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Sustainable Business in Biofuels

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About SGFIN

The Sustainable and Green Finance Institute (SGFIN) is a research institute established by National University of Singapore (NUS). SGFIN aims to develop deep research capabilities in sustainable and green finance with a focal point on Asia, and to provide thought leadership and shape sustainability outcomes in policymaking across the financial sector and the economy at large. Supported by exceptional domain experts across NUS, SGFIN equips businesses with critical cross-disciplinary knowledge, training, and toolkits to integrate sustainability dynamics into their business strategies and investment decisions to better quantify the environmental and social impacts of their business developments, operations, products, and services. In essence, SGFIN seeks to help companies embed sustainability as a key pillar in their business decisions.

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Foreword

It is my pleasure to present this whitepaper on the *Sustainable Business in Biofuels*; SGFIN's important contribution to the clean energy and biofuel sector. Amid the rising urgency to mitigate climate change, the search for reliable and scalable alternatives to fossil fuels has become more pressing than ever. Biofuels offer a pathway to decarbonise hard-to-abate sectors. However, despite their potential, biofuel producers continue to face challenges like high capital intensity, feedstock volatility and policy uncertainty. These barriers have often limited the inflow of private capital to the sector, constraining its potential to scale.

As the world moves toward net-zero commitments, Southeast Asia and other emerging regions must navigate the dual challenge of growing their economies while reducing dependence on fossil fuels. Biofuels, if effectively financed and supported, can be part of this solution. This paper, therefore, serves as a practical guide for biofuel producers, investors, and policymakers seeking to understand both the opportunities and gaps in the biofuel value chain.

The development of this whitepaper is the culmination of two years of dedicated research efforts led by Associate Professor Weina Zhang and her team, in collaboration with experts from the biofuel industry. This paper provides producers and potential financiers with a clearer view of the prevailing biofuel business models, risk-return profiles, and current financing landscape. It also examines how supportive policy frameworks like subsidies, tax incentives and mandates can provide more favourable ecosystem to reduce risk and enhance the sector's investment viability.

We hope that the insights presented here will stimulate constructive dialogue, catalyse innovation, and inform decisions that accelerate sustainable growth in the biofuel sector. The journey to a cleaner, more resilient energy future requires bold collaboration between the biofuel industry, financiers, and the policymakers. I am confident that this paper is an important step in advancing that collective agenda.

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Executive Summary

Biofuels have emerged as a crucial component in global efforts for energy transition and decarbonisation, especially in the transportation sector. Yet, their scalability potential remains constricted by high costs of production, intensive technological challenges, an ever-changing regulatory landscape, and sustainability challenges. As such, efforts in this space must be directed towards scaling and commercialising the biofuels in a more financially and environmentally sustainable manner.

This whitepaper aims to support the efforts towards this desired state, equipping stakeholders in the biofuel industry with the knowledge on key gaps and opportunities within biofuels' business models, financing, and policy landscapes.

For the biofuel industry to scale, both a scalable business model and sufficient capital resources are necessary. Through a comprehensive landscape analysis of the businesses in the sector, we highlight non-traditional revenue diversification sources and circular business model opportunities from by-products that can enhance revenue generation, cost efficiency, and operational synergies. Complementing this, case studies of three companies are presented to demonstrate the diversity of plausible business models within the biofuels industry.

On the other hand, biofuels companies are exposed to a multitude of risks. We identify the key risks and assess how they evolve across the lifecycle of a biofuel company, for each biofuel generation. Furthermore, we highlight the financing gaps that persist within private capital markets, where the risk-return trade-off remains disproportionately weighted towards risk, undermining the confidence of private financiers. Concessionary capital is thus required to de-risk the general financing structure of biofuel businesses. As such, the whitepaper posits the support of government policies in de-risking the sector and providing the foundation for a conducive demand-supply environment required to scale the biofuels industry to its full potential.

Through the findings presented, it is hoped that this whitepaper can assist in simplifying biofuels businesses' value propositions, attracting capital to address financing gaps, and helping to transition the global economy toward the adoption of cleaner energy.

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1 Introduction

The economic growth and rapid growth of the world's population have been driving up energy demand globally for decades. Today, fossil fuels still dominate the energy mix, accounting for around 80% of the supply, with the transport sector alone accounting for about % of the demand. At current rates of exploitation, oil and coal reserves are projected to be depleted by 2070 to 2080 (Moodley, 2021), demonstrating that continued dependence on fossil fuels is not viable in the long run. Additionally, the transportation sector accounts for about 37% of global greenhouse gas (GHG) emissions (UNEP FI, 2024), and remains highly dependent on fossil fuels, which supply approximately 95% of its energy needs (RHG, 2024).

Biofuels are gaining traction as a substitute for conventional fossil fuels due to their flexible and sustainable nature (OECD/FAO, 2023). Biofuels, derived from organic materials such as crops, algae, and waste, represent a renewable energy source and offer a pathway to reduce reliance on finite fossil resources. According to the International Energy Agency (IEA), the global demand for biofuels is projected to rise by 23% by 2028 (IEA, 2024a). This growth is anticipated due to advancements in transportation technology, higher blending mandates, and increased consumer demand (OECD/FAO, 2023). Strategically scaling biofuel commercialisation will be essential to address anticipated energy shortages, meet growing market demand, and, most importantly, mitigate the climate impact from mining and burning fossil-based fuels (Cavelius et al., 2023). In particular, biofuels are known to reduce the carbon footprint of transportation and industry. The IEA projects that biofuels could supply approximately 27% of total transportation fuel by 2050, cutting sectoral emissions by an estimated 2.1 gigatonnes annually (IEA, 2011).

However, unlocking these benefits at scale depends on successful commercialisation, which remains constrained by significant challenges.

First, the economic viability of biofuels remains a concern. High production costs relative to fossil fuels have hindered their competitiveness, particularly in markets with low carbon pricing mechanisms (Tuck et al., 2022). Second, technological challenges hinder the commercialisation of biofuels, especially higher-generation pathways. Advanced conversion technologies are often capital-intensive and not yet widely deployable at scale (IEA, 2023c). Many remain in developmental stages and require substantial investment in research and development (R&D) to achieve commercial maturity. Third, feedstock sustainability presents a dual challenge: ensuring a consistent supply while avoiding conflicts with food security and biodiversity conservation. Studies indicate that first-generation biofuels, which rely on food crops such as corn and sugarcane, have contributed to unintended consequences like deforestation and rising food prices (Searchinger et al., 2008). Fourth, the regulatory landscape for biofuels is fragmented, with varying standards and incentives across jurisdictions. Inconsistent mandates, shifting subsidies, and weak enforcement of blending targets increase uncertainty in demand for biofuels and undermine investors' confidence. The level of policy support that facilitates scalability differs significantly across jurisdictions, with biofuel producers in the United States and Brazil enjoying established infrastructures and policies, while emerging markets often struggle with scalability and cost-efficiency (Goldemberg et al., 2018). Lastly, volatility in global commodity and energy markets amplifies risk for biofuel producers. Fluctuations in oil prices often determine the competitiveness of biofuels; when fossil fuel prices fall, biofuels become less attractive to investors and consumers, discouraging long-term investment and slowing market uptake (OECD/FAO, 2025). Hence, many biofuel ventures face difficulties in securing long-term capital due to the perceptions of uncertainty or long payback periods.

To overcome these challenges, both the supply and demand side have to move their needles: 1) For producers, they need to have a scalable business model for biofuel producers that has consistent streams of demand and supply; 2) And for capital providers, they need to gain confidence in the risk-return profile of the biofuel business to provide the much-needed investment for producers to sustain their business in the long run.

In this whitepaper, we will highlight the opportunities for revenue diversification and cost savings through by-products and operational synergies, which can enhance the scalability and profitability of the biofuel business. If more producers can succeed, this will also help to improve the entire sector's risk-return profile. However, we also know there are still significant risks embedded in biofuel operations. These risks include feedstock risk, revenue stability risk, capital expenditure risk, technological risk and policy risk.

On the other hand, in emerging markets where uncertainties and risks are more pronounced, financiers will play a critical role in sustaining biofuel producers throughout the entire lifecycle of their businesses, from the R&D stage to the mature stage. We will utilise the existing data to identify the key financing gaps faced by producers at different lifecycle stages and provide recommendations for various stakeholders within the ecosystem.

As such, the structure of this whitepaper is as follows. Chapter 2 offers an overview of the four generations of biofuels, followed by Chapter 3, which examines biofuel business models in detail. It presents a comprehensive mapping of potential revenue and cost streams as well as approaches to adopting circular models. This is followed by three case studies of existing biofuel producers, offering practical insights and lessons. Chapter 4 discusses the five business risks for a biofuel business at various development stages. Chapter 5 examines the sources of capital across different stages and the risk–return profile of each. The analysis highlights financing gaps in the biofuel industry, particularly when producers seek to scale. Finally, Chapter 6 reviews global biofuel policy support and regulations, and compares the levelized cost of energy (LCOE) of biofuels with other clean energy alternatives.

Ultimately, this whitepaper aims to provide producers and potential financiers with a clearer understanding of the biofuel business models, risks, and current financing landscape. It is hoped that not only can this whitepaper contribute towards the scalability of the entire biofuels industry but also move the needle within the biofuels industry towards the more sustainable higher-generation biofuels, thereby encouraging more ambitious biofuel projects that positively impact climate change.

2 What is Biofuel?

Biofuel is a liquid fuel produced from organic matter, such as biomass. It plays a key role in energy transition as a low-carbon alternative for road transportation and hard-to-electrify sectors such as aviation and shipping. This chapter discusses the four biofuel generations and their strengths and weaknesses before looking into four biofuel products commonly used in the market: biodiesel, bioethanol, Sustainable Aviation Fuel (SAF), and maritime biodiesel.

2.1 The Four Generations of Biofuel

Biofuel is classified into four generations based on its feedstock type, with the end products varying depending on the production method and technology used. These biofuel generations encompass a range of sources, from edible crops of first-generation biofuels to algae of the third- and fourth-generation biofuels. Each generation reflects an improvement in production methods and progress in addressing the environmental impacts of biofuel production.

2.1.1 First-generation Biofuel

First-generation (1G) biofuel is produced from edible feedstocks such as corn, wheat, and soybeans (**Figure 1**). These feedstocks would undergo pre-treatment steps like drying, crushing, rendering, and milling before going through fermentation and further chemical processes.

***Figure 1**. Corn and soybean, examples of first-generation feedstock*

Source : Daniela Alchapar (L), Pierre Bamin (R), Unsplash

The first-generation biofuel products commonly used for commercial purposes are biodiesel and bioethanol (Fokaides et al., 2023). Vegetable oils and animal fats undergo transesterification and generate crude Fatty Acid Methyl Esters (FAME) biodiesel and glycerol. On the other hand, bioethanol is produced by fermenting sucrose or starch. Sugarcane juice and starch crops are first mechanically pressed and hydrolysed, respectively, before being fermented and distilled into bioethanol (Sims et al., 2008). In addition, edible feedstocks can be converted to SAF through oleochemical conversion processes such as hydro processing, producing Hydro processed Esters and Fatty Acids (HEFA) (IRENA, 2017).

The first-generation biofuel has simple conversion methods and pre-treatment processes, allowing for scalability and enabling small-scale production (Sims et al., 2008). Furthermore, first-generation biofuels can reduce a nation's dependency on imported energy and increase domestic energy consumption (RFA, 2023). Finally, compared to other biofuel generations, first-generation biofuel has a well-established commercial market, giving it the highest potential for commercialisation.

These strengths are not without weaknesses. Using edible crops to produce first-generation biofuel raises concerns over food security and land use change, contributing to the "food vs. fuel" dilemma. Rising demand may further drive up crop prices, incentivise deforestation for new crop plantations, and generate additional GHG emissions that may outweigh the reductions achieved through biofuel use. Lastly, land constraints linked to this "food vs. fuel" dilemma could restrict the scalability of the first-generation biofuel supply (Cavelius et al., 2023).

