approximately 5,000 to 10,000 square meters of deck space. However, not all of this area can be used effectively for PV installation due to shading, structural constraints, and potential conflicts with cargo operations. In marine environments, the average solar irradiance is approximately 200 W/m²—lower than the roughly 250 W/m² typical on land—due to greater cloud cover and atmospheric variability [1].

Assuming the deployment of 10,000 m² of solar panels operating at 15% efficiency under 200 W/m² irradiance, the peak power output would be [6]:

$$10{,}000\ \mathrm{m}^2 \times 200\ \mathrm{W/m}^2 \times 0.15 = 300{,}000\ \mathrm{W} = 300\ \mathrm{kW}$$

If these panels operate at peak for an average of four hours per day over the course of a year, the annual energy yield is calculated as:

$$300\text{ kW}\times 4\text{ hours/day}\times 365\text{ days}=438{,}000\text{ kWh/year}=438\text{ MWh}$$

Despite this potential, marine PV systems face challenges that are not present in land-based systems. Solar panels exposed to saltwater, high humidity, and variable motion experience accelerated wear and degradation. According to NREL, marine-grade systems cost approximately 20–30% more than conventional panels due to the need for corrosion-resistant materials and protective coatings. Furthermore, the available deck area often competes with space reserved for cargo, and frequent maintenance is necessary to address fouling from salt deposits and weathering [2].

### *Economic Feasibility*

From a financial standpoint, the cost of installing a marine solar PV system is substantial but potentially offset by fuel savings. Assuming a marine-grade system cost of $1.50 per watt, a 300 kW installation would result in a base cost of:

$$300{,}000\text{ W}\times \$1.50/\text{W}=\$450{,}000$$

Adding a typical 30% premium for marine installation and system integration brings the total capital expenditure to:

$$\$450{,}000\times 1.3=\$585{,}000$$

Fuel savings depend on the vessel's fuel consumption and the extent to which solar energy offsets auxiliary loads [4]. Large cargo ships typically burn around 150 tonnes of heavy fuel oil (HFO) daily, with a market cost of approximately $600 per tonne [4]. This results in a daily fuel expense of:

$$150\text{ tonnes}\times \$600/\text{tonne}=\$90{,}000$$

If solar PV provides 5% of the vessel's auxiliary load, this would equate to daily savings of:

$$\$90{,}000\times 0.05=\$4{,}500$$

Assuming the ship operates 200 days per year, the annual fuel savings would be approximately $900,000. Therefore, the payback period for the investment can be estimated as:

$$\$585{,}000/\$900{,}000\approx 0.65\text{ years}$$

However, this is an optimistic projection. In practice, because auxiliary loads are often lower and PV performance is less consistent, a more conservative assumption might reduce annual savings to 20% of the above, resulting in a payback period of around 6.5 years.

The environmental benefit is also significant. Based on an average emissions factor of 0.7 kg $CO_2$ per kWh generated by shipboard generators, the displacement of 438 MWh of diesel-generated electricity results in an annual carbon dioxide savings of approximately [4]:

$$438{,}000\ \text{kWh} \times 0.7\ \text{kg}\ CO_2/\text{kWh} = 306.6\ \text{tonnes}\ CO_2$$

## Conclusion

In conclusion, supplementary solar PV systems offer probably the most realistic method of solar PV that can be integrated into existing shipping systems . While limitations exist in terms of available space, corrosive environments, and variable solar exposure, careful system design can help overcome many of these barriers. The economic analysis suggests that although initial investment costs are high, long-term savings and environmental benefits can justify the implementation of such systems, particularly for auxiliary loads. As solar panel and energy storage technologies continue to improve and decline in cost, supplementary PV systems are expected to play a greater role in the transition toward sustainable maritime operations.

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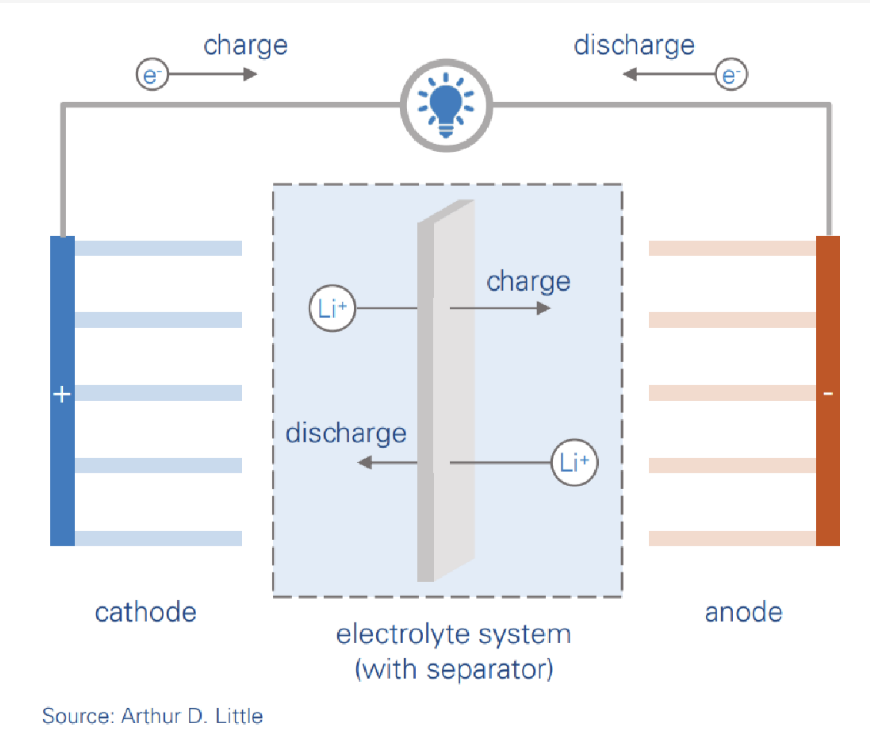
# ENERGY STORAGE

# Appendix G

## Appendix G1: Li-ion batteries

Li-ion batteries are made of four key components and work in two discrete phases: discharge and charge.

1. Discharge is the process by which the battery powers a device; $Li^+$ ions flow from the anode to cathode through the electrolyte, whilst electrons flow in the same direction via the external circuit, charging an external device in the process.
2. Charging is the process by which the battery gets recharged. It is the reverse of discharge in that the $Li^+$ ions move from the cathode back to the anode (via the electrolyte), with the electrons following suit via the external circuit




First commercialised in 1991 [25], Li-ion batteries have been constantly upgraded and improved over the last thirty years resulting in the creation of several novel battery designs. Each of these models vary in terms of the composition of their anode and cathode [26]. Current Li-ion batteries are classified by their cathode chemistry. Two examples of these are Lithium Ferro-Phosphate (LFP) batteries and Nickel Manganese Cobalt (NMC) batteries.

LFP batteries are a type of Li-ion battery known for their high power density, stability and long cycle lifetime. They have a cathode made of Lithium Iron Phosphate ($LiFePO_4$) whose rigid olivine structure gives LFP batteries their characteristic high power and long lifetime [26]. Despite this LFPs have low energy density due to LFP's intrinsic properties of having low voltage and energy capacity. This results in LFP's actually being one of the more expensive cell types when measured on a cost/kWh basis [26].

NMC batteries are another type of Li-ion battery known for their high energy density. Their cathode material is a Lithium Mixed Metal Oxide, made of varying compositions of Nickel (Ni), Manganese (Mn), and Cobalt (Co) in the general formula $LiNi_xMn_yCo_{1-x-y}O_2$. The stoichiometric balance between Ni, Mn and Co can be varied to produce different variants of NMC batteries, each with different properties. Commonly used NMC Cathode compositions include:

- NMC 111: made of equal parts Ni, Mn and Co, wherein each component makes up 33.3% [27] of the cathode
- NMC 622: made of 60% Ni, 20% Mn, and 20% Co [27]
- NMC 811: made of 80% Ni, 10% Mn, and 10% Co [27]

Each of the components found in NMC cathodes serve a specific purpose:

- Ni content provides high energy density and capacity. However it also lowers thermal stability and cyclability [28].
- Mn is electrochemically inactive and helps enhance structural and thermal stability [28].
- Co helps stabilise the cathode structure, whilst also enhancing conductivity and preventing structural degradation.

Varying the respective amounts of these elements in the cathode therefore affects the performance and properties of the cathode. This means the composition of a given NMC battery can be varied so that its performance is tailored to the specific application the battery is required for. For example, NMC 111 batteries have equal parts Ni, Mn and Co, and therefore showcase balanced performance, with good stability and moderate energy density. As you increase the Nickel content, the energy density increases as the cell is able to reach higher capacities at the same voltage [29]. The NMC 111 battery type is used in portable electronics, whilst more Ni-rich battery types like NMC 622 and NMC 811 are widely used in electric vehicles (EVs). A table comparing LFP with various NMC types is shown below.

| Material Formula | Abbreviation | Cost | Energy Density | Thermal Stability | Cycle life |
|---|---|---|---|---|---|
| $LiFePO_4$ | LFP | Low | Low | Good | Good |

| | | | | | |
|---|---|---|---|---|---|
| $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ | NMC 622 | High | High | Moderate | Good |
| $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ | NMC 811 | High | High | Poor | Moderate |

Source: Faraday Institution

## Appendix G2: LFP Waste Management

After the capacity of an LFP falls to 80% of its nominal value, it would be considered to be retired from EVs for the first use stage [1]. Due to the limited amount of lithium and the high demand of LFP for its use in EVs and renewable energy storage systems, it's increasingly important to develop low-carbon and cost-effective methods to deal with used LFPs. One useful way is using cascade utilization. Cascade utilization involves the transfer of retired batteries from EVs, to other uses with lower performance needs, allowing the continuous use of the batteries without simply throwing them away [2].

The route of cascade utilization is shown below.

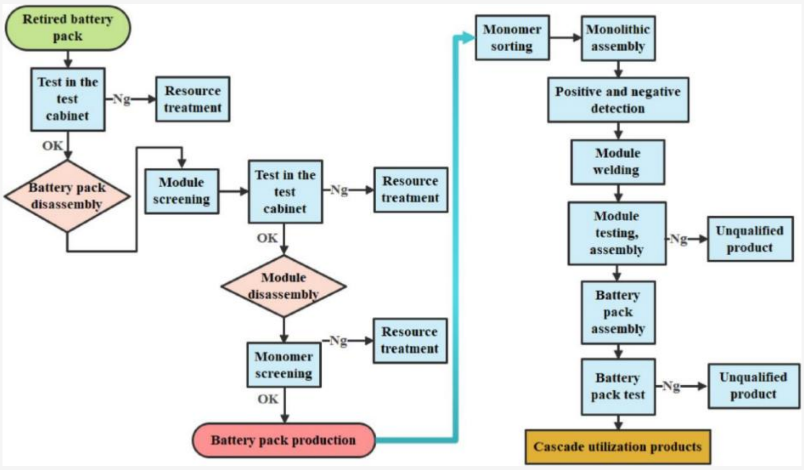



Fig.1 Flow chart of dismantling, sorting, and integrated assembly of LFP batteries into cascade utilization products [3]

This method has several benefits, such as prolonging the lifespan of LFP batteries, lowering EV costs, mitigating environmental pollution from battery disposal and simultaneously meeting the power battery needs of clean energy applications [4][5]. However, Mengmeng Wang et al. pointed out the necessity of a life prediction system [3] to solve some potential technical challenges. This includes the issue of the battery's regeneration capacity having a severe impact on degradation modelling and thus the prediction of their remaining lifespan [6][7].

There are distinctive early-stage prediction models in the battery health management field[9] that can be applied, including mechanism-guided model, experience-based model, data-driven model and fusion-combined model [8]. According to the comparative analysis of these models done by MinXing Yang et al, people should make reasonable choices based on the actual requirements [8]. Overall, the combination of individual models with appropriate interactions, such as the integration of mechanism-guided and data-driven techniques, are more accurate and stable than other types [8]. Moreover, to address the challenges of high computational resource demands in these life prediction models, Bo Zhao et al proposed a novel optimized approach. The structure of the new-introduced model has been shown below.