Currently, most first-generation biofuels depend on government subsidies to fund their production. The recent increase in the price of vegetable oil and food crops further lowered the competitiveness of biodiesel prices. Various upstream and downstream processing stages also contribute to high production and processing costs. Limited room for cost reduction makes subsidies and government grants indispensable to maintain the first-generation biofuel's market competitiveness (OECD/FAO, 2023). The strengths and weaknesses of first-generation biofuels have been summarised in **Table 1**.

***Table 1**. Strengths and weaknesses of first-generation biofuel*

FIRST-GENERATION BIOFUEL		
Aspect	**Strengths**	**Weaknesses**
Environmental	Reduce reliance on fossil fuels and lower GHG emissions associated with vehicular fuel combustion	Limited GHG emissions reduction in terms of lifecycle emissions if there is any land use change involved
		Land use change results in habitat loss and deforestation
Social	Enhance national energy security by reducing reliance on imported energy	Conflict with food production, thus the "food vs fuel" dilemma
Economic	Readily available raw materials in the form of commonly used feedstocks	High capital and processing costs
	Scalable, producible at a smaller scale	Highly dependent on subsidies and government support
	Established track record in commercial production and global widespread use	
Technological	Widely recognised production methods	–
	Simple pre-treatment processes	

Source: Compiled by authors

2.1.2 Second-generation Biofuel

***Figure 2.** Wood residue*

Source: Photograph by authors

Second-generation (2G) biofuel is derived from non-food feedstocks, wood residues (**Figure 2**), and other waste streams like industrial wastes. Before they are converted to biofuel, the feedstocks are pre-treated (e.g., through drying, briquetting, grinding, pelletising) to enhance the structure, moisture, size, and density (Osman et al., 2021). The biofuel conversion involves two main paths: thermochemical and biochemical. The thermochemical pathway exposes biomass to a controlled atmosphere and heat source, which transforms it into various energy forms (Osman et al., 2021). The conversion methods of this pathway include pyrolysis, gasification, liquefaction, and torrefaction. Pyrolysis heats the biomass in the absence of air, resulting in products like bio-oil. Gasification converts biomass into syngas, a combustible gaseous fuel mixture and intermediary of other products like methanol, dimethyl ether, and Fischer-Tropsch liquid (Fokaides et al., 2023). Liquefaction, deemed to be more energy-efficient than pyrolysis due to its superior physicochemical properties, involves the decomposition of lignin-rich biomass and produces, among other things, bio-crude oil. Torrefaction is an endothermic process that results in products like bio-coal and biochar (Osman et al., 2021).

On the other hand, in the biochemical pathway, feedstocks undergo fermentation under anaerobic conditions. The glucose in organic waste is converted into ethanol or bio-hydrogen via enzymatic hydrolysis, which is saccharified and fermented before being distilled into bioethanol (Fokaides et al., 2023). Similarly, biogas can be produced via anaerobic digestion of wet biomass (Fokaides et al., 2023).

Second-generation biofuel is considered more sustainable than first-generation due to its feedstocks being more abundant, less expensive, and not conflicting with food production (Moodley, 2021). Moreover, GHG emissions related to second-generation feedstock are attributed to original crops, which have been used for other purposes. As such, second-generation biofuel has lower Global Warming Potential (GWP), less land use change, and higher potential for the circular economy (Jeswani et al., 2020).

Nonetheless, second-generation biofuel has several caveats. Removing crop residues can lead to soil degradation and promote the growth of weeds, necessitating the use of herbicides, which are harmful to the environment. Harvesting woody residues can also disturb surrounding habitats and biodiversity (Jeswani et al., 2020). Moreover, feedstocks for second-generation biofuel are biochemically more complex than first-generation, which translates to lower fermentation efficiency. Additional pre-treatment steps are thus necessary, but they incur more production time and costs

(Cavelius et al., 2023). **Table 2** provides a summary of the key strengths and weaknesses of second-generation biofuels.

***Table 2**. Strengths and weaknesses of second-generation biofuel*

SECOND-GENERATION BIOFUEL		
Aspect	**Strengths**	**Weaknesses**
Environmental	Enhance the utilisation of wastes and by-products as part of the circular economy	Excessive removal of crop residues for biofuel production may result in environmental degradation
	Lower GWP than first-generation biofuel	
Social	Minimal conflict with food production	–
	Opportunity for farmers to generate an additional source of income	
Economic	Widely available feedstock, especially from agricultural and food wastes	High capital and processing costs due to extensive pre-treatments
Technological	Technology is mature and ready for commercialisation	More sophisticated technology is required for pre-treatments

Source: Compiled by authors

2.1.3 Third-generation Biofuel

***Figure 3**. Macroalgae a.k.a. seaweed*

Source: Lasse Møller on Unsplash

Third-generation biofuel is also known as "algae fuel" because it is derived from micro- or macroalgae. Microalgae is a unicellular organism while macroalgae is its multicellular counterpart commonly known as seaweed (**Figure 3**), both having high carbohydrate and lipid content (Paravantis, 2022). Algae can be cultivated in an open pond or closed photobioreactor. The former enables the algae to directly capture atmospheric CO_2 for growth and photosynthesis. As such, open system plants are usually located in places with high insolation. While it is more affordable than closed reactor, the closed photobioreactor provides a controlled environment for higher productivity (Abdullah et al., 2019; Cavelius et al., 2023). Harvesting algae also presents challenges, as such organisms are highly sensitive to acidity changes and have low structural density (Cavelius et al., 2023), making the process both complex and resource intensive.

Third-generation biofuel is produced by converting microbial oil derived from algae into biodiesel through transesterification. Algae cells are harvested after reaching maturity and are pre-treated using various techniques to disrupt the cells, such as bead beating and sonication. They then undergo transesterification, where catalysts like supercritical CO_2 are employed to accelerate reaction rate. Transesterified algae cells are washed and refined into end products (Saranya & Ramachandra, 2020) such as biodiesel, SAF, bioethanol, and biohydrogen (Sarangi et al., 2018).

Third-generation biofuel has been gaining traction in recent years due to its potential to address its predecessors' downsides. Algae cultivation requires less intensive land use compared to food crops, does not involve removal of crop residues, and can use salt- or wastewater for cultivation, ensuring that biofuel production would not conflict with food production (Paravantis, 2022). Moreover, as algae requires CO_2 for growth and photosynthesis, it reduces GHG emissions from the beginning of the biofuel's lifecycle, either from atmosphere or from industrial emitters (Cavelius et al., 2023).

However, in its current state, third-generation biofuel production is perceived as costly due to high upfront capital costs, resources, and subsequent maintenance. The algae need specific requirements of energy, water, and nutrients to grow optimally, which increases the production costs. Moreover, although production wastes and resources may be recycled, high energy requirements at downstream processes means that it still needs to rely on fossil fuel, at least in the short- to medium-term (Paravantis, 2022). **Table 3** below presents a summary of the strengths and weaknesses of third-generation biofuels.

***Table 3**. Strengths and weaknesses of third-generation biofuel*

THIRD-GENERATION BIOFUEL		
Aspect	**Strengths**	**Weaknesses**
Environmental	High land-use efficiency	Specific requirements of nutrients, energy, and water to generate a high yield
	Direct CO_2 capture during the cultivation process, leading to a net/negative carbon footprint	High energy inputs are required for the downstream process, necessitating reliance on fossil fuels in the short- to medium-term
	Less dependent on freshwater during the cultivation process	
Social	Minimal conflict with food production and security	–
Economic	High feedstock growth rate with short cultivation time	High infrastructure and production costs
Technological	–	More technological advancement is required to stabilise the harvested algae

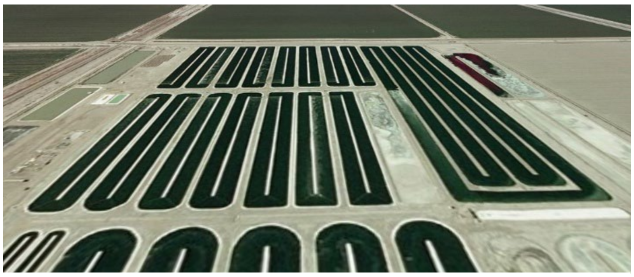
Source: Compiled by authors

2.1.4 Fourth-generation Biofuel

The fourth-generation biofuel relies on genetic modification to enhance feedstock's growth rate, adaptability to survive in poor-nutrient conditions, and efficiency. As such, this biofuel generation is mainly made from algae, whose genes can be easily modified compared to other feedstocks. Many microorganisms (e.g., cyanobacteria, yeast, fungi) can host the heterologous synthesis traits required for biofuel production.

This metabolic versatility diversifies the production pathways and the types of biofuels which can be produced, such as ethanol, modified fatty acids, and butanol (Cavelius et al., 2023). As an example, butanol pathway genes in *Clostridium* can be introduced to the *E. coli* and *Bacillus subtilis* strains to produce butanol. Genetic modification can maximise fourth-generation's algae yield (Paravantis, 2022) and increases its CO_2 intake for photosynthesis, creating an artificial carbon sink which reduces the production's carbon footprint (Abdullah et al., 2019).

Figure 4. *Open pond algae plantation*



Source: Pacific Northwest National Laboratory on Flickr

Like its third-generation counterpart, GM algae can be cultivated in a contained or uncontained system. **Figure 4** illustrates an example of an open pond algae plantation. The contained system minimises environmental exposure and chemical leakage through more controlled conditions but has higher capital and operating costs. An uncontained system (e.g., raceway, open pond) has lower costs but also higher risks of leakage and environmental contamination. (Abdullah et al., 2019).

However, the use of genetic engineering is accompanied by health and environmental risks. GM algae are capable of thriving in poor environments, which raises concerns about threats to human health and the local ecosystem if there is a potential leakage from the production ponds into the surrounding environment. This risk is particularly acute for outdoor cultivation of GM algae, which is more favoured for reasons of cost-effectiveness and scalability. Leaked GM algae may trigger allergies in living creatures, alter the natural habitats, compete with native species, cause horizontal gene transfer, or contaminate areas around the production plants. Moreover, some GM strains may synthesise toxic compounds, contributing to harmful algal blooms and sea surface discolouration, which poses serious threats to biodiversity (Abdullah et al., 2019).

These risks necessitate the enforcement of a stringent regulatory framework to prevent and minimise potential hazards linked to GM algae. For example, the European Union (EU) countries have strict regulations concerning GM products, requiring, on average, 995 days for authorisation, while in the US, it takes around 686 days to approve commercial production of GM crops. These long durations highlight the risk GM algae poses and the need for strong international regulations to be enforced before fourth-generation feedstock can be traded internationally. However, the absence of equivalent international regulations hinders the commercialisation of fourth-generation biofuels (Shokravi et al., 2022).

The lack of technological readiness is another major constraint for fourth-generation biofuels. Genetic modification remains experimentally unproven for many microalgal strains, with only a limited number of wholly sequenced strains currently suitable for fourth-generation biofuel production. Although existing technology still face many unresolved issues, Shokravi et al. (2022) remain optimistic about the future advancement of this biofuel generation. **Table 4** provides a summary of the strengths and weaknesses of fourth-generation biofuels.