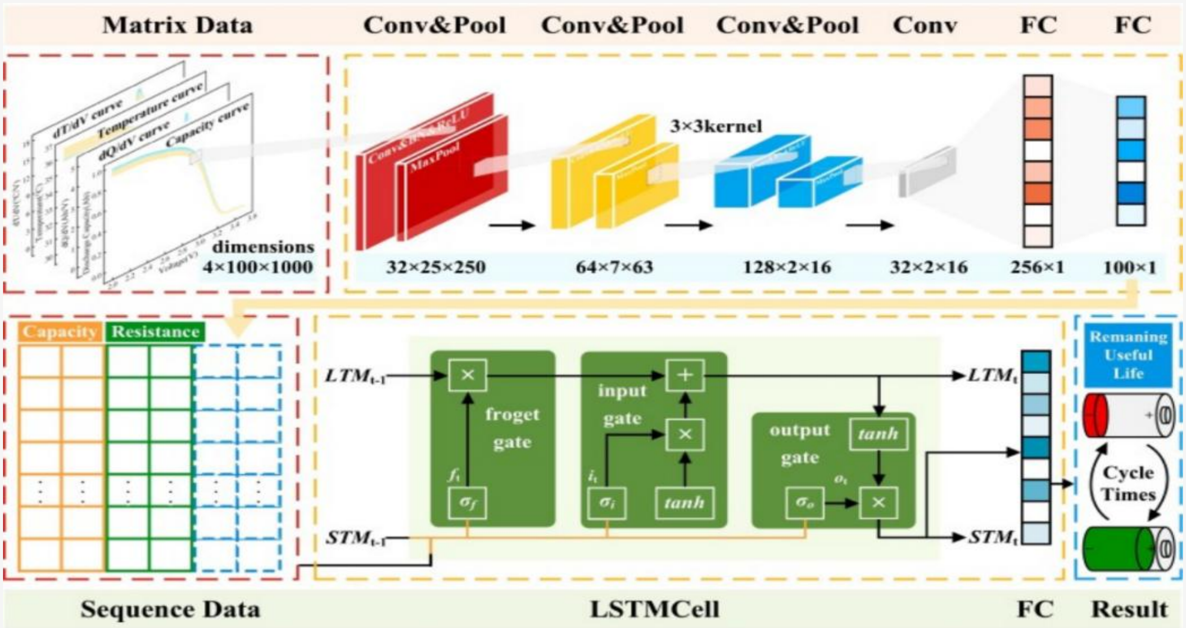



Fig.2 The overall framework of the proposed prediction model fused with CNN and LSTM.[9]

This model integrated convolutional neural network (CNN) and long short-term memory (LSTM) based on the deep learning framework. Meanwhile, it is pruned to discard redundant neuron parameters which cause computation resource waste and risk of overfitting parameters entirely. Overall, the optimized approach achieves end-to-end optimization from data sources to models, reducing computational load, enhancing processing speed and responsiveness, and ensuring stable model performance with accurate results even in resource-limited environments.[9]

## Appendix G3: ROI Analysis

Now we will carry out a generic return-on investment (ROI) analysis of an example of an LFP commonly used in industry, AMPOWR's BESS (Better Energy Storage Systems) LFP [20] to understand how much revenue a typical LFP battery brings in relation to its cost. This battery has a specification of 1 MWh capacity and 0.5C. For this analysis, we will assume that it is used for EV charging and charged with lowest-priced electricity at low demand (around 6.7p per kWh) and charging price is around 80p/kWh. We will assume it is fully charged and discharged once each day. Using the Energy Storage Technology and Cost Characterization Report [14], we can calculate the initial fixed cost and variable cost and determine the ROI of the first ten years.

| | Specific cost (£/kWh) | Total (£) |
|---|---|---|
| Initial installation cost | 530 | 530,000 |
| Fixed annual O&M cost by capacity | 10 | 10,000 per annum |
| Variable O&M cost | 0.1 | 0.1 * 1000 * 365<br>= 36,500 per annum |
| Round trip efficiency | 0.75 | / |
| Cost of power | 0.067 | 0.067 *1000 * 365<br>= 23,700 per annum |
| Price sold | 0.8 | 0.8 *1000 *365 *0.75<br>= 219,000 per annum |

**ROI (1$^{st}$ ten years) = Net Benefits/Total cost = (219,000*10 – 530,000)/530,000 = 313%**

[O&M - operation and maintenance]

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# Appendix H

## Appendix H1: Technical summary of SHS, LHS, and TCES

Sensible Heat Storage

The most common TES method in terms of development and commercial adoption globally

[2],[3]. Energy is stored by raising a material's temperature without changing its state. When the energy is needed, it is outputted by cooling the material [3],[7]. This makes SHS a low- tech, high-impact energy storage solution. Water-based Tank Thermal Energy Storage (TTES) is the most mature SHS in the British market (TRL 9) with examples seen in Bunhill 2 Energy Centre [29], Viking Energy Network [30] and Leeds PIPES [31]. However, these largely address district heating demands. Molten salt batteries address industrial demands in steel and chemical plants but have limited traction (TRL 6) due to its high cost, safety and environmental concerns of using nitrate salts [33],[34]. Sand batteries are currently at a similar level (TRL 6) but have greater potential for growth as demonstrated by Finland's Polar Night Energy [4],[6],[22].

Latent Heat Storage

A very dynamic TES method that utilizes PCMs with wide usage in small and medium scales (TRL7-9) but has low potential for grid-scale energy storage (TRL 4-5) [2], [5]. This is because it stores energy by freezing a material and then melting it when the energy is needed [2], [5]. The melting process is slow and gradual which is not ideal for fast grid load management but useful for long-term TES [5]. However, LHS has much higher energy density compared to SHS thus is better for compact applications [5]. In Britain, it's largely been deployed for HVAC applications in various hospitals, factories and offices around the UK [43] as well as developing novel plasterboard to increase energy efficiency in Nottingham "eco-homes" [42].

Thermochemical Energy Storage

A novel TES solution that is still in early development (TRL 3-5) in universities and projects such as AMADEUS [36], [37]. It has high potential as it exploits reversible chemical reactions to store heat indefinitely with near-zero energy loss, ultra-high energy density (2-10x more than LHS) with a wide temperature range [2], [5], [35], [36]. However, it is unlikely to be deployed within the next 5-10 years due to its high technical complexity that requires precise material and reaction control rendering it costly and unready for testing in pilot plants (TRL 6+).

# Appendix H2: UK Market Analysis

**Market Analysis & Operational Context**

The United Kingdom's commitment to achieving net-zero emissions necessitates the decarbonisation of heat demand, which currently accounts for approximately 15% of total emissions [11]. This imperative has spurred substantial demand for low-carbon heating technologies, notably sand batteries, which present strategic opportunities within district heating and communal systems. These systems are identified as priority segments for the technology, allowing heat networks to utilise large thermal stores to balance supply and demand effectively. Sand batteries enable operators to charge thermal stores using surplus electricity from overnight wind power and discharge heat during peak demand periods, thereby reducing reliance on traditional gas or electric boilers. The UK government anticipates that heat networks will account for approximately 18–20% of domestic heating by 2050, up from the current 2%[12]. New projects in cities such as Enfield, Newham, Bristol, and Manchester are integrating thermal storage solutions, establishing sand batteries as advanced alternatives to conventional hot water tanks.

The operational capabilities of sand batteries are characterised by low capital and operational costs per energy unit. Key expenditures involve constructing insulated silos and heating systems using abundant materials such as sand, steel, and insulation. Polar Night Energy estimates installation costs to be below €10 per kWh of heat storage capacity, which is significantly lower than that of lithium-ion batteries. Sand batteries harness electricity during low pricing periods or when surplus renewable energy is available, converting nearly all energy into heat with minimal conversion losses. The system's round-trip efficiency from electricity to heat is estimated between 85-99%, and it requires minimal maintenance due to its autonomous operation[13].

The cost of heat produced by a sand battery depends on the input electricity price and capital recovery rate. In the UK, instances of low-cost electricity are increasingly common, particularly during off-peak periods associated with wind energy generation. This allows sand batteries to capitalise on charging opportunities, aligning effective heat costs with competitive ranges. The business model leverages multiple revenue streams, primarily deriving income from the sale of heat through contracts with residential blocks, commercial clients, or heat network customers.

A distinctive feature of sand batteries is their ability to operate as flexible electrical loads, generating additional revenue from grid service markets. Operators can engage in frequency response or balancing services by adjusting charging loads without compromising heat supply. Furthermore, large sand batteries can participate indirectly in the Capacity Market by reducing grid demand during peak times.

Integration with renewable energy developers or wind and solar farms enhances the value of sand batteries by storing excess output that would otherwise be curtailed. The stored energy can be monetised strategically, allowing the battery to store energy at lower prices and utilise it later to displace gas heating, which commands higher market prices.

While comprehensive UK-specific cost data for sand batteries is limited, insights from international projects indicate favourable economic prospects. For example, a Finnish 8 MWh unit provides heating for several hundred homes at a construction cost of around $200,000 [14]. A larger 100 MWh unit under construction suggests economies of scale, with potential revenue from heat sales estimated at £40-£60 per MWh, presenting a robust investment opportunity [14].

## Regulatory & Policy Framework

The UK's policy and regulatory framework increasingly favours the adoption of thermal storage solutions and low-carbon heating technologies, although challenges persist. The legally binding commitment to achieving net-zero emissions by 2050 underpins a suite of policies promoting low-carbon heating alternatives. The Heat and Buildings Strategy, alongside the Ten Point Plan for a Green Industrial Revolution, prioritises the elimination of fossil fuel heating sources and the expansion of heat networks. Notably, from 2025, new homes in England will be prohibited from installing gas boilers, with a proposed phase-out of new gas boiler sales by approximately 2035. This policy landscape mandates alternative heating solutions, including electrification and thermal storage.

The UK government has established various incentives to encourage low-carbon heating technologies, although specific incentives for sand batteries are not yet in place. The Boiler Upgrade Scheme (BUS) provides grants for heat pump installations, indirectly promoting thermal storage adoption as a complementary system. Funding schemes for heat networks, including the now-concluded Heat Networks Investment Project (HNIP) and the successor Green Heat Network Fund (GHNF), offer capital support for developing district heating systems that incorporate low-carbon sources and storage solutions. For example, in 2022, the GHNF awarded approximately £15 million to the Enfield Council/Energetik project, facilitating waste heat delivery to 15,000 homes through a new network that integrates large thermal storage [15].

The UK is updating regulations to facilitate new heating infrastructures, with the regulation of heat networks under the Energy Act 2023 empowering Ofgem to oversee operators, ensuring consumer protection and equitable pricing. This regulatory shift is anticipated to enhance public confidence in district heating systems, vital for market adoption, while mitigating investment risks associated with heat networks and their storage assets. The government estimates that heat networks could supply between 18% and 20% of national heating requirements by 2050. Additionally, the forthcoming Heat Network Zoning policy will designate areas for mandatory or encouraged connections to heat networks, further propelling sand battery deployment as developers seek to optimise efficiency and renewable integration.

Recognition of energy storage within the electricity market is improving, with grid-scale electricity storage classified as a distinct asset class, alleviating concerns such as double network charges. Sand batteries, while not traditional electricity storage solutions, can absorb electrical energy on a large scale, functioning as controllable loads in flexibility markets. The National Grid's balancing mechanisms are technology-agnostic, allowing sand battery operators to engage in demand response programmes, generating revenue by adjusting loads in response to surplus generation or reduced power availability.

**UK Examples and Context for Sand Battery Technology**

Despite the nascent stage of sand battery technology, several UK initiatives exemplify its potential deployment. **The University of Nottingham's pilot project**, launched in 2021, utilises a thermochemical storage system connected to a district heating network, underscoring the UK's commitment to advanced heat storage solutions [16]. The project aims to replace gas boilers and leverage waste heat, signalling support for various thermal storage technologies. Similarly, **Caldera's Warmstone trials in Hampshire** demonstrate the viability of sensible heat storage at a domestic level, replacing oil boilers with a 100 kWh heat battery that operates on low-cost electricity[11]. **Sunamp, a Scottish company,** has successfully installed thousands of compact heat batteries in homes, indicating market acceptance of thermal storage solutions[18]. Furthermore, ongoing heat network projects, such as the **Gateshead District Energy Scheme and Meridian Water development**, exemplify the integration of thermal storage in existing systems, offering a pathway for future sand battery applications. Government-funded programs also support thermal storage research, creating a conducive environment for innovations like sand batteries, which could benefit from financial backing aligned with net-zero objectives.

Sand batteries (based on sensible heat storage) use cheap renewable electricity to heat a medium like sand, storing as high-temperature heat for later use. In the United Kingdom model, the concept is explored to decarbonized heating by charging thermal stores with surplus wind or solar power and discharging heat to buildings or industry when needed.

# Appendix H3: Market Analysis of Various Countries

United States

The United States presents substantial opportunities for the implementation of sand batteries, particularly in industrial heat applications and long-duration electricity storage. The technical feasibility is bolstered by an extensive grid, a robust industrial foundation, and the potential repurposing of retired coal plant infrastructures. Federal initiatives, notably under the Inflation Reduction Act and Department of Energy programmes, offer financial incentives that align with carbon reduction objectives, paralleling the benefits of sensible heat storage (SHS). Market demand is predominantly driven by industrial sectors necessitating process heat and grid operators in search of flexible storage solutions. Financial viability is contingent upon the successful replacement of fossil fuel-derived heat with stored renewable energy, utilising cost-effective off-peak electricity [17]. Prominent business models include B2B industrial service contracts, utility-scale retrofitting, and energy-as-a-service frameworks. However, challenges such as limited public awareness, the availability of inexpensive natural gas, and fragmented regulatory landscapes persist. Nevertheless, opportunities exist to leverage SHS for emissions reduction, grid stabilisation, and the reutilisation of coal plant assets [17].

Europe (Excluding UK)

Europe is at the forefront of SHS technology adoption, characterised by widespread district heating, elevated carbon prices, and robust policy support. The technical feasibility is commendable, with successful implementations noted in countries such as Finland. Market demand primarily emanates from district heating operators and initiatives aimed at industrial decarbonisation [10]. Support mechanisms such as the EU Green Deal, Horizon Europe, and emissions trading schemes facilitate deployment. Financially, SHS demonstrates competitive heating costs, particularly when supplanting fossil fuel systems and capitalising on inexpensive surplus renewable energy [18]. Typical business models encompass municipal or utility-owned storage solutions, B2B industrial integrations, and public-private partnerships. Challenges include urban land constraints and regulatory fragmentation, though enablers such as energy security priorities, heightened public awareness, and well-established heat networks are notable [18].

India

In India, the potential for SHS is significant, particularly within industrial settings and off-grid applications. Technical feasibility remains favourable, especially with the utilisation of locally sourced desert sand for high-temperature storage. While district heating systems are absent, SHS can effectively support industrial process heat, rural microgrids, and off-grid agricultural initiatives . Market demand is primarily driven by manufacturing sectors and rural applications, such as crop drying. Existing policies, including the National Solar Mission and Perform, Achieve and Trade (PAT) scheme, indirectly support SHS integration. Financial viability is linked to replacing costly diesel or liquefied petroleum gas (LPG) with renewable energy sources or off-peak power [18]. Business models are emerging, including energy service company (ESCO)-driven industrial deployments, public-private rural initiatives, and utility- scale solar plus SHS hybrids. Challenges such as affordability, low urban heat demand, and policy deficiencies must be addressed, while renewable energy expansion, pollution control objectives, and industrial efficiency targets serve as significant enablers [19].

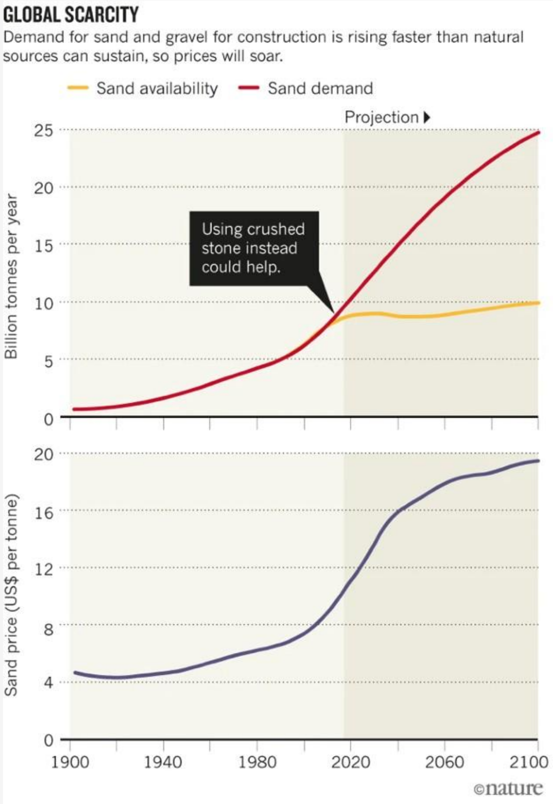
China

China stands out as a leading candidate for large-scale SHS deployment. The technical feasibility is notably high, supported by extensive district heating systems, a vast industrial sector, and stringent clean energy mandates. Market demand spans urban heating, grid integration, industrial heat needs, and rural clean heating applications. Policy support is robust, encompassing clean heating mandates, carbon neutrality objectives, and local subsidies. Financial viability is enhanced by low-cost materials, the curtailment of renewable energy on the grid, and escalating carbon costs. Business structures favour state-owned enterprises, public-private partnerships, and utility-driven initiatives [20]. Challenges related to integration into larger systems, competing technologies such as batteries and heat pumps, and regulatory complexities exist. However, China’s central planning, expansive infrastructure, and urgent decarbonisation priorities serve as substantial enablers for SHS technology advancement.

## Appendix H4: Sand Sourcing and Raw Material Availability

In the natural world, sand is primarily composed of silicon dioxide, typically in the form of quartz, along with carbonate materials such as volcanic elements and clay. Due to its silicon dioxide content, sand exhibits high resistance to both mechanical and chemical disturbances, making it an ideal material for construction purposes and one of the most exploited resources of the planet. [8]

However, the extensive use of sand in construction has led in addition to a global sand shortage, to significant ethical concerns, particularly with the rise of illegal mining in sensitive areas and displacement of communities, posing serious environmental and sustainability challenges [8]




Graph 1: the current global shortage of sand used for construction [14]

This global sand shortage, alongside its negative effects represents a challenge for the development of sand batteries, first because it creates an economic competition with other industries that rely on sand, and second because it is essential for the sand battery technology to be able to find a new way of sourcing it's raw material in a sustainable manner. [8]

One potential solution could be the use of wind-shaped sand, which differs from water-shaped sand found in oceans, lakes, and rivers and used in construction for its unique shape. Indeed, wind-shaped sand has a smoother texture, making it unsuitable for concrete nor glass production. Thus, its unique properties might offer alternative applications, such as in sand batteries [9].

The UK's silica sand industry is experiencing steady growth, supporting the foundation for emerging technologies like sand battery energy storage [10]. Export volumes are projected to reach approximately 73 million kilograms, while imports are forecast to climb to nearly 198 million kilograms by 2026, reflecting a consistent and expanding demand for high-purity sand. This upward trend suggests a reliable and scalable supply of raw materials critical for the manufacturing of sand batteries. [10] In parallel, the broader sand, gravel, and clay extraction industry is expected to grow at a compound annual rate of 3.1%, reaching a market value of £3.4 billion by 2024–25, with industry profit margins projected at 3.7%. These trends highlight economic stability and growing commercial interest in sand-related sectors, offering a supportive backdrop for new uses of sand, including thermal energy storage systems. [10]

At the same time, construction-related sand and gravel markets are undergoing notable shifts. Due to under-replenishment of land-won sand and gravel reserves and increasing planning constraints, the UK is gradually moving towards offshoring supply, particularly from marine- based sources [17] [18]. Forecasts indicate that marine aggregates will account for 50% of total sand and gravel supply by 2035, up from current levels, compensating for the fall in land-won resources [17] [18]. This shift underlines the importance of diversifying supply chains and ensuring long-term resource availability—both critical for scaling up sand battery production

[17] [18]. Additionally, construction output and total aggregates demand have shown a post- pandemic recovery and are forecast to grow modestly through 2024, supporting continued demand for sand in infrastructure, energy, and innovation-related applications. [17] [18]

# Appendix H5: Explanation of the 3 components within a sand battery

**Resistive Heaters:** In a typical resistive heating system, electrical energy is converted into heat by passing current through a high resistance element. The elements are arranged in a grid or coil pattern throughout the storage silo so that when surplus renewable power is available it flows through these elements and generates heating conducted into the surrounding sand. In our sand battery design, we suspend an array of ceramic-encapsulated heater assemblies at multiple depths to ensure a uniform temperature profile.

**Heat Storage Module (Silo):** The bed silo contains sand chosen for its high specific heat capacity. Its walls are composed of refractory panels and surrounded by multilayer insulation under vacuum.

**Heat Transfer Mechanism (Fluid Loop):** A closed-loop circuit circulates heat transfer fluid, through stainless steel coils embedded in the sand. The fluid absorbs stored heat and delivers it to shell-and-tube exchangers for distribution to end users.

# Appendix H6: Policy and Market Factors

The economic feasibility of sand battery technology is reinforced by strong market trends and increasing governmental support. In the UK, the government is actively promoting energy storage infrastructure through new investment schemes aimed at accelerating the transition to net zero [28]. These initiatives are designed to boost investor confidence and unlock billions in private and public funding for large-scale storage projects [28]. By supporting technologies that enhance grid flexibility and provide clean, reliable power, such schemes are expected to create thousands of jobs while contributing to a more sustainable energy system [28]. For emerging technologies like sand batteries, this policy landscape offers a fertile ground for commercial scaling and integration into national energy plans [28].

Moreover, a comparative analysis of leading companies such as Panasonic, Tesla and Albemarle provide valuable insights into the pathways for achieving commercial success in the energy storage sector [28]. They focused on technological innovation and R&D investments while having strong sustainability and market adaptations. As for developing strategies, building strong supply chain integration or strategic partnership while ensuring a steady market could increase the opportunities to enlarge and develop. Finally, adopting a sustainable business model is quite important. Prioritizing energy-efficient manufacturing, battery recycling, and carbon footprint reduction, while aligning with evolving environmental regulations, which can ensure long-term success in the energy storage industry. Sand battery developers can draw from these examples by aligning with similar principles, thereby improving market competitiveness and ensuring long-term profitability while meeting evolving regulatory and environmental expectations [28].

Sand batteries provide a wide range of possible energy storage applications in industry. Sand batteries could be used to capture excess thermal energy that is generated during a process and stored for later use, which could lower operational costs for processes by storing and reusing excess energy generated. There is little to no energy loss and no degradation of material that is associated with typical battery materials, which makes sand batteries a good choice for long term energy storage.

# Appendix H7: Economic Feasibility Analysis

Levelized Cost of Storage (LCOS)

In our study, the Levelized Cost of Storage (LCOS) serves as a metric that captures all of the key economic factors of a sand-battery system: upfront investment, ongoing operating expenses and the impact of efficiency losses; expressed as a cost per unit of heat delivered. We calculate LCOS by annualising capital expenditures over the project lifetime, adding fixed operating costs, and then dividing by the total thermal energy output adjusted for round-trip efficiency. Finally, we include the effective electricity-charging cost by scaling the input price according to system efficiency. By applying this formula to both our small and large designs, we obtain cost values that can be directly compared to alternative thermal storage technologies and which reveal how scale, cycle frequency and efficiency improvements drive down the cost of stored heat in the UK context.

RTE for economic feasibility

The difference in RTE showed in the technical feasibility assessment shows up directly in our Levelized Cost of Storage. In both cases we annualise CAPEX with an 8% capital recovery factor and add fixed OPEX before dividing by delivered energy. The electricity-charging cost (ECC) term, defined as the raw electricity price divided by

RTE, falls from about £36/MWh in the 2 MW model to around £32/MWh in the 10 MW case. As a result, our illustrative LCOS shifts from £66/MWh at small scale down to about £49/MWh at large scale. In other words, by growing the silo's volume, and thus improving retention and extraction, we not only boost overall efficiency but also save some £ per MWh off the storage cost.

Limitations and losses

Using [23], we were able to approximate a 7% per month loss of energy of the battery for our equivalent models, mainly due to thermal radiation in the insulation chamber. Since we want to harness electricity when electricity is cheap, in summer, we would only have to wait 2 to 3 months to deliver the required energy needed in the system without an excessive loss. Studies

[23] made on similar products showed that economic output, with the right insulation systems, and the right assumptions on the variability of the electricity prices shows economic gain from the saving for consumers, either households or for industrial purposes. Not only the LCOS is an advantage, but seasonal variation induces a specific change in the economic gain of using cheap electricity/heat when demand is high or prices up.

While our calculation shows promising results, the main limitation of sensible TES lies in its thermal efficiency. The energy density of sensible materials is lower compared to phase change or chemical-based systems. This means that, although cost-effective, they require significantly larger storage volumes to hold the same amount of energy, which can be a spatial challenge. Additionally, maintaining the stored heat requires extensive insulation to minimise energy loss to the environment, especially when storing heat at very high or low temperatures. This necessity can drive up initial investment costs and complicate system design.

# Appendix H8: Technology Readiness Level (TRL)

A method for assessing the extent of development necessary for a technology to reach commercialisation. First adopted by NASA in the 1970s. The chart below shows the generally agreed definitions for each level based on ISO 16290:2013 [11]

| TRL | Description | Example |
|---|---|---|
| 1 | Basic principles observed | Scientific observations made and reported |
| 2 | Technology concept formulated | Applications are speculative at this stage. Examples are often limited to analytical studies. |

| | | |
|---|---|---|
| 3 | Experimental proof of concept | Effective research and development initiated. Examples include studies and laboratory measurements to validate analytical predictions. |
| 4 | Technology validated in lab | Technology validated through designed investigation. The results provide evidence that envisioned application performance requirements might be attainable. |
| 5 | Technology validated in relevant environment | Reliability of technology significantly increases. Examples could involve validation of a semi-integrated system of technological and supporting elements in a simulated environment. |
| 6 | Technology demonstrated in relevant environment | Prototype system verified. Examples might include a prototype being produced and demonstrated in a simulated environment such as pilot plants. |
| 7 | System model or prototype demonstration in operational environment | A major step increase in technology maturity. Examples could include a prototype being verified in an operational environment. |
| 8 | System complete and qualified | System is produced and qualified. An example might include the knowledge. |
| 9 | Actual system proven in operational environment | System proven and ready for full commercial deployment. |

# Appendix H9: Financing

## *CAPEX*

| **Item** | **Average** | **Notes** |
|---|---|---|
| **Sand** | **£100 k** | **High-temperature grade & transport** |

| | | |
|---|---|---|
| Insulation | £1 M | Aerogel + refractory panels |
| Structural (silo) | £2 M | Steel/concrete, refractory lining |
| Heaters | £1.5 M | Ceramic elements |
| xchangers & piping | £1 M | Shell-and-tube exchangers + insulated piping |
| Pumps & controls | £0.65 M | Variable-speed pumps, PLC, sensors |
| Construction & labor | £4.5 M | , silo build, integration, commissioning |
| Subtotal CAPEX | £10 M | |
| gency & soft costs | ~£1.25 M | Permitting, design buffers |
| Total CAPEX | £11.25M | |