Table 4*. Strengths and weaknesses of fourth-generation biofuel*

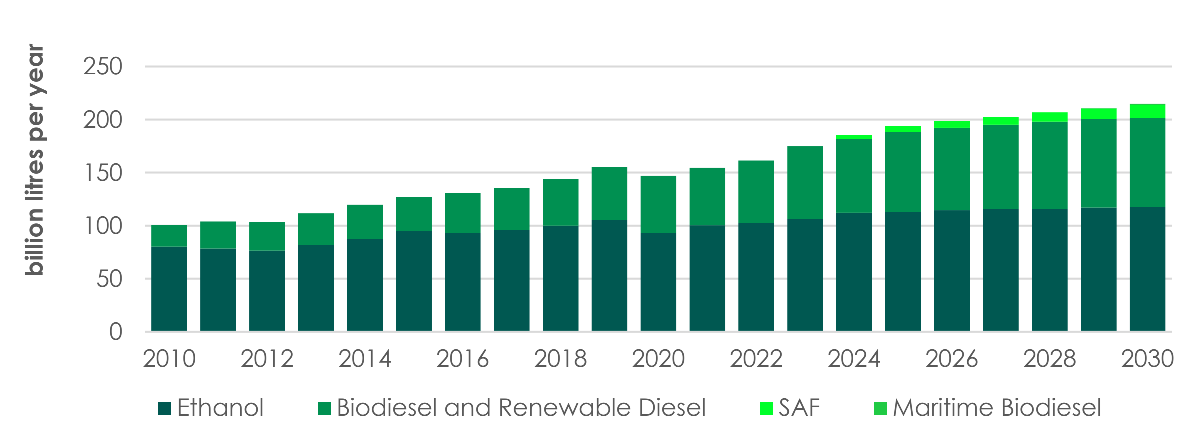
FOURTH-GENERATION BIOFUEL		
Aspect	**Strengths**	**Weaknesses**
Environmental	Produce biofuels with low lifecycle GHG emissions	Potential risks caused by leakage, e.g., changes in the natural habitat of protected species, competition with native species, toxicity, and horizontal gene transfer
Social	–	Public health threat as certain GM microorganisms trigger human allergies and infection
		Potential opposition from consumers and society
Economic	Higher yield due to genetic engineering	Still at an early development stage and requires massive investments for it to be commercially viable
		Additional costs to implement biosafety measures
Technological	–	More experiments and research are needed for safe large-scale production

Source: Compiled by authors

2.2 Biofuel Products and Their Market Overview

Biofuel demand is set to increase by 38 billion litres over 2023-2028, nearly 30% higher than the previous five-year period, and reach 215 billion litres a year by 2030 (see **Figure 5**) (OECD/FAO, 2023). Ethanol, biodiesel, and renewable diesel are expected to account for 94% of this demand, with SAF making up the rest (IEA, 2024). Biofuel demand is projected to rise faster in developing countries like Indonesia, India, and Brazil. These countries have robust biofuel policies, rising transport fuel demand, strict blending requirements, and abundant feedstock potential, which create a conducive environment for biofuel production and use (IEA, 2023b). For instance, sugarcane-based ethanol is projected to contribute towards India's target of an E16 blending rate by 2025 (OECD/FAO, 2023). In comparison, the demand for SAF and maritime fuel remains minimal but is gradually increasing, driven in part by legislation such as ReFuelEU Aviation in Europe that sets minimum blending requirements for SAF (IEA, 2024).

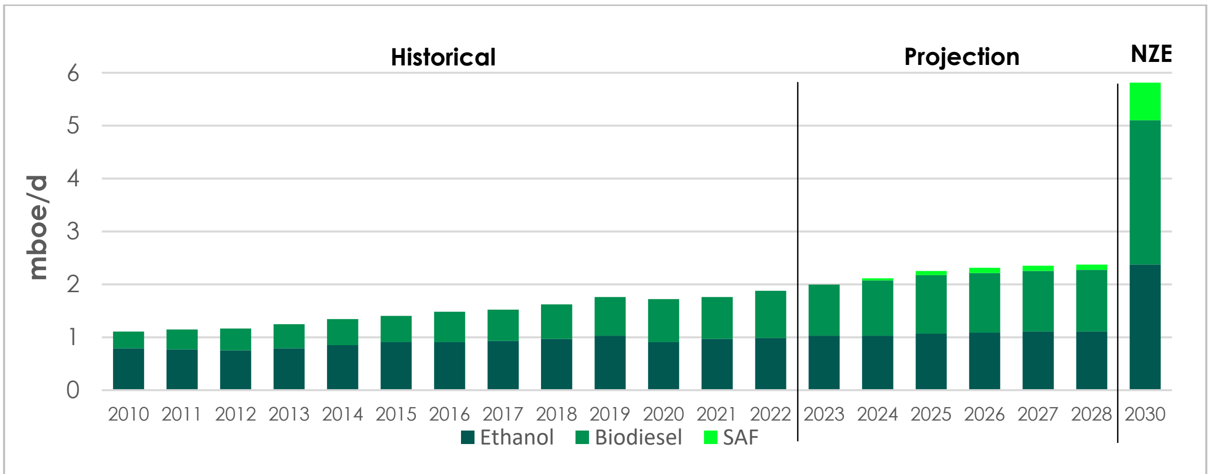
***Figure 5**. Global biofuel demand by fuel type*



Source: IEA, 2024

Despite positive trends from the demand side, more efforts are needed from the supply end to meet it. The IEA estimates that the world must p projection biofuels amounting to 6 million barrels of oil equivalent daily (mboe/d) by 2030 to achieve net zero by 2050 (see **Figure 6**
Figure 6), triple the amount of 2022 global daily production output (IEA, 2023a). As such, biofuel-producing nations must accelerate the development of their biofuel production lines to meet the future demand. In addition to backing biofuel production with advanced technologies and pushing for the use of second and third-generation feedstocks to avoid conflict with food production (IEA, 2023b), these countries can introduce increasingly higher blending rate mandates and tax incentives to support the growth of biofuel production (IEA, 2023a).

***Figure 6**. Global biofuel production outlook from 2010 to 2030 by fuel type in the "Net Zero by 2050" Scenario*



Source: IEA, 2023a

2.2.1 Product #1: Biodiesel

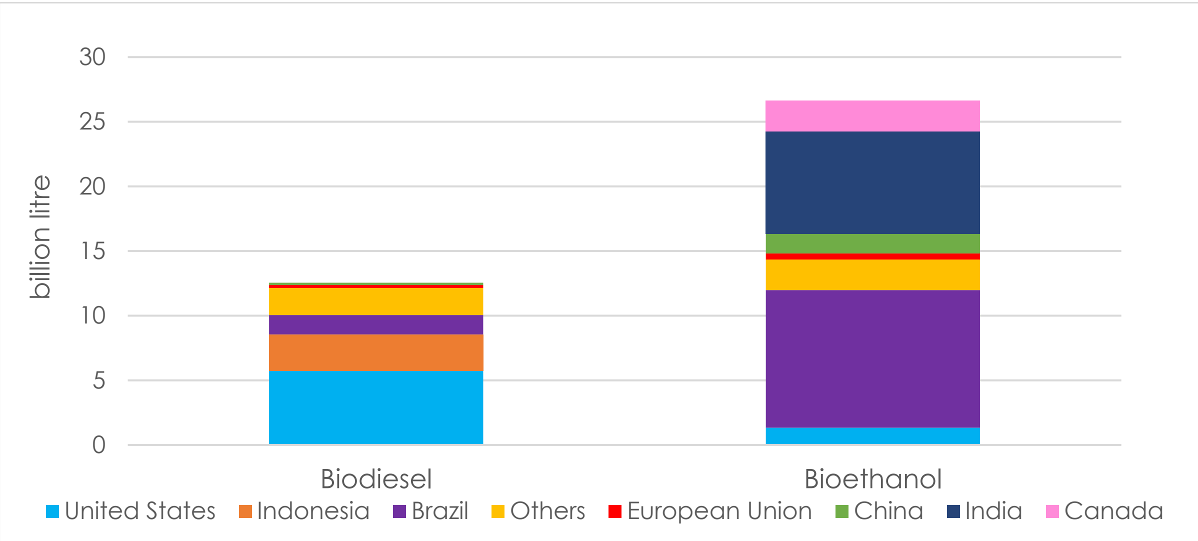
Biodiesel, a renewable substitute for petroleum diesel, is commonly blended with conventional diesel to meet fuel and vehicle specifications. The blending ratio is indicated by the naming convention B(X), where (X) denotes the proportion of biodiesel mixed with petroleum-based diesel.

B5, a blend of 5% biodiesel and 95% diesel, is often the biodiesel used for conventional vehicles due to their specifications. On the other hand, low biofuel blends like B2 are deemed suitable only for compression-ignition engines that use petroleum diesel, such as light-duty diesel cars (EERE, n.d.-a). Higher biodiesel fuel blend (e.g., B20) is only used in heavy-duty vehicles such as trucks and buses (Hsieh & Felby, 2017). Approximately 70% of global biodiesel production in 2022 still relied on first-generation feedstocks: palm oil (29%), soybean oil (23%), and rapeseed oil (14%). Used cooking oil, a second-generation feedstock, accounted for 25% with the rest using the third-generation algal-based feedstocks (OECD/FAO, 2023).

Other than road transport, biodiesel can also be used for rail transport (McCormick & Moriarty, 2023). B20 is compatible with most locomotives today. Further research is ongoing to test the compatibility of higher biofuel blends for rail transport (McCormick & Moriarty, 2023).

The biodiesel market is relatively stable compared to other biofuel products (OECD/FAO, 2023). When the global fuel use dropped due to the COVID-19 pandemic, the biodiesel market was less impacted thanks to higher blending requirements, tax credits, subsidies, and decarbonisation initiatives. Policies and government incentives contributed to the projection of high biodiesel consumption growth in the United States and Indonesia. Overall, global biodiesel use is expected to grow 12.55 billion litres by 2032, as depicted in **Figure 7** (OECD/FAO, 2023).

***Figure 7**. Projected biodiesel and bioethanol consumption growth by 2032*



Source: OECD/FAO, 2023

2.2.2 Product #2: Bioethanol

In 2022, bioethanol constituted the largest share of global biofuel production, 60% of which used maize as feedstock, 23% sugarcane, 7% molasses, 3% wheat, with the rest relying on cassava, other grains, or second- and third-generation feedstocks (OECD/FAO, 2023). Strengths of bioethanol as a petroleum-gasoline substitute include its quick biodegradation and lower GHG emissions during combustion. Gasoline with bioethanol blends has lower hydrocarbon emissions by up to 20% at high load and high-speed conditions, and lower NO_2 emissions by 40% at partial load (Aggarwal et al., 2022). Similar to biodiesel, bioethanol has a naming convention of E(X), where (X) denotes the proportion of bioethanol mixed with conventional fossil fuel.

Bioethanol can be used either as a fossil fuel blend (e.g., E10, 10% bioethanol and 90% gasoline) or as a stand-alone fuel (e.g., E100). E10, also known as gasohol, is compatible in most modern vehicles and light trucks without any modification to the engine and fuel systems. On the other hand, E85 is widely used for flexible fuel vehicles (FFVs) and variable fuel vehicles. Many automobile manufacturers offer vehicles that are compatible with 100% gasoline, E85, or any fuel blend up to E85 (Aggarwal et al., 2022).

Stability of bioethanol blends is among the most challenging obstacles that prevent their wider use. Bioethanol blends tend to absorb water and induce corrosion, leading to a significantly short shelf life. A stabiliser is essential to store fuel blends for more than two to three months (Aggarwal et al., 2022). Furthermore, bioethanol is not compatible with conventional marine vessels and rail engines because they are diesel-based.

Like biodiesel, bioethanol production is also policy-driven, with its projected growth driven by increasing blending mandates and fiscal incentives from the government. For instance, the highest projected growth in Brazil (see **Figure 7**) was driven by a combination of a mature FFV industry and RenovaBio regulation. India also has progressive blending mandates, with an E10 mandate in 2022 and an E20 mandate to be applied by 2030. The overall growth of bioethanol consumption is predicted at around 26.63% globally (Bacovsky et al., 2022; OECD/FAO, 2023).