***Annualized CAPEX: £11.25 M × 0.08 ≈ £900 000/yr***

## *OPEX*

| Item | Annual Cost | Notes |
|---|---|---|
| Maintenance (2 % of CAPEX) | £225 000 | Inspections, part replacement |
| Operations & admin staff | £200 000 | Technicians, engineers |
| Insurance & taxes | £170 000 | ~1.5 % of CAPEX |
| Auxiliaries (water, misc.) | £100 000 | Consumables, software, utilities |
| Subtotal OPEX | £695 000 | |

# Appendix H10: CAPEX/OPEX for Small Scale

*CAPEX*

| Item | ;caled Cost | Notes |
|---|---|---|
| **Sand** | **£20 k** | **~20 % of large system's sand cost** |
| **Insulation** | **£500 k** | **a of large silo; same material thickness** |
| **Structural & Silo** | **£1 000 k** | **ırge silo; refractory lining included** |
| **Resistive Heaters** | **£300 k** | **2 MW worth of elements** |
| **Changers & Piping** | **£200 k** | **20 % of large system's exchanger capacity** |
| **Pumps & Controls** | **£130 k** | **Scaled by power (2 MW vs. 10 MW)** |
| **Site Prep & Integration** | **£500 k** | **Excavation, foundations, sensor** |
| **Labor & Commissioning** | **£400 k** | **EPC staff, testing, commissioning** |
| **Subtotal CAPEX** | **£3 050 k** | |
| **Contingency (10 %)** | **£305 k** | **Design changes, price fluctuations** |
| **Soft Costs** | **£200 k** | **Environmental assessments, fees** |
| **Total CAPEX** | **£3 555 k** | **≈£3.6 M** |

**Annualized CAPEX = £3.6 M × CRF(5 %, 20 yr≈8 %) ≈ £285 k/year**

*OPEX*

| Item | ınnual Cost | Notes |
|---|---|---|
| **Maintenance (2 %)** | £72 k | Routine inspections, part replacement (2 % of £3.6 M) |

| | | |
|---|---|---|
| **Operations Staff** | £100 k | Technician/engineer salaries |
| **Admin & Overhead** | £50 k | Compliance, safety, support |
| **Insurance & Taxes** | £54 k | ~1.5 % of £3.6 M |
| **aries (water, misc.)** | £50 k | Consumables, software, utilities |
| **Total OPEX** | **£326 k** | **≈£330 k/year** |

## Appendix H11: Analysis for round trip efficiencies.

First, *input* captures how effectively our resistive heaters turn electrical energy into thermal energy, we use a figure near 98%. Next, *storage* measures what fraction of that heat remains in the sand after a resting period, it depends on the silo's insulation and geometry.

In our smaller, 2 MW/200 MWh design, the relatively high surface-to-volume ratio drives *storage* down to about 90 %, whereas in the larger, 10 MW/1 000 MWh silo the same insulation thickness yields closer to 92 % retention. Finally, *extraction* quantifies how much of the stored heat can be mobilised through our heat exchangers and delivered to the end-use network; small-scale exchangers and longer piping runs gives a 90 % extraction efficiency, but when we scale up, larger exchanger surfaces and lower relative pumping losses drive this term up to 98 %.

By multiplying these terms, we arrive at overall RTEs of approximately 85 % for the 2 MW unit and 90 % for the 10 MW system, in line with Polar Night's values.

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# Appendix I

## Appendix I1: Renewables and the Need for LDES

The intermittent and distributed nature of renewable energy (RE) creates significant challenges for grid stability and long-term energy planning. This variability occurs across multiple timescales—from daily fluctuations to year-to-year anomalies. On a seasonal level, long-duration energy storage (LDES) is essential to bridge predictable gaps between generation and consumption - for example, storing surplus solar energy produced in summer for use in winter months (Breyer, 2022). Beyond seasonal shifts, inter-annual variations such as prolonged periods of low solar irradiance or weak wind conditions further complicate reliability and could cause energy shortages without sufficient LDES capacity (Smith and Torrente-Muricano, 2024).

The effectiveness of a renewable energy system is also highly dependent on its geographic context. Local resource quality - such as consistent wind patterns or solar irradiation - directly influences capacity factors, determining how much power can be generated and how much storage is needed (Kebede et al., 2022). Geographic constraints and the availability of existing infrastructure also play a critical role. For instance, regions lacking access to hydroelectric power may need to depend more heavily on LDES solutions. These storage systems help resolve temporal mismatches between generation and demand that vary by location. For example, a sunny region with high summer cooling demand may also face winter heating needs when solar output is low (Smith and Torrente-Muricano, 2024).

Curtailment, the intentional reduction of electricity generation despite available capacity, is another key issue that intensifies with higher RE penetration. Curtailment typically occurs when the electricity supply exceeds demand or transmission infrastructure cannot transport the generated power. In the UK, curtailment is primarily caused by transmission constraints (Atherton et al., 2023). A concentration of wind farms in Scotland, combined with limited transmission capacity to England's main demand centres, results in grid congestion and forces wind turbines to reduce output. In other countries, the relatively small size of their grids drives curtailment, requiring multi-billion-dollar expansions to accommodate full decarbonisation (Cole, 2021). These supply-demand mismatches delay new RE projects and financially undermine their business case by lowering marginal energy prices and increasing reliance on expensive fossil fuel generation (Ambrose, 2023). Expanding affordable LDES is the only viable solution to absorb surplus renewable power when supply is high and release it during deficits, thus reducing curtailment, stabilising the grid, and supporting further RE deployment.

## Appendix I2: Ammonia as a Long-Term Energy Storage Vector

Several molecules have been proposed as vectors for LDES, including green ammonia, formic acid, methane, and methanol. These can all be produced from sustainable feedstocks (e.g., biomass, $CO_2$, or nitrogen) using green hydrogen derived from water electrolysis. Many of these same molecules are also considered low-carbon fuels for difficult-to-decarbonise sectors such as aviation and shipping (Smith, Hill and Torrente-Muricano, 2020).

Of these, ammonia stands out as a carbon-free energy carrier. Unlike hydrogen, ammonia can be liquefied under relatively mild conditions (8 bar or -33°C), enabling low-cost storage in standard pressure vessels (RSC, 2020). In its liquefied form, ammonia has an energy density of ~11 MJ/L, slightly lower than fossil fuels but significantly higher than hydrogen[13]. Moreover, ammonia benefits from mature global infrastructure due to its long-standing use in the fertiliser industry (RSC, 2020).

Today, roughly 85% of ammonia production is used for fertiliser manufacture, such as urea and ammonium nitrate, helping sustain nearly half the global population (Reese, et al. 2016). However, as ammonia's potential as a green energy vector becomes recognised, its production profile is expected to change dramatically. Global output, currently around 180 million tonnes annually, could rise to 688 million tonnes by 2050 - over three times today's levels (IRENA & AEA, 2022).

Currently, ammonia synthesis relies predominantly on fossil fuels, accounting for 1–2% of global $CO_2$ emissions (IRENA & AEA, 2022). Consequently, there is a growing academic and industrial focus on developing "green ammonia" produced exclusively with renewable electricity, water, and nitrogen from air.

## Appendix I3: Haber-Bosch Process

The conventional production of ammonia relies upon the Haber-Bosch (HB) process, that sees the conversion of nitrogen and hydrogen at high temperatures (>400°C) and pressures (>200 bar) over an iron-based catalyst (Chaban and Prezhdo, 2016). While the laws of thermodynamics limit the conversion to ammonia to a low <20% under these conditions, the conditions favour a sensible kinetic rate. The reactor effluent is cooled, the ammonia is condensed, and the remaining product is recycled to maximise hydrogen utilisation.

Fundamentally, the HB process has not changed significantly since its commercial birth in 1913, but rather optimised to take fossil fuels (mainly methane) as the hydrogen feedstock. This has led to substantial $CO_2$ emissions (1.7 $tCO_2/tNH_3$) and the HB process accounting for 1-2% of anthropogenic emissions (Sánchez-Bastardo, Schlögl and Abánades, 2022).

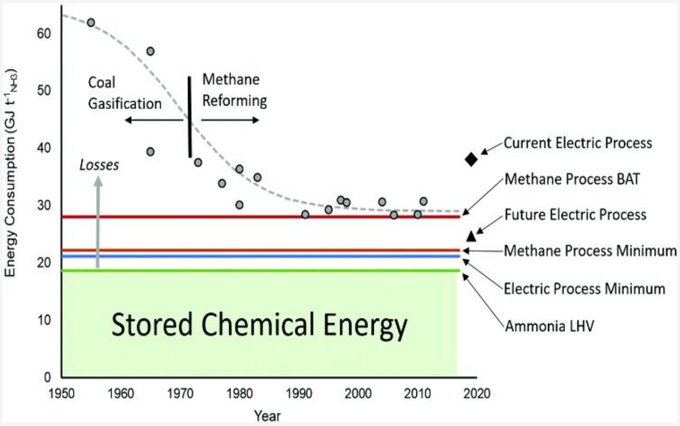


**Figure 2:** Current and Future Role of Haber-Bosch process (Collin, 2020).

More recently, the sure in availability of renewable energy deployment and the increasing desire for the electrification of the chemical industry has exposed a falsely optimised HB process when fossil fuels are the only energy source (Smith, K. Hill and Torrente-Murciano, 2020). Should ammonia synthesis be decoupled from fossil-fuel-generated electricity and paired with renewable electricity, ammonia will not only function as a sustainable fertiliser but realise its role as an energy-dense storage vector.

Hydrogen, rather than fossil fuels, can be produced through electrolysis operating entirely on renewable electricity, resulting in considerably lower $CO_2$ emissions – as low as 0.3 $tCO_2/tNH_3$ (Hydrogen Council, 2021). Despite this, due to its inherently isolated and intermittent nature, renewable energy is incompatible with the conventional steady-state operation, heat integration, inflexible recycling, and capital-intensive compressors of the HB process. To remedy this, large battery stores and hydrogen tanks are required to create a buffer between fluctuating energy supply and the rigid HB process.

Considerable academic and industrial efforts are being made toward the production of green ammonia using exclusively RE, $H_2O$ , and $N_2$ (from air). One of the most notable efforts is the Absorption-Enhanced Haber-Bosch (AEHB) process.

## Appendix I4: Description of AEHB

The absorption-enhanced HB process modifies the conventional HB process by integrating a solid absorbent to capture ammonia as it is produced, to increase conversion and to simplify ammonia synthesis. Like the conventional approach, AEHB reacts nitrogen and hydrogen in the presence of a catalyst, with the nitrogen being obtained by the pressure swing absorption of air, and the hydrogen being obtained from the electrochemical splitting of water (Smith, Hill and Torrente-Murciano, 2020).

The key difference lies in ammonia separation. Instead of cooling the gas mixture in a condenser, the introduction of a solid absorbent such as magnesium chloride or calcium bromide supported on alumina, silica, or zeolite Y in a separate absorber unit allows for the ammonia to be selectively captured. Alternatively, a thin, ammonia-selective membrane could be used, but it only functions at 360°C, a temperature well below that of the reactor.

Upon saturation of the absorbent, the feed is stopped, and the pressure is released or the temperature is raised to recover the ammonia and regenerate the absorbent (Onuoha, Kale and Cussler 2023). Due to the unsteady nature of the process, AEHB requires at least two beds to operate. While one bed absorbs ammonia, the other undergoes regeneration to release it. Like in the conventional process, any under-reacted gas is recycled back into the reactor.

The Absorption-Based Haber-Bosch process is one of the best potential solutions to the current costs associated with producing ammonia – a process currently optimised for fossil fuel feedstocks. Continued research efforts in this area could drive efficiency and make ammonia a reliable, green long-term energy vector.

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# WASTE MANAGEMENT

# Appendix J:

## Appendix J1: PBSAT and PHA material properties

PBSAT is a biodegradable polyester that has shown to have moderate tensile strength, high flexibility and ability to decompose in marine environments. Research shown that PBSAT fishing nets can decompose within the span of two years in the ocean with helps significantly to reduce the issue of ghost fishing [8]. While Polylactic Acid (PLA) is also a common biodegradable plastic, it is less suitable for marine applications as it degrades primarily under industrial composting conditions. PBSAT has better performance in saltwater conditions and releases fewer microplastics when degrading [9].

PHA is a biopolymer produced by a variety of bacteria and archaea that can degrade in both marine and terrestrial environments [10]. Unlike conventional plastics, PHA fully decomposes into $CO_2$ and water, leaving no microplastics that can harm marine life [11]. Like PBSAT, PHA also has good flexibility due to its long side chains but a lower mechanical strength, making it a viable alternative to traditional fishing nets. However, pure PHA lacks durability due to its high crystallinity, and may require blending with other materials, such as PBSAT, to improve its performance [12].

## Appendix J2: Methods to reduce bycatch and improve fuel efficiency

Efforts have been suggested to reduce bycatch, including placing cameras inside nets and using sensory deterrents such as LEDs and acoustics [17]. Additionally, pressure sensors can help minimise bycatch by detecting excessive force exerted by larger non-target species attempting to escape and reduce strain and stress on the structure. These sensors can trigger pressure-sensitive escape hatches, used in EcoTrawl, that operate with low-energy hydraulic systems, allowing trapped non-target species to leave with minimal harm [16]. Compared to conventional panels, these are not rigid and work on a toggle switch, where a threshold pressure is detected, allowing for release based off feedback. While pressure alone cannot identify species, it helps differentiating non-target catch based on physical interactions with the net.

Since wear and tear sustained by fishing nets leads to frequent ruptures and increased waste, development of modular net panels which can be replaced when damaged should be incorporated.

Figure 2 features a multi-layered netting system with a reinforced polymer weave and hydrodynamic shaping. The upper portion in the net outlines a pyramid-based structure – distributing strain evenly and reduces the likelihood of tears in high-pressure zones. This adheres with the requirements, where it is “essential to maintain consistency in knot orientation” [18]. The adaptive mesh system works in conjunction with the pressure-sensitive escape hatches, allowing for variations in mesh size dependent on the target species. Flexible, larger apertures are present in the front, reducing bycatch rates. [19]

Central sections have reinforced trapezium netting and square frames, allowing for optimal strength with minimal water resistance. The variations in shapes present, with pyramidal,

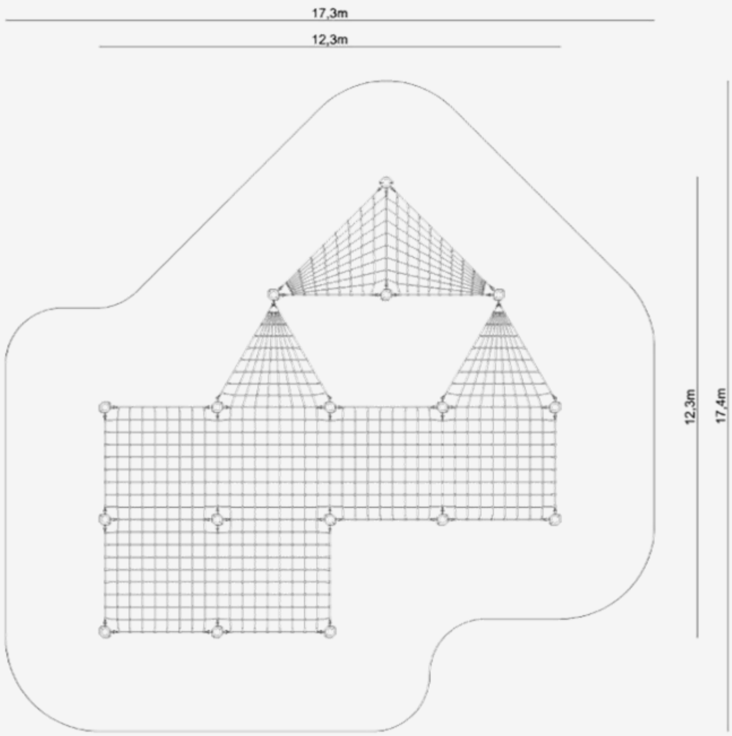


Figure 2. Top-view schematic of a multi-layered netting with its dimensions. Spanning an overall width of 17.3 m, the layout features a central 12.3 m-wide pyramidal mesh that seamlessly integrates with adjoining trapezoidal and rectangular panels to create a streamlined, strain-balanced net assembly

trapezium, and square shapes present allow for low-drag and a streamlined hydrodynamic frame. Reduction of net resistance can improve efficiency and lower the carbon emissions associated with trawling operations. A self-adjusted buoyancy system could be implemented into the design [19]. This involves reinforcements which include anti-turbulence panels, which adjust the flow through the net and reduce energy expenditure.

The orientation of knots in the horizontal netting panels and mesh geometry has also been suggested as a strategy to reduce bycatch [18]. Positive hydrodynamic lift generated by specific knot orientations can optimise trawl performance by enhancing wing-end spread and headline height, ultimately reducing bycatch rates. Maintaining a consistent positive angle of attack (AOA) in knot orientation minimises sediment accumulation and net drag, improving fuel efficiency and preventing unnecessary environmental disturbance. Additionally, a well-optimised AOA can elevate the trawl slightly, reducing seabed contact, preventing excessive debris retention, thereby lowering bycatch mortality, especially for benthic and demersal species.

To further refine net performance, integrating real-time monitoring with hydrodynamic modelling can ensure consistent knot orientation throughout fishing operations. Adaptive mesh structures reinforced with high-strength polymer blends, can enhance selectivity while maintaining durability, addressing issues like net rupture and ghost fishing.

The hydrodynamic performance of trawl nets is heavily influenced by mesh size and twine thickness, both of which directly impact drag coefficient and fuel consumption. Larger mesh sizes reduce the surface area of netting exposed to water resistance, thereby lowering drag and decreasing the energy required to tow the net. This effect is noticeable in the wing, square, and top belly sections of the net, where increasing mesh size has been shown to reduce total drag by up to 56.7% compared to conventional designs [20]. Conversely, smaller mesh sizes increase resistance, leading to greater fuel consumption as more force is needed to overcome drag.

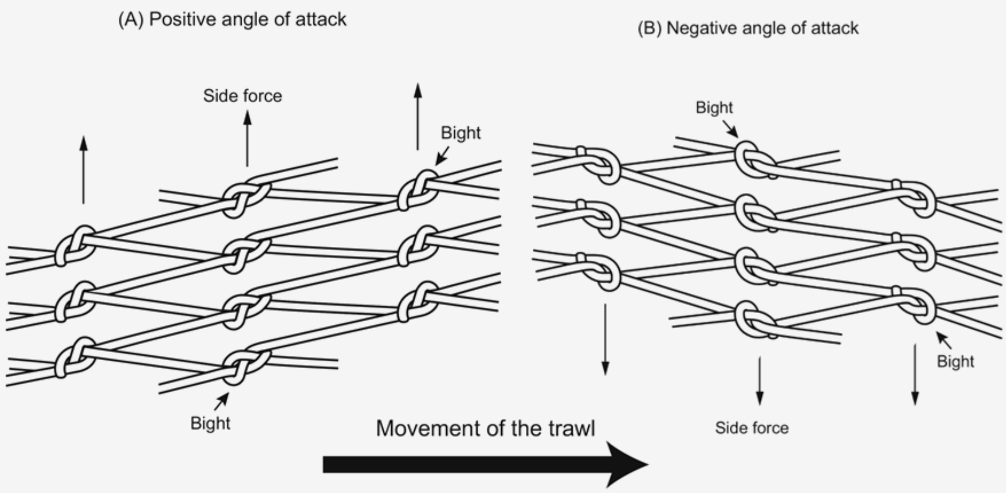


Figure 3. Diagram representing knot orientation with (a) positive and (b) negative angles of attack from [18].

Twine thickness also plays a crucial role in determining net resistance. Thicker twines increase drag due to their greater cross-sectional area, creating higher turbulence and resistance against water flow. In contrast, nets constructed with thinner twines exhibit lower Reynolds numbers, resulting in a smoother hydrodynamic profile and reduced fuel consumption. Experimental studies show that optimising twine diameter and mesh size together can lead to significant improvements in trawl efficienc

y, with drag reductions exceeding 50% in some cases. By incorporating these hydrodynamic principles into net design, fisheries can achieve lower operational costs while simultaneously reducing the environmental footprint of bottom trawling.

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# Appendix K

## Appendix K1 - Cotton

### *Bacteria Degradation*

Bacteria degradation works through the enzymes bacteria secrete. Firstly, these enzymes help in the absorption of cotton fibres, followed by hydrolysis, which breaks the glycosidic bonds in cellulose into simpler sugars like glucose and cellobiose [8]. The bacteria then metabolise these sugars through various biochemical pathways to generate energy for their growth and reproduction. This microbial activity plays a crucial role in the biodegradation of waste cotton, reducing landfill accumulation and contributing to bioremediation by removing cotton-based pollutants from soil and water ecosystems [28].

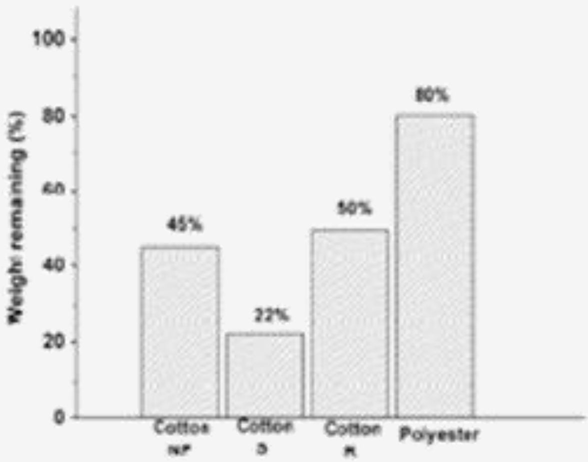


Figure 1: Shows biodegradation of different cotton such as cotton softener, cotton no finish and cotton resin. Where cotton softener shows highest lost in weight of 77% and cotton resin with 50% weight loss in 90 days.

According to Figure 1, significant weight loss in cotton samples (especially Cotton D at 22% remaining) suggests that bacteria can efficiently break down cotton fibers. This indicates that cotton is highly biodegradable, which is beneficial for reducing textile waste.

Cotton is made up of 90%–95% cellulose, a polysaccharide composed of long chains of glucose molecules. Cellulose provides structural strength to plant fibers but is biodegradable under the right conditions. Certain bacteria, including *Cellulomonas*, *Bacillus*, and *Clostridium* species, produce cellulase enzymes that initiate the breakdown of cellulose in cotton fibers. This process begins with endoglucanases, which cut cellulose into smaller fragments called cellooligosaccharides. Next, exoglucanases further degrade these fragments into cellobiose, a compound consisting of two glucose units. The final step involves β-glucosidase enzymes, which convert cellobiose into glucose, a simple sugar that bacteria can utilize as an energy source. As bacteria metabolize glucose for growth and reproduction, they generate byproducts such as carbon dioxide ($CO_2$) and water, completing the natural degradation cycle of cotton.

## *Compost system*

Different types of microorganisms play crucial roles in the composting process. Psychrophilic bacteria thrive at temperatures as low as -18°C (0°F) and up to 13°C (55°F), generating small amounts of heat that help transition compost to the next stage. Mesophilic bacteria become active at 21–32°C (70–90°F), further raising the temperature and paving the way for thermophilic bacteria. Thermophilic bacteria, which thrive at 46–60°C (115–140°F), work rapidly to break down organic matter, kill pathogens, and destroy weed seeds, but they die off if the compost exceeds 71°C (160°F). Nitrifying bacteria play a key role in nutrient cycling by converting ammonium into nitrates, making nitrogen more available to plants, sometimes overlapping with thermophilic bacteria. Actinomycetes, thriving in moderate temperatures, help break down tough, woody materials after the thermophilic stage and form threadlike filaments in compost [21]. Additionally, fungi contribute to decomposition by breaking down resistant materials and are tolerant to heat, often appearing during the thermophilic stage to aid in the final stages of organic matter breakdown [23].

**Onsite Institutional Composting Program Costs**

| Facility | Tons Composted Per Year | Capital Costs | Operating Costs | Total Costs | Costs Per Ton |
|---|---|---|---|---|---|
| **Low-Technology** | | | | | |
| Kelley Air Force Base | 800 | $47,143 | $20,000 | $67,143 | **$84** |
| GDCC | 1,040 | $11,429 | $28,000 | $39,429 | **$38** |
| NYDOC [a] | 7,800 | NA | NA | NA | **$22** |
| Weighted Average Low-Technology | | | | | **$29** |
| **High-Technology** | | | | | |
| NRCan | 94 | $5,853 | $11,274 | $17,127 | **$182** |
| Rikers | 4,000 | $152,070 | $230,000 | $382,070 | **$96** |
| Weighted Average High-Technology | | | | | **$98** |
| **WEIGHTED AVERAGE** [b] | | | | | **$49** |

Table 1: Cost breakdowns of onsite institutional composting programs by facility type and technology level.

**Table 2-2**
**Avoided Mixed Waste Collection Costs Associated With Leaf and Yard Trimmings Composting Programs**

| Program Stipulations | Average |
|---|---|
| Costs per house per year—no yard trimmings collection | $63.06 |
| Costs per house per year—with yard trimmings collection | $53.44 |
| Costs per house per year saved | $9.62 |
| Annual tons of yard trimmings diverted per house | 0.416 |
| Avoided collection cost per ton | $23.12 |

**Source**:
Franklin Associates/Keep America Beautiful. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*. Appendix H.

Table 2: Estimated avoided mixed waste collection costs resulting from leaf and yard trimmings composting programs.

# Appendix K2 - Polyester

## *Microbial PET Degradation*

The hydrolysis of PET is done by hydrophilization of PET to expose the end of polymer chain to enable the hydrolysis of carboxylic acid or hydroxyl group. This makes microorganisms more easily adhere to the surface of PET, facilitating the enzymatic action. The intermediates produced during hydrolysis may be toxic to cells, and coulddegrade enzymes. This could also inhibit the growth of the microorganism and degradation efficiency. The products of PET hydrolysis are also a competitive inhibitor of PET hydrolases [27].