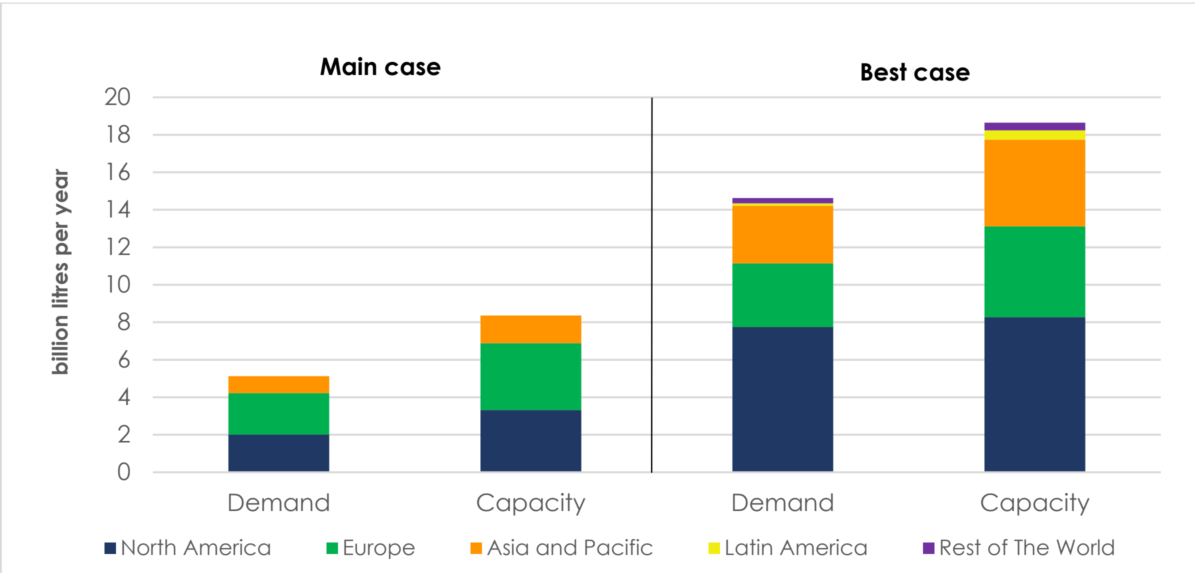
2.2.3 Product #3: Sustainable Aviation Fuel (SAF)

Sustainable Aviation Fuel (SAF), or Bio-jet fuel, is a substitute for the fossil-derived conventional jet fuel (CSIRO, 2023). It can be derived from a wide range of feedstocks from all generations of biofuels. There are four pathways to produce SAF. The HEFA pathway involves oleochemical conversion processes using lipid feedstocks (e.g., algae, used cooking oil (UCO), oilseed crops), while the Fischer-Tropsch (FT) pathway uses thermochemical conversion and syngas as an intermediary. Synthesised Iso-Paraffinic (SIP) pathway's SAF are derived from biochemical conversion. Finally, the

Alcohol to Jet (ATJ) pathway utilises hybrid thermochemical and biochemical technology using ethanol as an intermediary (CSIRO, 2023; IRENA, 2017).
However, currently, unblended pure SAF cannot be used directly by aircraft. SAF must be blended with conventional jet fuel with ratios up to 50% to ensure compatibility with existing aircraft, engines, and fuel infrastructures. Within this limit, certain pathways face additional restrictions: for example, synthetic iso-paraffins (SIP) fuels are currently approved for blending at a maximum of 10% (EERE, n.d-b). As such, while SAF offers a promising pathway to decarbonise the aviation industry, technical and regulatory constraints mean it cannot yet fully replace conventional jet fuel. At present, only HEFA SAF can be produced at a large scale by a handful of commercial-scale facilities, making it most feasible for commercialisation (IRENA, 2017).

Globally, SAF demand is expected to increase to approximately 5 billion litres, which will contribute 1% of overall jet fuel supplies by 2028 (see **Figure 8**). This growth is mostly contributed by the US, Europe, and Japan due to their strong policies and enforcement. Other countries like Brazil, India, Indonesia, Singapore, and the United Kingdom are also considering enhancing their SAF blending and policies. If this positive trend is realised, the earlier projection could triple, amounting to 15 billion litres or 3.5% of global SAF supply, as shown in the best case scenario of **Figure 8** (IEA, 2024).

***Figure 8**. Projected SAF demand and capacity growth, 2023–2028*



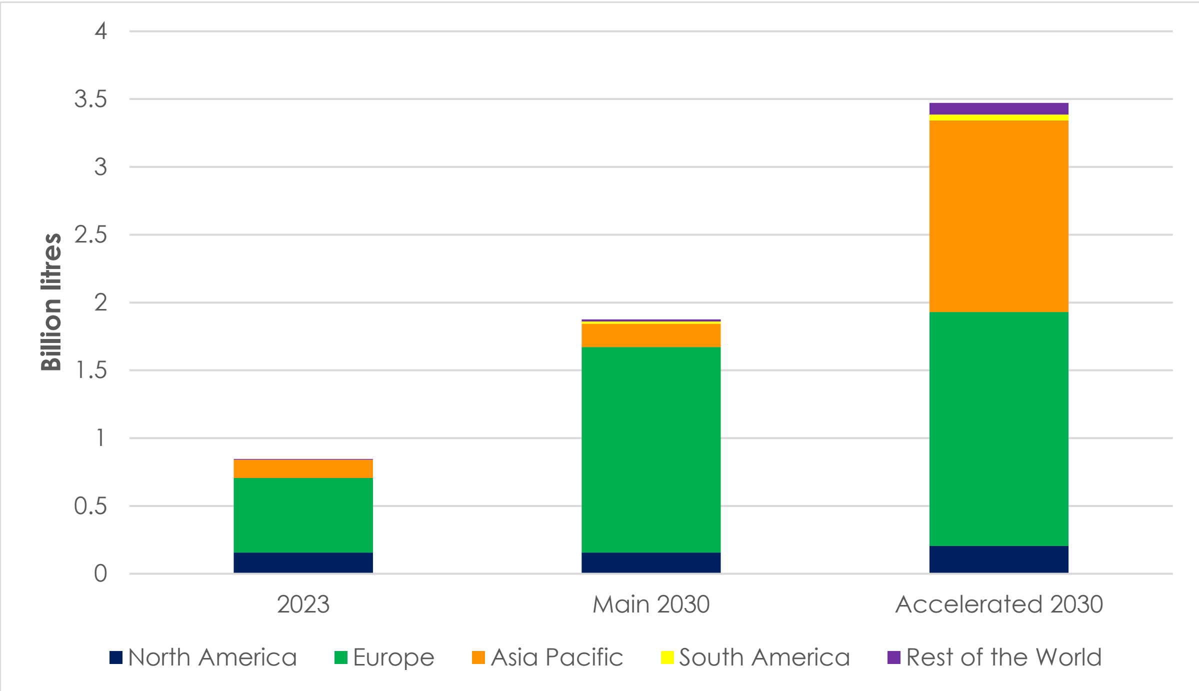
Source: IEA, 2024

2.2.4 Product #4: Maritime biodiesel

Maritime biodiesel is an alternative to the traditional fuel used for maritime transport. According to the International Energy Agency (IEA, 2024), global maritime biodiesel consumption is projected to reach 1.8 billion litres by 2030. This growth is primarily attributed to the FuelEU Maritime initiative, which came into effect on 1 January 2025 and mandates a 2% reduction in the carbon intensity of marine fuels (ABS, n.d.). Under this regulation, ships operating within the European Union (EU) must use fuels with GHG intensity (measured in gCO_2e/MJ) below a specified threshold that will progressively tighten until 2050. This policy incentivises shipping companies to increase the share of renewable and low-carbon fuels in their energy mix.

Under the main case, by 2030, global maritime biofuel consumption is expected to increase to around 2 billion litres (**Figure 9**), with Europe being the main driver, as Europe must comply with the regulations by FuelEU Maritime. Europe is likely to increase its consumption by 1 billion litres. In the Asia-Pacific region, maritime biodiesel consumption is also set to rise significantly, nearly doubling its 2023 level, as the effects of FuelEU Maritime extend beyond the EU. Given that many of the world's largest ports, including Shanghai, Singapore, and Shenzhen, are located in Asia (WSC, n.d.), vessels traveling between the EU and Asia will increasingly require compliant marine biofuels, especially at major bunkering hubs. This regulatory spillover is expected to drive up biofuel demand in Asia.

Figure 9*. Projected maritime biodiesel consumption growth*



Source: IEA, 2024

In summary, biofuels are classified into four generations, with the first generation being the most utilised. Subsequent generations aim to mitigate environmental concerns and drawbacks associated with previous ones. However, scaling up biofuel production from later generations requires further technological advancements and research. The primary biofuel products across all generations include bioethanol, biodiesel, SAF, and maritime biodiesel, which are increasingly being used as blends in road, rail, marine, and aviation fuels. Despite rising demand and supply of biofuels, significant efforts are required to expand their utilisation and effectively contribute to global carbon emissions reduction.

3 Business Models of Biofuel

This chapter discusses the possible revenue and cost streams available to entities involved at any stage of biofuel production. The coverage of this chapter includes both end-to-end biofuel operators and other entities that engage in biofuel-related activities as part of a broader business. The findings in this chapter are based on a landscape analysis we performed on 2,204 biofuel-related companies listed on Pitchbook, highlighting the common business models adopted by these entities.

This chapter is designed to apply to both financiers and project developers. For financiers, it aims to present **a holistic picture of the various business models** that any biofuel-related entity can adopt, enhancing their understanding of this complex ecosystem. For project developers, it highlights opportunities for **revenue diversification and cost savings**, helping to identify additional pathways for value creation and scalability that can reduce producers' cashflow risks, therefore potentially increasing the confidence of prospective financiers.

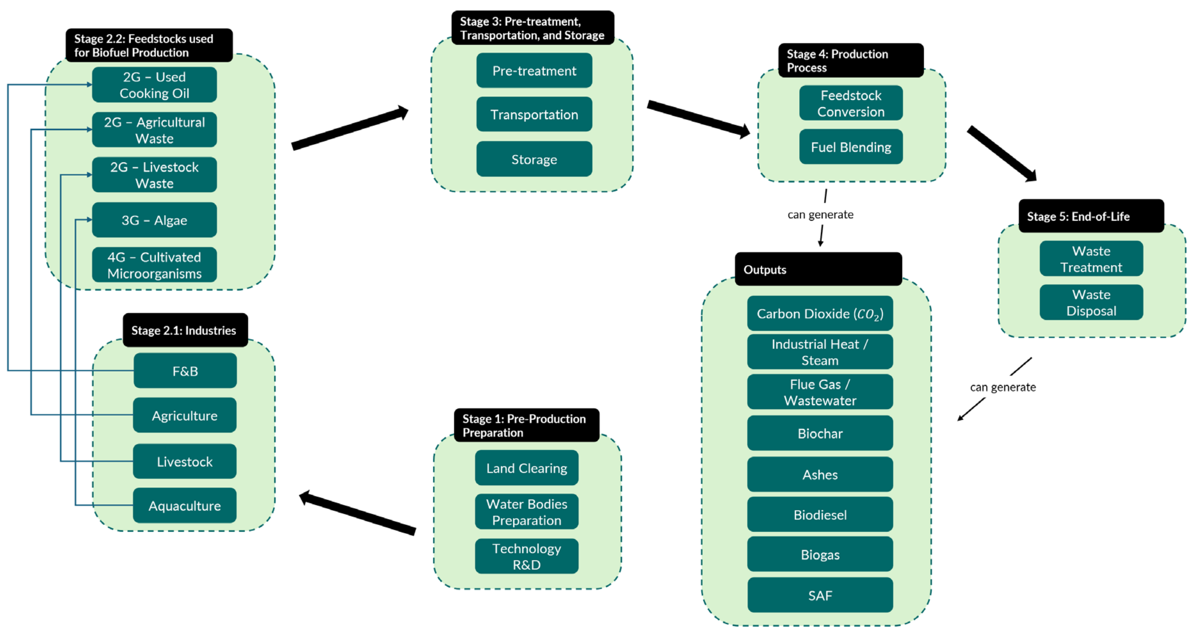
In section 3.1, we examine both the **traditional and non-traditional revenue and cost streams** associated with the **full chain of biofuel production line** – thereby highlighting the full range available to an end-to-end biofuel operator and the partial streams accessible to entities engaged in only specific stages of the value chain. Following, in section 3.2, we explore further opportunities to **diversify revenue sources** from products and by-products and **achieve cost savings** through **circular business models**. In the same section, we also identify **entry points** for **entities from other business lines and industries** that would like to leverage their existing capabilities and products to enter the biofuel ecosystem.