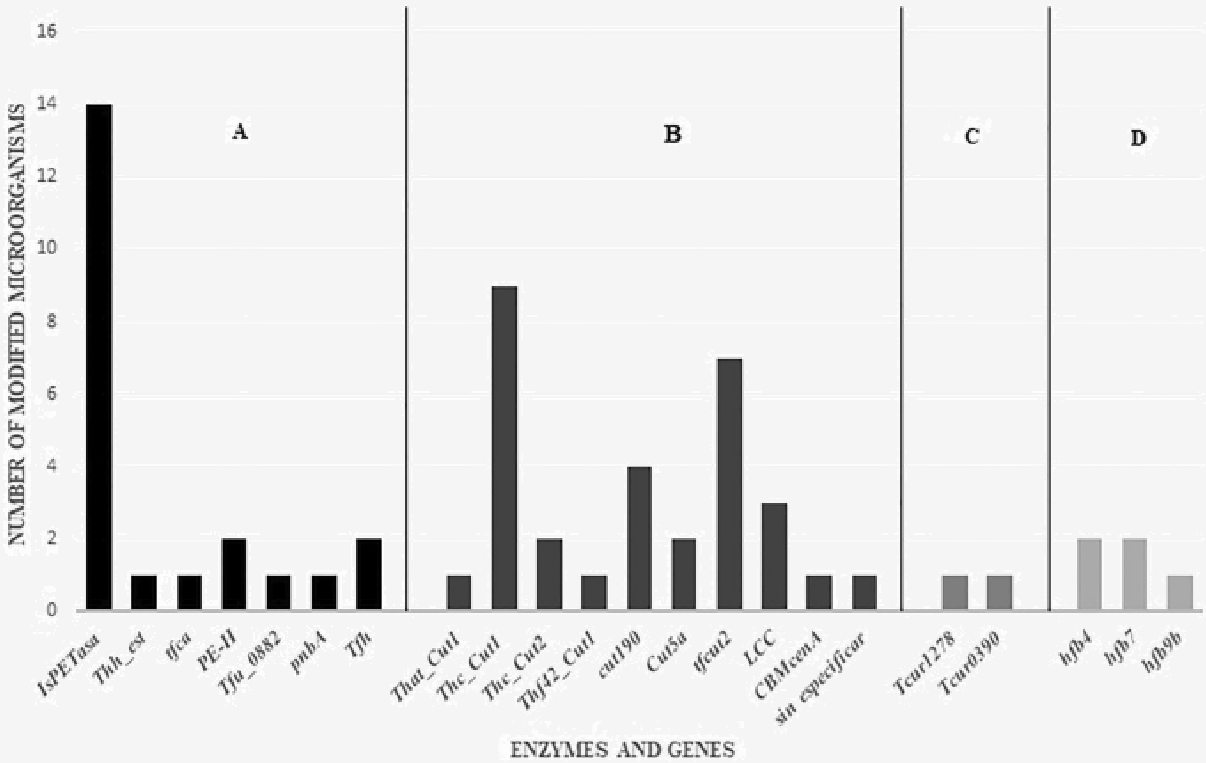


Figure 2: The enzymes and genes manipulated for increased capacity of PET degradation. Figures obtained from Benavides et al [2].

## *Enzyme assisted processes*

Wild types such as Bacillus sp. and genetically modified organisms such as E.Coli produce enzymes that degrade PET and produce simpler molecules without producing toxic waste or large amounts of greenhouse gases.

Cutinases can be extracted by some species of bacteria, such as H*umilica insolens* (HiC), *Pseudomonas mendocina* (PmC) and *Fusarium solani* (FsC). pH-stat assay shows that the enzymes had 10-fold higher activity for PET with lower crystallinity, *Ic*PET compared to *bo*PET. In this study, the best results obtained was incubation of HiC at 70ºC, resulting in a 97 ± 3 % weight loss recorded in 96 hours shown in figure 2. Besides that, initial rate of hydrolysis for HiC is 7-fold higher than PmC and FsC, contributed mainly by its ability to function at higher temperatures [29].

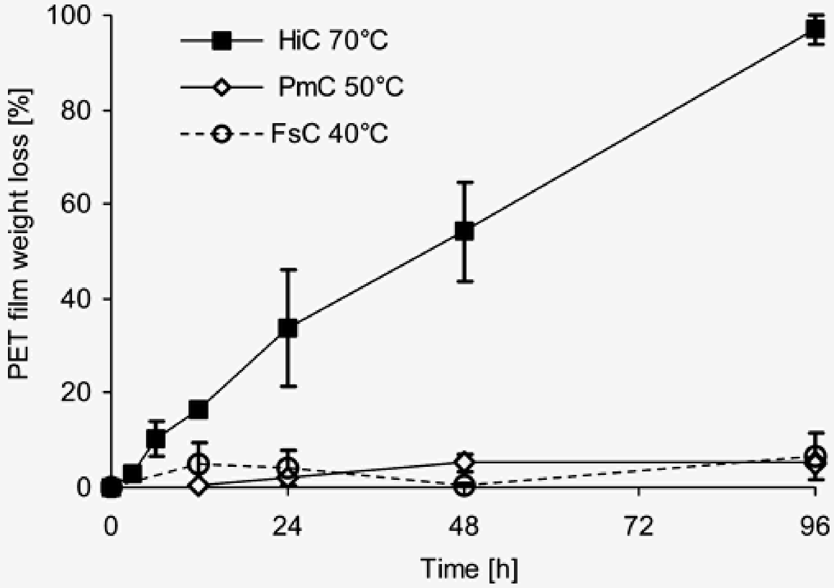


Figure 3. Degradation study of IcPET incubated in 1 M Tris-HC; with 10% glycerol, pH 7.5 and 10 nmol/mL of either HiC, PmC or FsC at 70, 50, and 40 ºC respectively

| Enzyme | Source | Temperature (Cº) |
|---|---|---|
| **HiC** | *Humicola insolens* | 70 |
| **IsPETase** | *Ideonella sakaiensis* | 30 |
| **LCC** | Uncultured bacterium | 70 |
| **PE-H** | *Pseudomonas aestusnigri* | 30 |
| **BsEst** | *Bacillus subtilis* | 40 |

Table 3: This table shows different types of enzymes that can break down polyester, their source and the optimum temperature for high efficiency (Qiu et al., 2024).

## *Mixed waste processing*

The proposed method utilizes microwave-assisted glycolysis over a ZnO catalyst followed by solvent dissolution to selectively break down polyester and spandex into monomers [11]. In the first step, mixed textile waste is heated in ethylene glycol with a ZnO catalyst at 210°C, breaking polyester and spandex into BHET and MDA within 15 minutes. Next, formic acid is used to dissolve nylon, allowing its recovery by evaporation. Finally, the cotton remains as a solid residue and is separated from the other recovered components. Polyester depolymerization is rapid, occurring in 15 minutes at 210°C, making it potentially scalable. However, dyed polyester requires longer processing times, which increases energy costs. The material and operational costs also play a significant role in the feasibility of this method. A high volume of ethylene glycol is required for effective glycolysis, significantly adding to raw material costs [11]. ZnO, used as a catalyst, is relatively inexpensive at approximately $2 per kg [36], but its losses and replenishment could contribute to long-term costs. Microwave heating to 210°C demands substantial energy input, estimated at $0.10–$0.20 per kg of textile [9]. Solvent recovery is another key cost factor, as formic acid recycling is essential but may require additional purification, adding an additional cost.

The recovered materials also have varying market values. BHET, derived from polyester, is typically valued at $0.10 per kg depending on purity [7]. MDA from spandex can be used in dyes and adhesives, with a market value of $4–$5 per kg [24]. Recovered cotton can be repurposed into viscose fiber at around $1.50-2 per kg [26], while recovered nylon, usable in clothing, is valued at $2.36 per kg (Mike, 2020). However, scalability and challenges remain. The separation of BHET from oligomers increases purification costs, and dyed polyester reduces BHET yield, which affects economic viability. Additionally, the remaining solid cotton residue complicates the process, requiring additional mechanical or chemical treatment. Lastly, high ethylene glycol usage raises sustainability concerns and regulatory considerations.

# Appendix K3 - Wool

## *Fungal Degradation*

Fungal degradation works by the enzymes fungi such as *Trichophyton simii* and *Aspergillus niger* secrete. These enzymes break down the tough keratin fibres into smaller peptides and amino acids, facilitating microbial consumption and contributing to wool decomposition.

## *Enzymatic treatment*

Enzymatic treatment used lipases and proteases. Proteases break wool fibres into smaller peptides and amino acids, making it easier to recycle or repurpose. Lipases assist in cleaning by removing oils and other impurities
Separation of mixed fibre waste poses a major recycling problem because fibres must be separated into single components for effective recycling. By using enzymes, we can depolymerise end-of-life textiles into their monomers. Which is typical selective, uses low energy and benign chemicals, which helps in sorting and recycling blended textile waste. Based on this research paper, data in Figure 3 shows that fabric degradation with presence of sodium thioglycolate significantly improved compared to treatment without reducing agent. Up to 73% weight loss is recorded for 100% wool woven, and 73% for 45/55% wool/polyester woven. This is due the reducing agent

being a crucial component for keratinases and proteases to access and breakdown peptide bonds in wool. The stronger the reducing capacity of the reducing agent, will result in a higher degree of reduction of disulfide bonds, leading to increased access of protease and improved degradation (Navone et al., 2020).

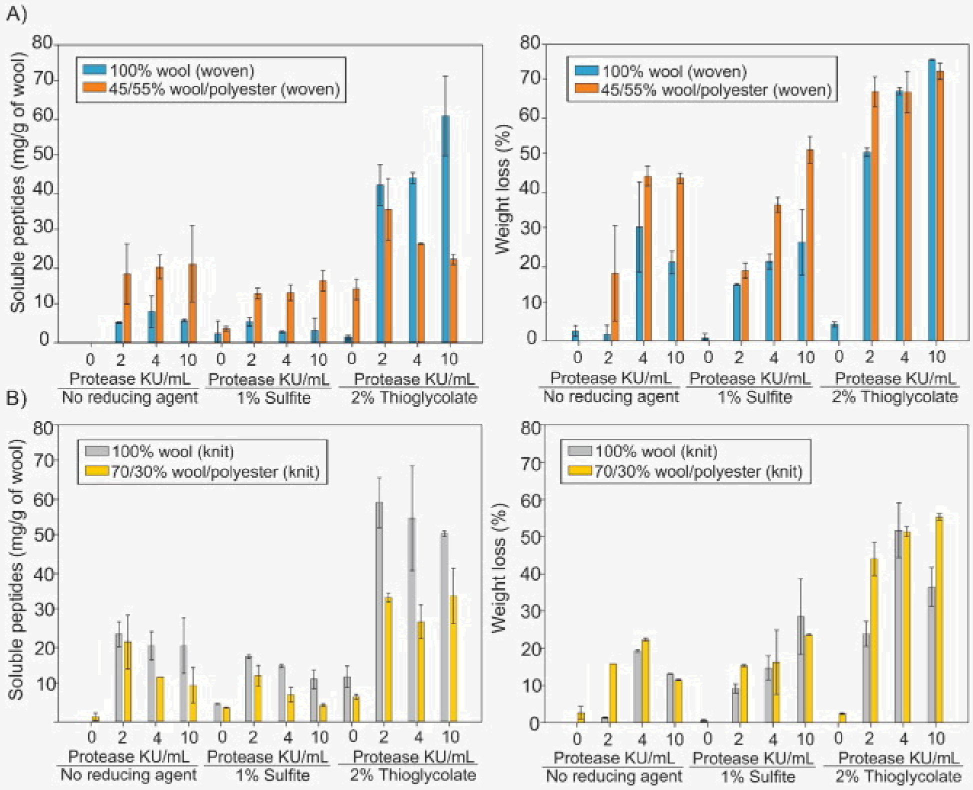


Figure 4. Enzymatic degradation of wool fabric at 37C with 2, 4 or 10 KU/mL of protease with or without reducing agents.

## *Bioaugmentation*

Standard wool degradation methods rely on natural microbial decomposition, which is slow due to the hydrophobic nature of wool that resists enzymatic attack. Bioaugmentation introduces keratinolytic microorganisms, such as Streptomyces species, which produce enzymes that cleave disulfide bonds and hydrolyse peptide bonds in keratin. This speeds up the process significantly.

In the early stages of biodegradation, during the first few months, the mechanical properties of the wool, such as strength, began to deteriorate. The surface scales of the wool fibers started breaking down, and the disulfide bonds in keratin were cleaved. As the process progressed into the intermediate stage over the following months, a further decline in mechanical properties was observed. The degradation extended deeper into the fiber structure, affecting the cuticle and inner layers. Additionally, peptide bonds began breaking, leading to fiber defibrillation. In the advanced stages, fibers that were already mechanically weakened degraded at an accelerated rate, resulting in extensive fiber defibrillation [3].

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# Appendix L

## Appendix L1: Methane Pyrolysis Mechanism

Methane pyrolysis is simply converting methane to low-carbon hydrogen (the UK's low-carbon hydrogen standard is a hydrogen produced with a final GHG emission intensity of 20g $CO_2$e/MJ $H_2$ or less) and solid carbon by splitting the atoms.

$$CH_4\,(g) -> 2H_2\,(g) + C\,(s)$$

Solid carbon, then, can be converted to other materials such as graphite, graphene, and carbon nanotubes (CNT) .