As a structure to the discussion of revenue and cost streams in this chapter, we utilize the stages of the common value chain of a biofuel production line and attempt to map each revenue and cost stream to its most relevant stage. Generally, the full value chain of a biofuel production line can be segregated into five distinct parts, as shown in **Figure 10** on the next page.

1. **Pre-production preparation** – This stage covers the mobilisation of natural and technological resources required to support future feedstock cultivation activities. This includes the initial development of land/water bodies required for feedstock cultivation, as well as the research and development of technology, prior to any feedstock cultivation.
2. **Feedstock cultivation and sourcing** – This stage can comprise of two scenarios, dependent on how the biofuel producers procure their feedstock. Firstly, biofuel producers can obtain their feedstock from other industries that produce them, the scenario reflected by the link from Stage 2.1 to Stage 2.2 in **Figure 10**. On the contrary, biofuel producers might also generate the feedstock themselves, for example through own agricultural or livestock operations, thereby skipping over Stage 2.1 and jumping straight to Stage 2.2 in **Figure 10**.

3. **Pre-treatment, transportation, and storage** - This stage includes the pre-treatment required to convert the feedstock into a form ready for conversion to biofuel and covers up to the storage and transportation of the pre-treated feedstock to the refinery for conversion to biofuel.
4. **Production process** – This stage includes all processes within a biofuel refinery to convert, blend, and produce biofuel products and by-products. Common processes include anaerobic digestion, pyrolysis, and hydroprocessing**.**
5. **End-of-life** – This stage includes all operations that manage waste, residues, and emissions from refinery operations. End-of-life operations could also produce by-products such as flue gas, wastewater, or ashes.

Figure 10*. Common Value Chain of a Biofuel Production Line*



Source: Compiled by authors

3.1 Revenue and Cost Streams of a Biofuel Production Line

The following discussion identifies the common revenue and cost streams associated with each stage of the biofuel value chain, based on our landscape analysis. While not exhaustive, it outlines the availability of **alternative, non-traditional revenue streams** beyond the sales of biofuel products at the end of the value chain, especially for newer biofuel generations. These streams can be capitalised upon to **diversify revenue sources** and **generate supporting revenue** to enhance financial resilience, especially in their early operational years.

3.1.1 Pre-Production Preparation

Pre-production preparation is the first stage of the biofuel value chain and refers to the mobilisation of natural and technological resources required to support future feedstock cultivation activities.

Pre-production preparation is often **capital expenditure-intensive,** driven by the possible need for research and development, as well as the establishment of physical infrastructures to cultivate feedstock. For land-based 1G and 2G projects, this typically includes land preparation and agricultural system development, especially if they produce their own feedstock. In contrast, 3G and 4G projects are more research-intensive, requiring significant upfront investment in laboratory facilities, pilot trials, and technological developments. Additional costs may also arise from land and water acquisition rights, as well as conducting environmental and social impact assessments before project initiation.

While revenue opportunities might be limited at this stage, we have identified two potential non-traditional revenue sources. Firstly, projects that involve clearing land or water bodies may generate income from the **sale of pre-existing biomass**, such as unused timber and crop residues, that is not needed for future operations. Secondly, under some jurisdictions, **subsidies and grants** are available for initiatives that rehabilitate infertile or degraded land. For instance, India provides monetary incentives for projects that cultivate jatropha for biodiesel use on arid, non-fertile land (Advance Biofuel, n.d.). **Table 5** organises these potential streams into value items for inclusion in a cashflow or P&L analysis.

Table 5. *Revenue and Cost Streams during Pre-Production Preparation*

Value Chain Stage	Type	Streams	Generations Applicable
Pre-Production Preparation	Revenue from sales of by-products	Sales of pre-existing biomass that were cleared from the land (e.g., crop residues, timber)	1G, 2G
	Revenue from policy subsidies	Government grants/subsidies for rejuvenating degraded/infertile land [1]	2G
	Legal/compliance expenditure	Land/water acquisition cost [2]	All
	Legal/compliance expenditure	Environment and social impact assessments	All
	Capital expenditure	Soil/Water testing	All
	Capital expenditure	Agricultural system installation (e.g., irrigation)	All
	Capital expenditure	Land clearing/tillage machinery cost	1G, 2G, 4G

Value Chain Stage	Type	Streams	Generations Applicable
	Capital expenditure	Algae inoculum procurement	3G, 4G
	Capital expenditure	Research and development cost [3]	All

[1]Applicable only if the initial land was infertile or degraded.
[2]Significant sources include legal fees for land and operation rights, as well as compensation fees for affected communities.
[3]R&D cost can also occur at other stages of the value chain.
Source: Compiled by authors

3.1.2 Feedstock Cultivation and Sourcing

Feedstock cultivation and sourcing include all feedstock cultivation activities performed by the biofuel producer up to the point of harvesting, or feedstock sourcing if agricultural activities are not performed directly by the biofuel producer and procured instead from other activities or industries that can supply the feedstock required.

The costs associated with this stage mainly include the **operational expenditure** required for feedstock cultivation activities such as water, fertilizer, and labour inputs. Another substantial cost is the implementation of measures to manage environmental and social impacts arising from more intensive agricultural activities within the area. If feedstock is sourced from another company, there might be cost needed to purchase the feedstock.

At the same time, this stage offers substantial opportunities for revenue diversification through non-traditional means. Across all biofuel generations, additional revenue can be obtained from the **sale of excess biomass** that is not needed for biofuel purposes. Common biomass sold includes dried grains from 1G projects, rice and wheat straws from 2G projects, whole algal and seaweed trimmings for spirulina supplements in 3G, and high-carbon biomass residues from 4G projects that can be sold to carbon capture and storage projects.

For newer generations that utilise waste, projects can earn significant revenue from **tipping fees for collecting unused waste**. For instance, 2G biofuel projects that utilise waste residues can charge farmers or companies disposal fees for collected waste. Similarly, 3G biofuel operations that require wastewater to supply the nitrate and phosphate nutrients for the algae can earn fees from industries that supply these effluents.

Other possible revenue sources lie in the **sale of cultivation technologies or specialised equipment**, especially for 3G and 4G biofuels, where technological novelty is higher. Producers may also **sell the carbon credits generated** from operations that reduce greenhouse gas emissions. For instance, projects that demonstrate an increase in soil organic carbon (SOC) from improved agricultural land management can issue carbon credits under Verra. **Table 6** organises these potential streams into value items for inclusion in a cashflow or P&L analysis.

Table 6. *Revenue and Cost Streams during Feedstock Cultivation and Sourcing*

Value Chain Stage	Type	Streams	Generations Applicable
Feedstock Cultivation and Sourcing	Revenue from sales of by-products	Revenue from sales of surplus biomass not needed for own's fuel production	All
	Revenue from feedstock collection fees	Revenue from crop residue/waste feedstock collection fees	2G, 3G, 4G
	Revenue from policy subsidies	Revenue from government grants/subsidies for planting specific feedstocks [1]	All (More common for 1G & 2G)
	Revenue from sales of services	Revenue from leasing cultivation area for co-use by other entities [2]	All
	Revenue from sales of technologies/ infrastructures	Revenue from the sale of proprietary technologies or intellectual properties for feedstock cultivation [3]	3G, 4G
	Revenue from sales of carbon credits	Revenue from carbon credits from improving agricultural land management/reforestation of degraded land [4]	1G, 2G
	Operational expenditure	Feedstock purchased	All
	Operational expenditure	Soil management and maintenance	1G, 2G
	Capital expenditure	Irrigation machinery and equipment	1G, 2G
	Operational expenditure	Maintenance of machinery and equipment	All
	Operational expenditure	Water inputs	All
	Operational expenditure	Agrochemicals and fertilizer inputs	All
	Operational expenditure	Labour and skills training	All
	Operational expenditure	Harvesting equipment and activities	All
	Operational expenditure	Management measures for environmental impact (e.g., soil quality, biodiversity) and social impact (e.g., engagement with local stakeholders) [5]	All

[1] applicable if the feedstock chosen aligns with the government's strategy (e.g., native plants)

[2] For example, sharing of farmland or water basin for other non-biofuel usage
[3] For example, proprietary cultivation processes, proprietary higher yielding genetically modified strains
[4] The following carbon credit methodologies can be applicable: Verra's VM0042 for projects increasing Soil Organic Carbon (SOC) through improved agricultural management; Verra's VM0047 for projects restoring vegetative cover in non-forested areas
[5] Includes cost for Monitoring, Reporting, and Verification (MRV) costs if carbon credits are generated.
Source: Compiled by authors

3.1.3 Pre-Treatment, Transportation, and Storage

Harvested biomass and feedstock often need to be pre-treated to transform them into the ideal form for conversion to biofuel. For instance, milling harvested biomass for 1G and 2G biofuel increases the surface area of feedstock, resulting in higher energy yields (Shukla et al., 2023). In the case of harvested 3G algae, de-watering & drying might need to be performed. Some outputs from pre-treatment can be sold as **by-products to create other products**, thereby generating additional sources of revenue. For instance, bagasse resulting from sugarcane milling can be an alternative to wood pulp-based paper.

For operators equipped with storage facilities, they may provide **storage services** to other biofuel operators that might lack the necessary infrastructure. Similarly, an operator with transportation capacity can capture additional revenue from **transporting other entities' feedstock or processed biofuels**.

Costs associated with this stage include the capital and operational expenditure to pre-treat, store, and transport post-treated feedstock. **Table 7** organises these potential streams into value items for inclusion in a cashflow or P&L analysis.

Table 7. *Revenue and Cost Streams during Pre-Treatment, Transportation, and Storage*

Value Chain Stage	Type	Streams	Generations Applicable
Pre-treatment, Transportation, and Storage	Revenue from sales of by-products	Revenue from selling pre-treated biomass by-products	All
	Revenue from sales of services	Revenue from providing feedstock/biomass transportation services to other entities	All
	Revenue from sales of services	Revenue from providing feedstock/biomass storage services to other entities	All
	Capital expenditure	Infrastructure for pre-treatment facilities	All
	Operational expenditure	Fuel and energy for pre-treatment facilities	All
	Capital expenditure	Transportation vehicles	All

	Capital expenditure	Storage building infrastructure	All
	Operational Expenditure	Transportation and storage operations	All
	Operational expenditure	Labour and skills training	All
	Operational expenditure	Outsourced pre-treatment [1]	All

[1]Applicable only if pre-treatment is done through an external party

Source: Compiled by authors

3.1.4 Production Processes

This stage considers the various processes within the refinery to **convert, blend, and produce biofuels**. Apart from the biofuel itself, the refinery process can generate other **by-products which can be applied to other industries** beyond transportation, such as pharmaceuticals, cosmetics, and food. For instance, biodiesel production yields glycerine, which can be used as a moisturiser in the cosmetics industry. From 2G biofuel, hemicellulose sugars extracted from crop residues can serve as sugar substitutes in food applications. 3G biofuel production can produce algal cake, a nutrient-rich material that can be repurposed as animal feed. More advanced 4G biofuel processes may enable carbon-capturing materials, offering a decarbonisation pathway for materials-heavy industries such as manufacturing and construction.

These by-products play a key role in **diversifying sources of downstream revenue** and **creating opportunities for circular business models**, which lead to cost savings. This will be explored further in section 3.2.