There are four types of methane pyrolysis: thermal, plasma, catalytic, and molten metal. Each type has advantages and drawbacks. Thermal pyrolysis is a straightforward method; however, it requires a lot of energy to reach the conventional temperatures to decompose methane. On the other hand, plasma can reduce the required temperature, but it is not commercially mature yet. Only Monolith Inc is producing hydrogen and carbon black via methane pyrolysis at the moment.

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# Appendix M

## Appendix M1: Recycling aseptic cartons

The recycling of aseptic cartons begins with collection and sorting, where used cartons are gathered and separated from other waste streams. These cartons undergo a hydropulping process, where they are mixed with water and agitated to separate the paper fibres from plastic and aluminium components (Pivnenko et al., 2015). The extracted fibres are then cleaned, refined, and used in the production of recycled paper products. The residual plastic and aluminium fractions can be repurposed through energy recovery or manufacturing composite materials (Tetra Pak, 2021).

## Appendix M2: Benefits and Challenges of Recycling Paper

There are many environmental benefits to recycling paper. Studies indicate that producing recycled paper requires approximately 60% less energy and up to 80% less water compared to virgin paper production (Smith et al., 2019). Additionally, landfill waste is reduced, decreasing methane emissions associated with decomposition (Environmental Protection Agency, 2020).

However, contamination makes recycling paper much harder. Examples of contaminants include food residues, polyethylene coatings, and printing inks. These materials are difficult to remove during pulping and interfere with the separation of clean fibres. Food residues, for instance, increase microbial load and reduce the purity of recovered fibres, while ink and coatings introduce chemicals that can lower paper quality or damage recycling equipment (Pivnenko et al., 2015). Moreover, the quality of recycled paper diminishes with each cycle due to fibre degradation, limiting its usability in high-strength applications (Hubbe et al., 2007). Economic viability remains another concern, as fluctuating market demand and processing costs influence the feasibility of aseptic carton recycling programs.

## Appendix M3: Benefits and Challenges of Composting paper

Composting of aseptic carton fibres involves shredding the material to increase surface area for microbial activity, followed by mixing with nitrogen-rich organic waste to balance the carbon-to-nitrogen (C:N) ratio (EPA, 2020). The mixture is aerated and maintained at optimal moisture levels to facilitate decomposition, after which the compost undergoes curing before application as soil amendment.

Composted paper improves soil structure, enhances water retention, and provides essential nutrients. It also aids carbon sequestration, potentially offsetting greenhouse gas emissions (Lal, 2018). Diverting cartons from landfills further reduces environmental impact by minimising methane emissions from anaerobic decomposition.

The presence of ink, coatings, and chemical additives in aseptic cartons poses contamination risks. Additionally, certain paper types, particularly those with high lignin content or wax coatings, decompose at slower rates, requiring extended composting periods (Hubbe et al., 2007). Maintaining an optimal C:N ratio is crucial, as excessive paper content can disrupt microbial balance and slow degradation (EPA, 2020).

# Appendix M4: Thermodynamic and Economic Comparison of Incineration and Anaerobic Digestion

## *4.1 Direct Combustion (Incineration)*

The incineration of cellulose-rich paper can be simplified by the combustion reaction of cellulose:

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O \quad \text{(Eq.4.1)}$$

This highly exothermic reaction produces heat, which is converted into electricity through steam turbines. Net electrical efficiency is typically between 20% and 30% (Arena, 2012).

## *4. 2 Anaerobic Digestion (AD)*

In anaerobic digestion, the cellulose is first hydrolysed into glucose, which is then converted into volatile fatty acids (VFAs), hydrogen, and ethanol. Methanogenic bacteria subsequently convert these intermediates into methane ($CH_4$) and carbon dioxide ($CO_2$), producing biogas suitable for electricity and heat generation:

1. Hydrolysis

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 \quad \text{(Eq.4.2)}$$

2. Acidogenesis & Acetogenesis

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 + H_2 \quad \text{(Eq.4.3)}$$

3. Methanogenesis

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad \text{(Eq. A.4)}$$

The methane-rich biogas can be used in combined heat and power (CHP) units, with overall system efficiencies between 35% and 45% (Appels et al., 2008; Holm-Nielsen et al., 2009).

### *4.3 Energy and Emission Metrics*

**Table 2.** Energy and Emission Metrics

| Metric | Incineration | Anaerobic Digestion (CHP) |
|---|---|---|
| **Net Energy Efficiency (%)** | 25 (avg) | 40 (avg) |
| **$CO_2$ Emissions (g/kWh)** | ~850 (Zhang et al., 2020) | ~550 (Holm-Nielsen et al., 2009) |
| **Operational Cost ($/MWh)** | 100 | 120–140 |
| **Residual By-product** | Toxic ash | Fertilizer-grade digestate |

# Appendix M5: Gasification and RDF production

Gasification involves heating wastepaper in a low-oxygen environment to produce syngas, a mixture of hydrogen and carbon monoxide. This process offers several advantages over direct combustion, including higher energy efficiency due to greater energy extraction, cleaner emissions with fewer harmful byproducts, and the production of vitrified slag, which is non-toxic and can be utilized in construction, thereby minimizing landfill waste. However, despite these benefits, gasification is associated with high initial costs, complex operational requirements, and the necessity for waste pre-treatment, such as drying and contaminant removal, which can limit its widespread adoption (Chen et al., 2022).

Refuse-derived fuel (RDF) production offers another viable strategy for utilizing wastepaper. This method involves processing waste paper into compacted pellets or fluff, which can then be co-fired with other fuels to enhance energy density while reducing landfill waste. However, its effectiveness is contingent on extensive sorting and processing to remove contaminants and improve fuel quality (Singh & Bhatia, 2023). Fermentation presents another approach by converting cellulose from paper into ethanol through enzymatic hydrolysis and microbial fermentation. The resulting bioethanol can serve as a renewable alternative fuel for transportation and industrial applications, but the process faces challenges related to pretreatment requirements and the high costs of enzyme production, which hinder its large-scale implementation (Hassan et al., 2020).

# Appendix M6: Bioelectrochemical Systems (BES)

Bio electrochemical systems (BES) leverage specialized enzymes to degrade cellulose into glucose, which then undergoes enzymatic oxidation. This process releases electrons and protons, with the electrons captured by electrodes to generate an electric current while protons react with oxygen to form water.

## *B.1 System Overview*

The mechanism of BES resembles a microbial fuel cell.

Anodic Reaction

$$C_6H_{12}O_6 \rightarrow 6CO_2 + 24H^+ + 24e^- \quad \text{(Eq. 6.1)}$$

Cathodic Reaction

$$6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O \quad \text{(Eq. 6.2)}$$

## *B.2 Technical Considerations*

- Electrical efficiency: 10–15% (Wang & Zhao, 2021)
- Advantages: Low emissions, minimal sludge
- Limitations: Low power density, microbial sensitivity, high electrode costs

# Appendix M7: Carbon Capture Technologies in Waste-to-Energy

Carbon capture techniques help remove hydrogen sulphide ($H_2S$) and $CO_2$, thereby enhancing environmental performance (Gupta et al., 2022). These techniques are summarised below.

## *C.1 Overview of Key Technologies*

**Table 3.** Overview of carbon capture mechanisms

| Technology | Mechanism | Notes |
|---|---|---|
| **Chemical Absorption** | $CO_2$ captured by amines (e.g. MEA) | High efficiency, high energy penalty |
| **Physical Adsorption** | $CO_2$ binds to porous solids like zeolites | Moderate efficiency, reusable media |
| **Membrane Separation** | Selective gas diffusion through membranes | Modular, mid-range performance |
| **Biotechnological** | $CO_2$ fixed by algae or microbes | Environmentally friendly, experimental |

## *C.2 Integration with Paper-to-Energy Systems*

Amine-based chemical absorption systems can capture up to 90% of $CO_2$ emissions from incineration or gasification plants (Gupta et al., 2022). Membrane systems are better suited to small-scale digesters. Biocapture using algae or bacteria is under development and shows promise in circular waste-to-energy systems when integrated with anaerobic digestion outputs.

# Appendix M8: Mechanical Recycling

Mechanical recycling follows a multi-step process involving collection, sorting, washing, shredding, and reprocessing of plastic waste (TWI, n.d.). The first step, collection and sorting, involves gathering plastic waste and categorizing it based on material type and color. Sorting can be manual or automated, often combining multiple methods to enhance accuracy. After sorting, washing is crucial to eliminate contaminants such as food residues, adhesives, and dirt, which could compromise the purity of the recycled plastic (Given, 2024). Once cleaned, the plastic undergoes shredding or grinding to produce smaller flakes, which facilitate handling and processing. These flakes are then melted, extruded, and cut into pellets, which serve as raw materials for manufacturing new plastic products.

# Appendix M9: Chemical Recycling

Chemical recycling, although less common than mechanical recycling, involves breaking down the chemical bonds within the plastic structure, converting it into its fundamental components such as polymers, monomers, oligomers, or hydrocarbon products (BPF, 2024). Various methods exist within chemical recycling, including pyrolysis, gasification, depolymerization, solvolysis, and biochemical recycling (Luu, 2024). These approaches offer potential advantages, such as the ability to process contaminated plastics and produce high-quality recycled materials; however, their large-scale implementation is still in its early stages.

**Table 4.** Pyrolysis comparison

| Aspects | Thermal pyrolysis | Catalytic pyrolysis |
| --- | --- | --- |
| **Optimal conditions** | 1. Fixed bed reactor at 500°C<br>2. Heating rate of 10°C per minute<br>3. High pressure | 1. Fixed bed reactor at 500°C<br>2. Heating rate of 10°C per minute<br>3. Highly acidic catalyst (i.e. bentonite) with catalyst to waste ratio of 0.05 |
| **Oil yield (wt%)** | 95 | >85 |
| **Product properties** | 1. >96% similar to diesel<br>2. Require further refinements (i.e. distillation and upgrading) | 1. >96% similar to diesel<br>2. Less further refinements needed due to the presence of catalysts |
| **Environmental impact of pyrolysis** | Higher due to<br>- The absence of catalyst<br>- Longer reaction time<br>- Higher operating temperature range | Lower due to<br>- The presence of catalyst<br>- Shorter reaction time<br>- Lower operating temperature range |
| **Engine performance** | 1. Engine power comparable to diesel<br>2. Greater CO and CO2 emissions (compared with catalytic pyrolysis oil) | 1. Engine power comparable to diesel<br>2. Less CO emission compared with diesel |

| | | |
|---|---|---|
| **Economic performance** | 1. Positive and higher NPV compared with catalytic plant at a plant capacity of 20,000 tons/yr | 1. Positive and lower NPV compared with thermal plant at a plant capacity of 20,000 tons/yr<br>2. Better economies of scale as capacity increases |

# Appendix M10: Plastic Recycling Challenges and Solutions

To address the challenges of recycling polyethylene from aseptic packaging, alternative materials could replace LDPE. Some potential alternatives include biodegradable plastics, recyclable PE variants, and paper-based packaging. Biodegradable plastics, such as PLA (polylactic acid), are compostable materials that could offer a more sustainable alternative to polyethylene. Recyclable PE variants focus on innovations in polyethylene that make the material easier to recycle and less prone to contamination. Paper-based packaging involves using paperboard with coatings designed for easier recycling, potentially reducing the reliance on multi-material laminates currently used in aseptic packaging.

Despite the environmental benefits of recycling, such as reducing landfill waste and lowering emissions compared to incineration or the production of virgin plastics, several challenges persist. Contamination from food residues, paperboard fibres, and aluminium traces can compromise the quality of recycled polyethylene. In fact, contamination rates average 25%, meaning that one in four items cannot be effectively recycled (Rachelson, 2023). Cleaning processes typically involve water mixed with detergents or corrosive chemicals, necessitating drying and wastewater treatment (Jung et al., 2023). However, some pollutants remain difficult to remove, making contamination a major barrier to efficient recycling.

In addition to contamination, degradation of plastic during the recycling process presents another significant challenge. Repeated thermal, mechanical, and oxidative processing can weaken polyethylene, leading to loss of strength, flexibility, and durability while increasing brittleness (Lancen, 2023). As a result, plastics that have undergone multiple recycling cycles may become unsuitable for reuse in high-performance applications.

To address these issues, several innovative solutions have been developed to enhance the quality of recycled polyethylene. Strategies to reduce contamination include the use of self-cleaning plastic films to minimize food residue adhesion, thereby reducing the need for extensive cleaning (Jung, 2023). Additionally, optical scanning systems capable of detecting contaminants in the PE stream can help redirect contaminated materials for further cleaning (Pawelec, 2024; Tomra, n.d.).

Optimized washing procedures with controlled conditions and temperatures have also been shown to effectively remove organic residues, improving the purity of recycled PE (Bichler et al., 2024).

To mitigate degradation, the incorporation of nanoparticles into recycled polymers has been explored, with graphene nanoparticles demonstrating the ability to enhance mechanical strength and resistance to further degradation (Kharmoudi et al., 2024). Another promising approach is reactive extrusion, in which reactive agents are introduced during the extrusion process to repair broken polymer chains, increasing the molecular weight and improving the properties of recycled polyethylene (Kari et al., 2024).

# Appendix M11: Pyrolysis overview

Pyrolysis is operated under heat and in the absence of oxygen. The process uses plastic wastes as feedstock and converts them into oil, gas and char. The different phases of end products simplify the separation process. Gas and char produced can be combusted through the heat generated during pyrolysis to input energy back to the system for the temperature of pyrolysis to be maintained, self-sustaining the reaction. It has been shown that char combustion to sustain the reaction has a lower emission and environmental impact compared to char activation for other uses since it does not require additional energy and input resources (Garcia-Garcia, 2024).

The oil produced through pyrolysis has a high calorific value, with an energy output comparable to diesel. Even though the combustion of pyrolysis oil is found to release more nitrogen oxides and carbon emissions, the replacement of diesel can still be necessary as the process of diesel production relies on non-renewable fossil fuels as one of the sources and it involves in many other processes such as drilling and fracking that can be damaging to the environment. The primary aim of pyrolysis is to handle plastic wastes while minimising the impact on the environment. The study by Garcia-Garcia et al. (2024) measures the life-cycle environmental impact of four scenarios. Scenario 1 to 3 involve pyrolysis, followed by either char combustion or activation with carbon dioxide or potassium hydroxide. Scenario 4 involves conventional methods such as landfilling. Their result shows that pyrolysis is found to be more sustainable than landfilling and therefore it does not only address the challenge of energy recovery but also the processing of plastic waste.

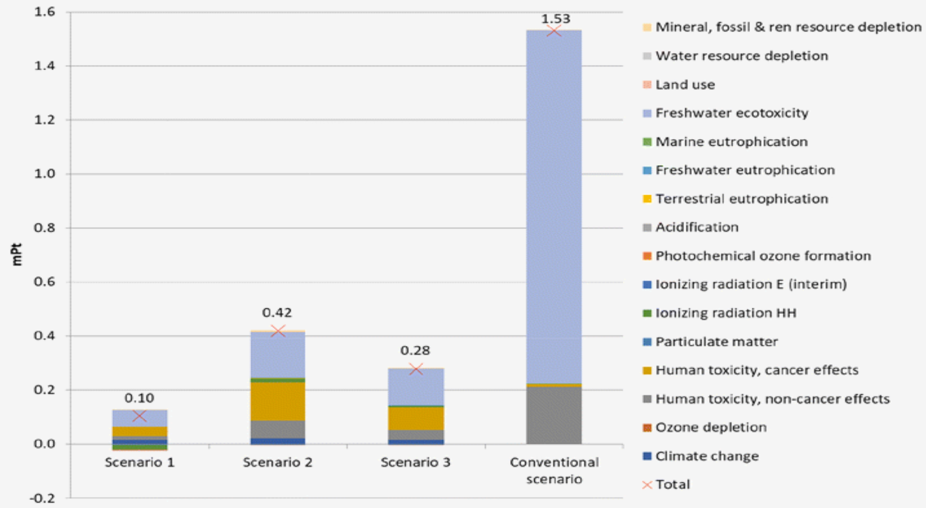


**Figure 2.** Normalised life-cycle environmental impact results of pyrolysis-based and conventional scenario (Garcia-Garcia et al., 2024)

A study that investigated the thermal pyrolysis of polyethylene, a high liquid oil yield of 95 wt% is found when using a fixed-bed reactor at 500°C under a heating rate of 10°C per minute. If the reactor is operated at a lower temperature, although the yield decreases, the oil will contain more alkanes which are stabler and more suitable to be used as fuels (Cheng, 2020). High pressure has also been discovered to increase the yield. In catalytic pyrolysis, the use of compatible catalysts such as zeolites also lowers the energy requirement, which addresses the challenge of high energy required over a long reaction time as well as resulting in a higher yield of desirable fuels (Paavani, 2024).

A research by Budsaereechaia, Hunt, and Ngernyen (2019) has shown that as the heating rate increases, the oil yield from thermal pyrolysis decreases. Low heating rate with an optimum being 10°C per minute is found to enhance the oil yield. The oil yield of catalytic pyrolysis can exceed the yield of thermal pyrolysis when highly acidic catalyst like bentonite, as its strong acidity promotes the decomposition of waxes into lighter products. In contrast, pyrolysis with less acidic catalysts like zeolite tends to lead to wax production, which reduces the yield. Furthermore, the use of catalyst is discovered to increase the calorific value and the flash point of the oils produced to levels that are comparable to commercial fuels.

The optimum catalyst to plastic waste ratio is found to be 0.05. The results from studies also demonstrated that further increases in the amount of catalyst above the optimum does not contribute to yield and fuel properties. When low-density polyethylene and high-density polyethylene are used as the feedstocks for both catalytic and thermal pyrolysis, the resulting pyrolysis oils contain compounds that are similar to those found in diesel, and their FTIR spectra are observed to be more than 96% similar to diesel, as shown in figure 3.

| Type of plastic waste | % Similarity with diesel | | % Similarity with gasohol 91 | |
|---|---|---|---|---|
| | No catalyst | Catalyst | No catalyst | Catalyst |
| PS | 17.90 | 20.75 | 63.20 | 66.35 |
| PP | 86.18 | 87.63 | 58.67 | 61.01 |
| LDPE | 96.89 | 96.08 | 56.78 | 62.80 |
| HDPE | 96.75 | 96.53 | 56.95 | 62.75 |

**Figure 3.** FTIR spectrum similarities between pyrolysis oils and commercial fuels (Budsaereecha§ia, Hunt, and Ngernyen, 2019)

Pyrolysis oils derived from catalytic and uncatalysed pyrolysis have also been tested to run engines in the study by Budsaereechaia, Hunt, and Ngernyen (2019). Although carbon dioxide emissions are higher when pyrolysis oil is used compared to diesel, carbon monoxide emissions are lower when operating an engine with catalytic pyrolysis oil. The difference in performance between non-catalytic and catalytic pyrolysis oils was also evaluated. Carbon monoxide and carbon dioxide released were lower when using oil derived from catalytic pyrolysis compared to thermal pyrolysis during engine operation. However, they both are found to be able to generate engine power that is comparable to diesel, as shown in figure 4.

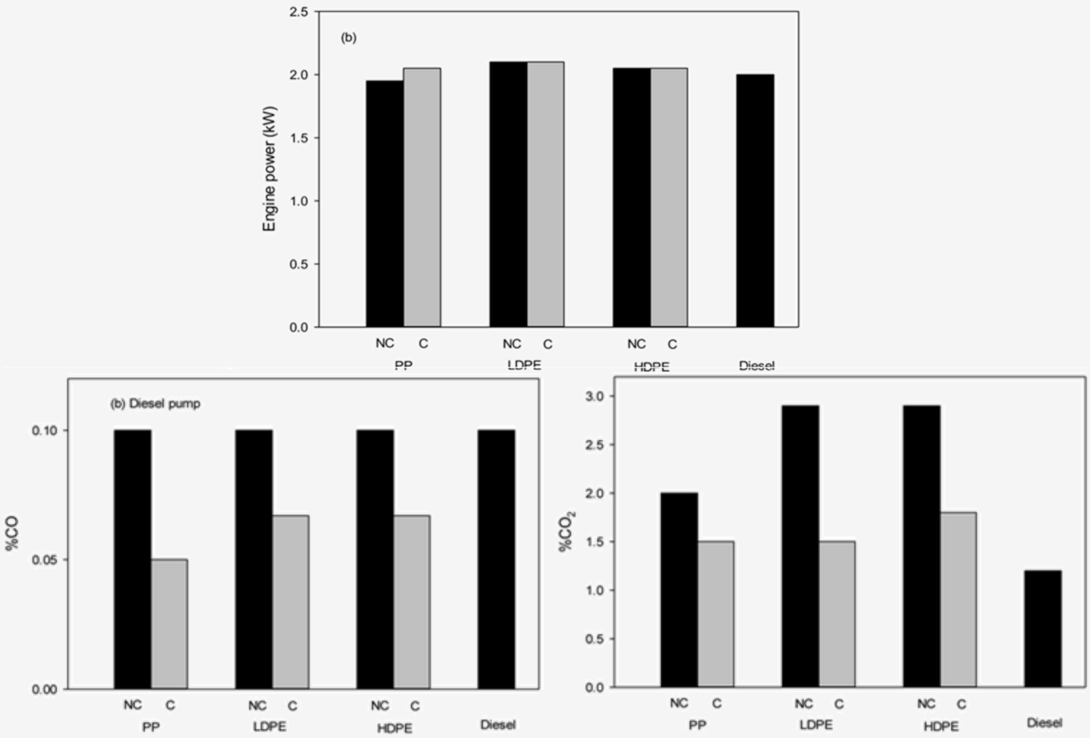


**Figure 4.** Carbon monoxide and carbon dioxide emissions, and engine power achieved at 2000 rpm when using pyrolysis oils and diesel to operate an engine (Budsaereechaia, Hunt, and Ngernyen, 2019)

The key challenge of pyrolysis lies in its scalability, high upfront and operational cost despites its production of useful products and environmental benefits. A study by Fivga and Dimitriou (2018) estimated the costs involved in the pyrolysis oil production. The capital investment was found to be £999,492 per unit, where one unit corresponds to a pyrolysis plant with a capacity to process 100 kg of plastic waste per hour. The total operating costs were £416,325 per unit each year, while the fuel production costs and sale price were 0.87 £/kg and 0.55 £/kg, respectively, indicating that at this plant capacity, the process is not economically viable. Nonetheless, their cost estimation methodology suggested that as plant capacity increases, the pyrolysis fuel production costs per kilogram decreases, as shown in figure 5.

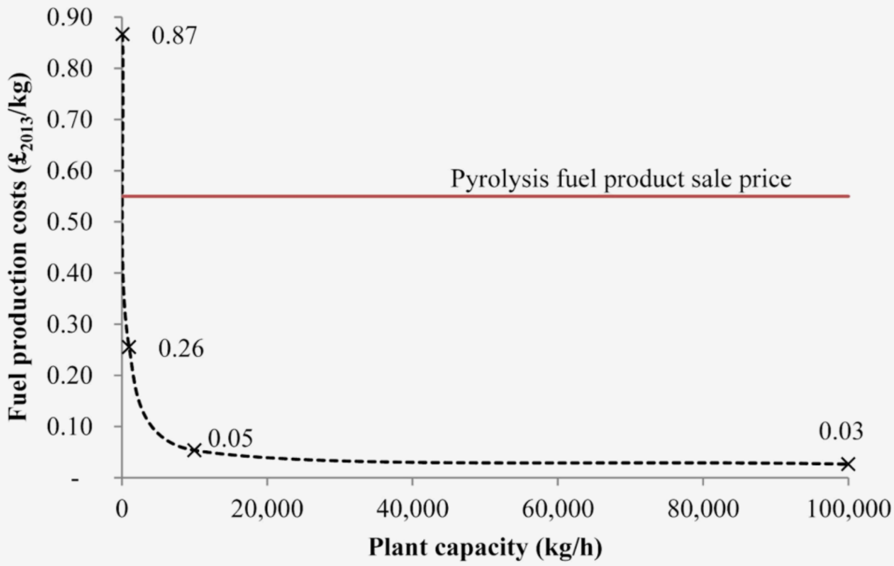


**Figure 5.** Fuel production costs of pyrolysis at different plant capacities (Fivga & Dimitriou, 2018)

Their study also examined whether pyrolysis is an economically feasible approach by estimating the net present value (NPV) of a pyrolysis plant. An investment is considered as profitable when NPV>0. Their findings suggested that although a plant with greater capacity requires higher upfront costs, it also leads to a shorter break-even period. A plant with a capacity of 100,000 kg/h was estimated to break even and have a positive NPV of £3,454,892 within one year, whereas a plant with a capacity of 100 kg/h had a negative NPV even after 20 years.

The economic viabilities of thermal and catalytic pyrolysis were also compared and evaluated by a previous study (Osung & Alibi, 2022). The addition of catalysts resulted in higher operating costs for the catalytic plant compared to the thermal plant. Although the NPV of thermal plants processing 20,000 tons of plastic waste per year was higher than the catalytic plants, both types of pyrolysis plants had positive NPVs, indicating profitability at this capacity. However, their results also demonstrated that the cost per unit of production for the catalytic plant decreases more rapidly than the thermal plant. The catalytic plant also produces higher quality fuel. This indicates that the catalytic plant becomes more economically efficient at larger capacities.

Previous studies have shown that the capacity of a pyrolysis plant has a significant impact on its economic feasibility. At intermediate capacities, thermal pyrolysis tends to have a higher profitability, whereas at larger capacities, catalytic pyrolysis demonstrates a better economies of scale. This aligns with its environmental advantages as well, since catalytic pyrolysis has a lower environmental impact than thermal pyrolysis. Future research could explore alternative reactor designs compatible with both types of pyrolysis to further reduce costs, and investigate whether there is an optimal proportion of thermal and catalytic pyrolysis that maximises the yield and minimises the environmental impact.

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