Additional revenue from **removal carbon credits and Renewable Energy Certificates** (RECs) can be generated from biofuel projects. Biochar credits are popular among refineries that perform pyrolysis, especially for operators who perform agricultural activities, as the generated biochar can be applied directly to their own soil to produce feedstock more sustainably. Biofuel operators that are more technologically savvy might also perform carbon capture activities, which can generate bioenergy with carbon capture and storage (BECCS) credits. Alternatively, RECs can be generated if the biofuel produced is used for renewable electricity generation.

Apart from the sales of biofuel products and by-products, revenue can also be obtained **from providing refinery services to other entities,** such as offering to process other entities' feedstock and providing blending services. Additional revenue can also be generated through **the sale of proprietary technologies or equipment** to other refineries in need.

The significant costs associated with this stage include the capital expenditure of the conversion and blending machineries, the purchase of fuel and heat required for refinery operations, and the human resources and licensing needed to sell the biofuel. **Table 8** organises these potential streams into value items for inclusion in a cashflow or P&L analysis.

Table 8. *Revenue and Cost Streams during Production Processes*

Value Chain Stage	Type	Streams	Generations Applicable
Production Processes	Revenue from sales of biofuels	Revenue from sales of biofuels	All
	Revenue from sales of by-products	Revenue from sales of by-products and their applications	All
	Revenue from sales of services	Revenue from processing other entities' feedstock	All
	Revenue from sales of services	Revenue from providing blending services for other entities	All
	Revenue from policy subsidies	Revenue from government grants/subsidies for satisfying mandates to produce biofuels	All
	Revenue from sales of technologies and infrastructures	Revenue from the sale of proprietary technologies for conversion and production	All
	Revenue from sales of carbon credits	Revenue from sales of carbon credits for carbon removals through biochar and/or carbon capture projects [1]	All
	Revenue from sales of carbon credits	Revenue from sales of Renewable Energy Credits (REC) [2]	All
	Capital Expenditure	Conversion/Blending machinery and equipment [3]	All
	Operational expenditure	Fuel, energy, and heat for refinery operations	All
	Operational expenditure	Fossil fuel for blending with biofuels	All
	Operational expenditure	Labour and skills training	All
	Legal/Compliance expenditure	Certification and license fees	All
	Legal/Compliance expenditure	Insurance and compliance fees	All
	Legal/Compliance expenditure	IP/licensing fees for proprietary organisms or technologies	4G
	Legal/Compliance expenditure	Carbon credit issuing fees [4]	All

[1]Biochar and BECCS credits can be generated through puro.earth. Work is ongoing by puro.earth and Verra to develop microalgae carbon capture methodology

[2]Applicable only if the biofuel is used to generate electricity
[3]For example catalytic converters, anaerobic digesters, heat recovery steam generators
[4]For example issuance fees, project registration and project validation fees
Source: Compiled by authors

3.1.5 End-of-Life

End-of-life refers to all operations that manage waste, residues, and emissions from refinery operations. The main cost in this stage is the waste treatment and disposal fees, as well as any technology that is required to ensure that the environment and surrounding communities are not affected by the generated waste. For specific process residues such as ash and char, there is a possibility to generate revenue from them as by-products that could be sold or used for the circular economy. **Table 9** on the next page organises these potential streams into value items for inclusion in a cashflow or P&L analysis.

Table 9. *Revenue and Cost Streams during End-of-Life*

Value Chain Stage	Type	Streams	Generations Applicable
End-of-life	Revenue from sales of by-products	Revenue from sales of process residue as raw materials	All
	Capital expenditure	Waste treatment infrastructures	All
	Operational expenditure	Waste treatment fees [1]	All
	Operational expenditure	Waste disposal fees	All
	Capital expenditure	Carbon capture facility and operations [2]	All

[1]Includes treatment fees of all solid, liquid, and gaseous waste
[2]Applicable only if carbon capture is performed
Source: Compiled by authors

As discussed above, each stage of the value chain is associated with distinct revenue and cost streams. For entities that are only operating at a specific stage, they may consider exploring additional corresponding revenue streams. Additionally, they may also leverage opportunities for revenue diversification and cost savings through circular business models that by-products of biofuel can enable, which will be discussed in the next section.

3.2 Circular Business Models through By-Products

In this section, we explore how the products and by-products of biofuel production enable **revenue diversification** and **cost savings** through **circular business models** for newer generation biofuels (2G to 4G).
By-products are non-biofuel products that are simultaneously generated during the production of biofuel. These by-products often have applications beyond the traditional energy and transportation use of biofuels, thereby generating possibilities for additional revenue through the sale of these by-products to other companies that can use them.

Furthermore, several biofuel products and by-products can be **reintegrated** back into earlier stages of the biofuel value chain, reinforcing a circular business model. This offers two potential benefits for biofuel operators: (1) **reducing operational costs by substituting external inputs**, and (2) **opening new revenue streams** through sales of by-products to other biofuel operators who require these inputs in their processes.

Our landscape analysis identified **4 usages of by-products** that can be leveraged upon by biofuel operators:

1. By-products as inputs to the operator's own feedstock cultivation.
2. By-products as inputs to external activities/industries supplying feedstock.
3. By-products as inputs to pre-treatment and refinery operations.
4. By-products and their applications to other industries.

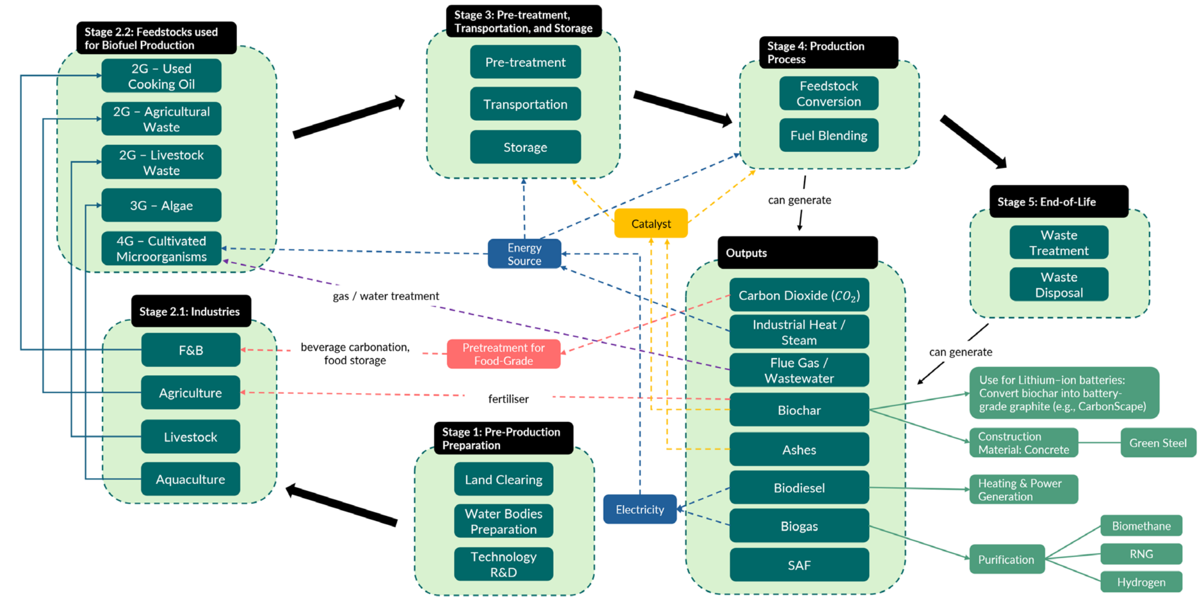
An important implication is that if a non-biofuel company already produces a non-biofuel product that can be used as any of the 4 usages above, they can leverage on that product in two ways:

1. Generate additional revenue from selling it to a biofuel operator (**external partnership**).
2. Use it as an **entry point into one or more stages of the biofuel value chain** directly, therefore accessing the revenue and cost streams associated with that stage (**business expansion**).

Figure 11 visualises how these four usages can be integrated into a circular model within the biofuel value chain, along with some common examples for each that we would like to highlight in the following sub-sections.

The following sub-sections delve deeper into **Figure 11** by dissecting the four functional groups in terms of the opportunities for a circular economy model, and how external partnerships and business expansion could be performed. Representative but non-exhaustive examples are provided for each function to illustrate the available opportunities.

__Figure 11__. Visualisation of the 4 Usages of By-products Enabling Circular Economy Models in the Biofuel Value Chain



Source: Compiled by authors

3.2.1 By-Products as Inputs to the Operator's Own Feedstock Cultivation

If a biofuel operator independently cultivates their feedstock source, some downstream by-products can be repurposed to partly substitute external inputs required to cultivate feedstock. This could potentially result in cost savings due to the reduced reliance on purchased inputs, as well as revenue diversification through selling these by-products to other entities performing feedstock cultivation activities. This is reflected by the purple lines connecting the "Sample Products and By-Products" box with Stage 2.2 in **Figure 11**.

A prime example is the utilisation of flue gas and wastewater generated from biofuel refinery operations as inputs for third- and fourth-generation algal cultivation. Captured flue gas serves as an additional source of carbon dioxide for algal photosynthesis, while wastewater supplies essential nutrients such as nitrates and phosphates that support algal growth. This integration of by-products not only enhances resource efficiency but also reduces the need for external nutrient inputs, resulting in potential cost savings.

Another example is biochar, a by-product when 2G feedstocks undergo pyrolysis. Pyrolysis is the process of burning in the absence of oxygen to break down the molecules of the biomass, creating biochar out of the biomass. When applied to agricultural soil, biochar is reportedly able to hold nutrients and water longer, potentially leading to reduced need for fertilizers and frequency of irrigation (An et al., 2022). Application of biochar to their own agricultural soil allows operators to save costs from purchasing less fertilisers and water for their 2G agricultural activities.

It is important to note that non-biofuel companies can also leverage their existing produced outputs or resources that can be used as inputs for biofuel feedstock cultivation. In such cases, both external partnerships and business expansions are possible, allowing a non-biofuel company to capitalise on the output or resource as an entry point into biofuel involvement.

3.2.2 By-Products as Inputs to External Activities/Industries Supplying Feedstock

For biofuel operators that form external partnerships with other entities to procure their feedstock, by-products could also contribute to the supplier's businesses which creates another possible dimension for a circular economy model. This is reflected by the red lines connecting the "Sample Products and By Products" box to Stage 2.1 in **Figure 11**.

Biochar, for instance, could also be sold or supplied to villages performing the agricultural activities that provide the agricultural waste used for 2G biomass. This could increase not only the yield for biofuel production but also have a positive externality on their other farming outputs, leading to a mutually beneficial circular business model. Another potential by-product is carbon dioxide, which is a by-product to biomethane production. Two of the possible applications of carbon dioxide are for creating carbonated drinks and prolonging the shelf life of certain foods, which could be used in the food and beverages (F&B) industry. An external partnership with an F&B entity to provide carbon dioxide in exchange for food waste for anaerobic digestion could be established.

Note that this interaction could also be internally integrated within an entity. If an initially non-biofuel company has an existing business line that could potentially produce a feedstock source, there could be a stronger business case of venturing into biofuel if the products or by-products of the biofuel production could be used to support the existing activity.

3.2.3 By-Products as Inputs to Pre-treatment and Refinery Operations

Several products and by-products could be used as inputs for energy sources and catalysts required to process biomass in the pre-treatment and refinery stage, as reflected by the blue and yellow lines connecting the "Sample Products and By Products" box to Stage 3 and 4 in **Figure 11**.

Biogas and biodiesel, for instance, could replace pure fossil fuels in generating the electricity required for pre-treatment and burning processes in the refinery, thereby acting as an internal source of energy. Another plausible by-product that could be used as an energy source is industrial heat or steam. If harnessed, this excess thermal energy could be used to power refinery operations. More importantly, the applicability of industrial heat also enables internal integration if industrial activities are also performed for other products that the entity produces. Therefore, industrial heat is one of the more general entry points for an entity to venture into biofuel production. One of our case studies, discussed in Section 3.3, has industrial heat as its entry point into biofuel.

Catalysts are essential for chemical processes during pre-treatment and refinery operations, such as transesterification. Certain by-products, including biochar and residual ashes, can serve this purpose due to their high composition of metal oxides and carbonates. This reduces the need to purchase dedicated metal oxides for catalyst purposes, creating opportunities for cost savings. In addition, surplus by-products can also be sold to other entities that require them to catalyse their own operations, generating an additional revenue stream.

Companies can also leverage technology and infrastructure overlaps to support business expansion. Where existing industrial infrastructure and equipment can be applied to biofuel processing, shared use of these assets reduces the need for additional capital investment and enables greater cost efficiency.

3.2.4 By-Products and their Applications to Other Industries

While sections 3.2.1 to 3.2.3 examine how by-products can be utilised within the biofuel value chain to support a circular business model, and how non-biofuel products with similar functions can be integrated into this chain, this section shifts focus to how biofuel products and by-products can, in turn, be applied onto non-biofuel value chains. This is reflected by the green lines going outwards of the "Sample Products and By Products" box in **Figure 11**.

Biochar, for instance, can be further processed into biocoke, which is a low-carbon substitute for coke in industrial processes, such as cement and steel production. Biochar could also be converted into battery-grade graphite, which acts as an alternative to carbon black in lithium-ion batteries. Biogas produced, instead of merely for transportation, can be further purified to form biomethane, renewable natural gas (RNG), and green hydrogen, each of which has its own application in various industries.

These applications provide pathways for downstream biofuel and by-products to be inputs into the value chain of other non-biofuel production lines. This provides opportunities for a **two-way business expansion** between an entity's non-biofuel and biofuel production lines.

Ultimately, biofuel products and by-products offer significant opportunities to establish a circular business model that delivers both economic and environmental benefits. By maximising resource efficiency, diversifying revenue streams, and reducing reliance on external inputs, such a model strengthens the financial resilience of biofuel companies while reinforcing their long-term sustainability.

3.3 Case Studies of Existing Biofuel Producers

In this section, we demonstrate the practical applications through three corporate case studies: **MacroCarbon, ecoWise,** and **Earthnote**. Each case illustrates the process chain of the respective biofuel producers and highlights how their innovations enable them to maintain profitability.

3.3.1 MacroCarbon S.L.

Headquarters	Geography Focus	Founding Year
Las Palmas de Gran Canaria, Spain	Macaronesia Region and Morocco	2023
Biofuel Generation	**Products**	
3rd Generation	Biofuel (SAF or Bionaphtha), Biostimulant, Biochar, Carbon Black	

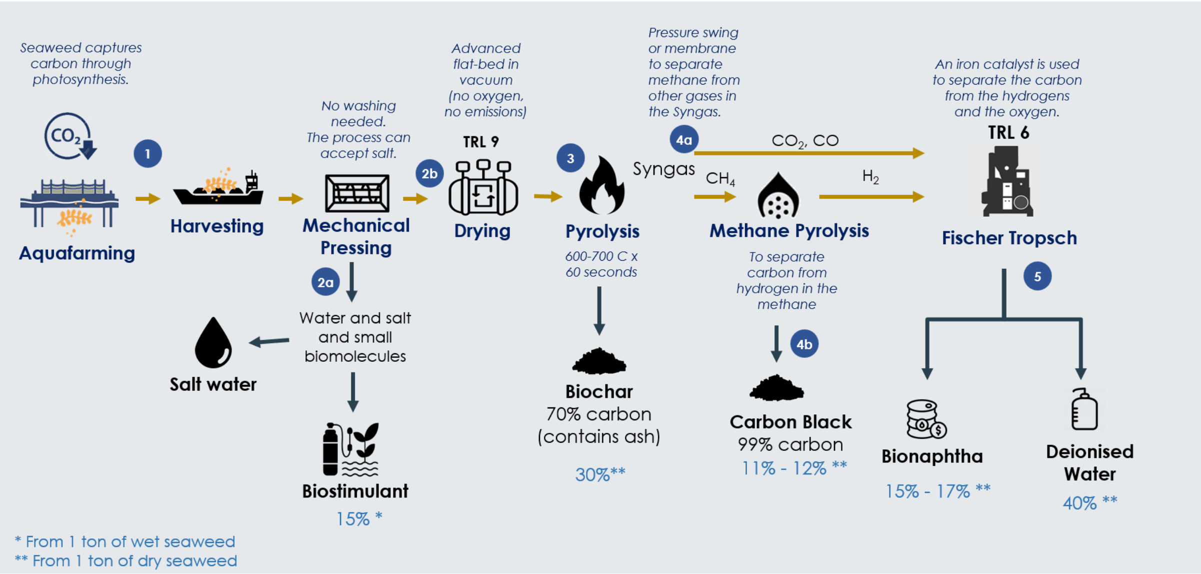
MacroCarbon, a startup based in Las Palmas de Gran Canaria, Spain, specialises in cultivating pelagic and benthic Sargassum seaweed in a novel floating manner using stationary aquafarming systems in open ocean environments (see top of ***Figure 12***). Sargassum fluitans and natans are two free-floating brown macroalgae that do not require conventional longline infrastructure for cultivation (see bottom of ***Figure 12***), significantly reducing capital and operational costs. Its rapid growth rate and high adaptability to a range of marine environments make it an ideal candidate for scalable ocean-based carbon removal. Through photosynthesis, Sargassum sequesters carbon dioxide with high efficiency.

***Figure 12**. MacroCarbon's Pilot Aquafarm Facility at the harbour of Las Palmas, Spain (Top); Pelagic sargassum cultivation at MacroCarbon's pilot aquafarm (bottom)*

Source: MacroCarbon

Following harvest, the carbon-rich biomass is processed into renewable feedstocks, such as biostimulant, biochar, and bionaphtha for the chemical industry, offering a sustainable alternative to fossil-derived inputs and contributing to industrial decarbonisation. The full process chain can be observed in **Figure 13**.

***Figure 13.** MacroCarbon's seaweed-to-product process chain*



Source: MacroCarbon

Step 1: MacroCarbon cultivates *Sargassum* seaweed in its aquafarms. During growth, the seaweed captures atmospheric carbon through photosynthesis, contributing to carbon sequestration.

Step 2: After harvesting, the seaweed undergoes mechanical pressing.

a. The liquid fraction, which contains water, salt and small biomolecules, undergoes reverse filtration. This process separates the saltwater, which is released into the ocean, and a biostimulant extract, which is refined for commercial sales.
b. The solid biomass fraction will undergo drying. This process reduces moisture content and enhances the efficiency of downstream thermal processes like pyrolysis.

Step 3: The dried biomass undergoes pyrolysis in an advanced flat-bed vacuum dryer [Technology Readiness Level (TRL) 9], which operates without oxygen and produces no emissions at 600 to 700°C for 60 seconds, yielding biochar and synthesis gas (syngas). The syngas primarily consists of carbon monoxide (CO) and hydrogen (H_2), along with carbon dioxide (CO_2) and methane (CH_4).

Step 4: The syngas is cooled, allowing a trace amount of pyrolysis oil to be retrieved and recycled back into the pyrolysis process.

a. A pressure swing or membrane separation is used to separate methane from other gases in the syngas
b. A plasma torch is then applied for methane pyrolysis, splitting methane into carbon black and hydrogen gas to enrich the proportion of hydrogen in the syngas for the Fischer-Tropsch conversion step.

Step 5: The processed syngas enters the Fischer-Tropsch reactor (TRL 6), where an iron catalyst is used to convert the syngas to liquid hydrocarbons. This process creates hydrogenated carbon chains and water and can be optimised to selectively produce desired hydrocarbons as end products more efficiently. At the end of this process, bionaptha, marine biodiesel or SAF and deionised water are obtained.

Impact

This section highlights some of MacroCarbon's key contributions to the United Nation Sustainable Development Goals (UN SDGs). Its innovations are expected to generate positive impacts, such as in Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13).

Affordable and Clean Energy

7 AFFORDABLE AND CLEAN ENERGY

MacroCarbon supports the transition to cleaner energy pathways and renewable feedstocks by producing bio-based inputs.

Industry, Innovation and Infrastructure

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

MacroCarbon exemplifies industrial innovation by applying marine biotechnology and aquafarming systems to transform ocean biomass into useful chemicals and materials, creating a sustainable value chain.

Responsible Consumption and Production

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

MacroCarbon uses a low-input, circular seaweed cultivation process that produces renewable materials and sequesters carbon.

Climate Action

13 CLIMATE ACTION

The Sargassum aquafarms sequester 12,000 tons of CO_2 per km² per year. MacroCarbon aims to sequester 100 million tonnes of CO_2 annually by 2040, with a cumulative target of one gigaton by 2050 (Algae Planet, 2023).

As MacroCarbon is currently in the proof-of-concept phase, the valuation framework outlined in the previous chapter was applied based on forward-looking projections. We assume MacroCarbon will commence commercial operations in 2030 and continue scaling through 2050. **Table 10** presents the key valuation components used to derive the projected ROI for MacroCarbon over this period.

Table 10. *ROI Breakdown for MacroCarbon*

Valuation Item	Investment/ Cost/Benefit	Present Value in 2025 (€ m)	% of ROI
ROI = 2.82X			
Economic			
• Capital Expenditure	Investment	(88.9)	
• Operational Expenditure	Cost	(168.9)	-67%
• Non-operational Expenditure	Cost	(22.2)	-9%
• Revenue from sales of biofuels	Benefit	224.3	89%
• Revenue from sales of by-products	Benefit	218.2	87%

Source: MacroCarbon

Using the economic valuation items, we estimated an ROI of **2.82X** for MacroCarbon. This is promising for MacroCarbon as it indicates that, for every unit of capital invested, the company can expect to generate nearly three times the initial investment in net economic returns. Notably, this estimate has not accounted for the substantial gains anticipated from its planned major expansion in 2050, which could further increase production capacity and unlock additional revenue streams, potentially driving the ROI well above the current level.

What's Next

Once commercial viability is demonstrated, MacroCarbon plans to scale up its operations significantly, from an initial 12 hectares in its first commercialisation phase to 240 hectares. In parallel, the company is exploring the integration of Hydrothermal Carbonisation (HTC) into its production process. This technology would enable the conversion of macroalgae into high-value products such as hydrochar, while also generating by-products like HTC liquor with a lower capital expenditure. These developments are expected to diversify and expand MacroCarbon's revenue streams.

3.3.2 ecoWise

Headquarters	**Geography Focus**	**Founding Year**
Singapore	Singapore, Malaysia	1979
Biofuel Generation	**Products**	
2nd Generation	• <u>Current</u>: Dried soya and Dried spent grain as feed stocks • <u>Future</u>: Wholemeal, Fat Oil	

Founded in 1979, ecoWise Group is a Singapore-based company that focuses on three core business segments: Renewable energy, Resource recovery, and Integrated environmental management solutions. The Group has projects and operations across two main regions, with Singapore serving as its global headquarters alongside operations in Malaysia. The Group is also currently listed on the Singapore Stock Exchange board. As a major player in the environmental sector, ecoWise positions itself as an integrated sustainable environmental solutions partner. The company delivers innovative and cost-effective waste management and treatment strategies, supported by ongoing R&D and the adoption of advanced technologies. Drawing on its extensive engineering expertise and operational experience from numerous waste-to-energy and resource upcycling projects, ecoWise is able to address challenges across the waste management value chain. These efforts contribute to the development of sustainable and environmentally responsible waste management practices that benefit both the industry and society.

***Figure 14**. ecoWise's Energy Resource Centre in Gardens by the Bay, Singapore*

Source: <u>ecoWise</u>

Some of ecoWise's noteworthy projects include:

- Energy Resource Centre, tri-generation biomass power-plant (electricity, heat and cooling) at Gardens by the Bay, Singapore
- Co-generation biomass power-plant (electricity and heat) with integrated fuel management and resource recovery facility at Sungei Kadut, Singapore
- Integrated rubber compounding manufacturing and tyres re-treading factory in Seremban, Malaysia

This case study focuses on its Singapore-based activities, with **Figure 14** showing their site at Gardens by the Bay (GBTB). Currently, ecoWise operates two biomass energy plants in Singapore.

Sungei Kadut Co-Generation Biomass Power Plant (Figure 15)

- A 1 MW_e co-generation facility that converts horticultural and industrial wood waste into electricity and steam.
- Agro-waste and waste derived from food processing industries, such as spent barley grains, soya waste and milk powder, are collected from local major food-processing factories and recycled into food additives for poultry feed.
- Integration with co-generation biomass power plant – use of electrical power and steam produced by the plant to heat-dry and process the food waste.
- Facility is capable of processing 50,000 tons of horticultural and industrial wood wastes each year.

***Figure 15**. ecoWise's Sungei Kadut Power Plant, Singapore*

Source: Photograph by authors

Gardens by the Bay Tri-Generation Biomass Plant (Figure 16)

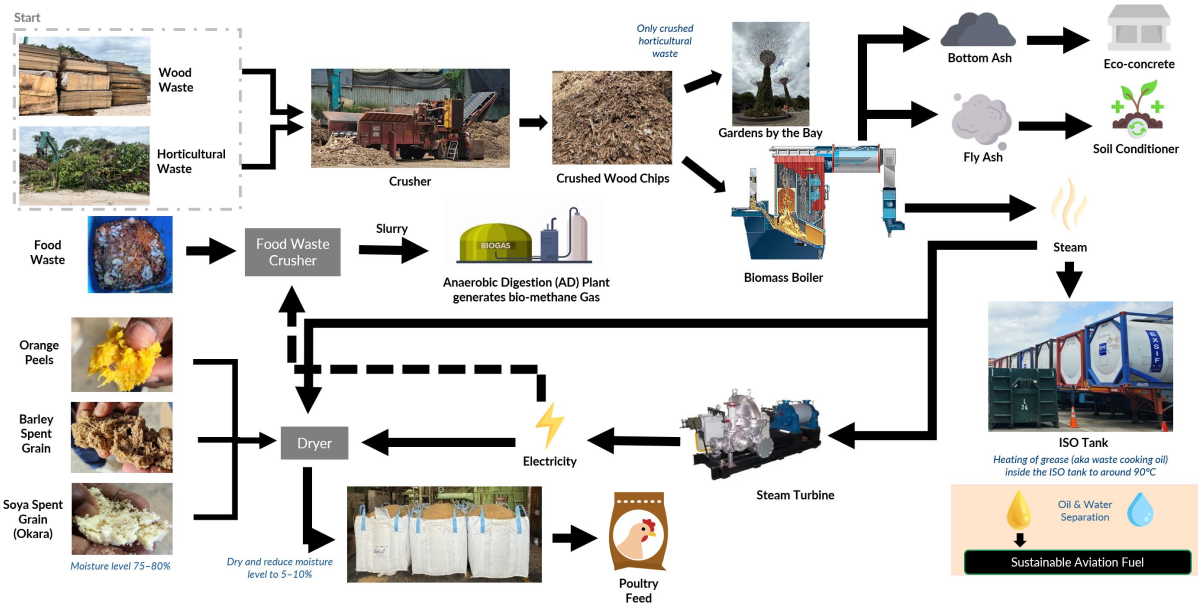
- Horticultural and industrial wood waste that was processed at the Sungei Kadut plant is transported to GBTB.
- The plant supplies electricity (0.93 MW) to the GBTB's power grid, and hot water (5.4 MW) to generate chilled water for cooling of the conservatories in GBTB.
- Chilled water (~675KW) is generated to cool the biomass boiler room.
- With the use of renewable energy, ecoWise was able to reduce 13,280 tons of CO_2 annually.

***Figure 16**. ecoWise's Gardens by the Bay Biomass Plant, Singapore*

Source: Photograph by authors

Figure 17 and **Figure 18** provide a detailed overview of the plant operations at Sungei Kadut and Gardens by the Bay, respectively.

__Figure 17__. Operational Process Flow of the Sungei Kadut Biomass Power Plant

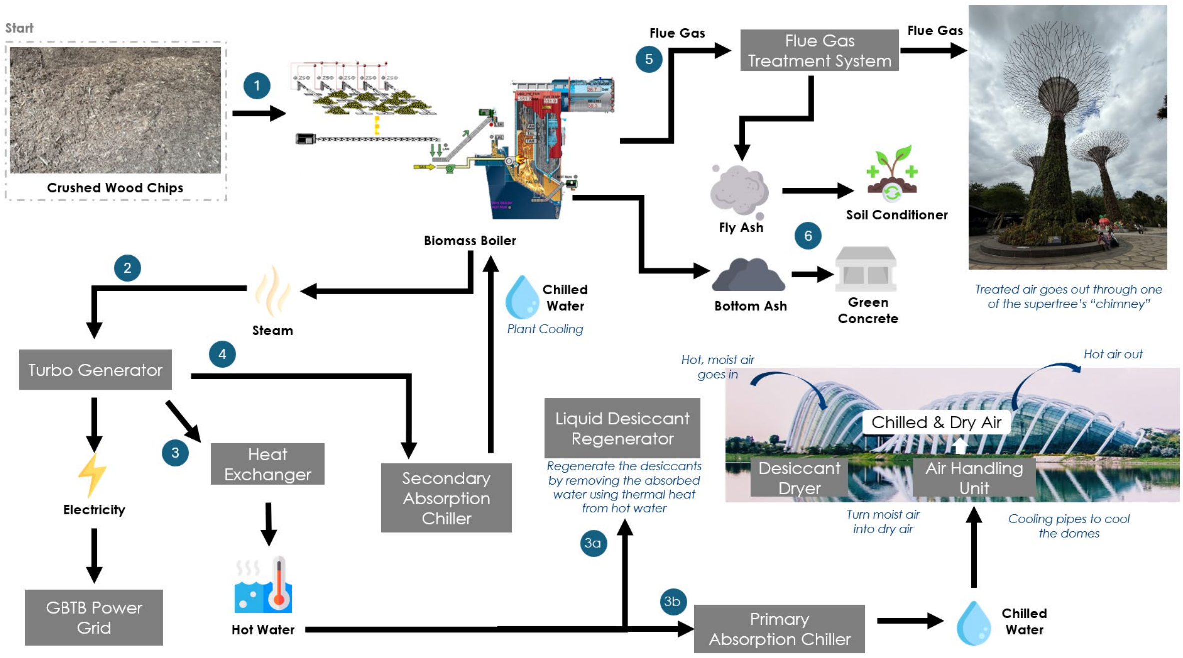


Source: ecoWise and compiled by authors

Step 1: Wood waste and horticultural waste collected are crushed to form wood chips. A portion of the wood chips is transported to the Gardens by the Bay site.
Step 2: The remaining wood chips are combusted in Sungei Kadut's Biomass Power Plant to generate steam and electricity. The steam is being utilised in the resource recovery process and for electricity for its own consumption.
Step 3: The steam is used to drive the steam turbine and produce electricity.
Step 4: A portion of the steam is used to heat the isotanks from PUB (greasy waste) and other logistics customers.
Step 5: The steam is also channelled directly to the dryer to dry the spent grains.
Step 6: Electricity generated from the steam turbine powers the dryer to dry and reduce the moisture level of the spent grain (e.g., orange peels, barley spent grains, okara) collected from 75% to 10%.
Step 7: After drying, the end products are used as additives for poultry feedstocks.
Step 8: A portion of the electricity powers the food waste crusher to produce food waste slurry, which will be used as a feedstock in the anaerobic digester to produce bio methane gas at ecoWise's partner facility.
Step 9: After the combustion of the wood chips, two kinds of ashes are generated from the biomass power plant, which are disposed to third parties:

a. Bottom ash can be used to make eco-concrete
b. Fly ash can be used for soil conditioner

***Figure 18**. Operational Process Flow of the Gardens by the Bay Plant*



Source: ecoWise and compiled by authors

Step 1: Wood chips transported from the Sungei Kadut site are combusted in the biomass power plant to generate electricity, hot water and chilled water.
Step 2: The superheated steam from the biomass boiler drives the turbine in the turbo generator to generate electricity, which will be supplied to the Gardens by the Bay (GBTB) Power grid.
Step 3: A portion of the exhaust steam from the turbine is channelled to the heat exchanger, where the heat from the steam is transferred to the hot water.

a. Hot water is used to regenerate the desiccant by removing absorbed moisture. Once regenerated, the desiccants in the desiccant dryer will dry the hot and moist air from Singapore's atmosphere before it enters the conservatories.
b. Hot water is also channelled to the primary absorption chiller to produce chilled water to cool the conservatories.

Step 4: Exhaust steam from the turbo generator is also channelled to the secondary absorption chiller to produce chilled water for biomass plant cooling.
Step 5: The flue gas generated is treated to comply with National Environment Agency standards before being released into the atmosphere through a chimney located within one of the Supertrees. The process also collects fly ash, which can be repurposed as a soil conditioner.
Step 6: Bottom ash and fly ash generated from the combustion of wood chips are collected and disposed to third parties, which can be used to make eco-concrete or used as soil conditioner, respectively.

Impact

This section highlights the key UN SDGs that ecoWise supports through its core operations and initiatives.

Affordable and Clean Energy

ecoWise's biomass plants use organic waste to produce hot water, electricity, and chilled water, reducing dependency on fossil fuels and promoting localised, renewable energy generation

Industry, Innovation and Infrastructure

As one of the first biomass power plants in Singapore, ecoWise delivers innovative waste-to-energy solutions and is exploring the conversion of collected food waste into ingredients for animal feed production and feedstock for energy generation.

Responsible Consumption and Production

ecoWise embodies circularity by converting waste into energy and valuable products like biochar, extending the resources lifecycle, and offering sustainable alternatives to landfill or incineration.

Climate Action

The GBTB Tri-Generation Biomass Power Plant reduces 13,280 tons of CO_2 on an annual basis.

Partnerships for the Goals

ecoWise entered into a Design, Build, Own, and Operate (DBOO) agreement with the National Parks Board (NParks), establishing a partnership with GBTB to develop and operate the GBTB plant.

ecoWise commenced operations at its Sungei Kadut site in 2004 and subsequently expanded to a second facility at Gardens by the Bay in 2012. With the Sungei Kadut lease due to expire in 2026, the company is in the process of securing a new site to support its planned expansion. Hence, for the ROI calculation, the analysis spans from 2004 through 2050, with the assumption that ecoWise will relocate to the new site in 2026. **Table 11** summarises the key valuation items underlying the projected ROI for ecoWise.

Table 11. ROI Breakdown for ecoWise

Valuation Item	Investment/ Cost/Benefit	Present Value in 2025 ($ m)	% of ROI
ROI = 1.53X			
Economic			
• Capital Expenditure	Investment	(84.7)	
• Operational Expenditure	Cost	(491.1)	-378%
• Certification & Recertification Fee	Cost	(2.4)	-2%
• Revenue from sales of biomass	Benefit	278.9	215%
• Revenue from sales of by-products	Benefit	222.0	171%
• Revenue from organic waste collections	Benefit	122.6	94%

Source: ecoWise and compiled by authors

Footnote: The summarised financial information, projections, ROI analyses, and other financial metrics in this white paper are based on publicly available data and authors' own assumptions and methodologies. They have not been reviewed or verified by ecoWise Group, which makes no representation as to their accuracy or reliability. This information does not reflect the views of ecoWise Group and should not be relied upon as financial advice.

Our ROI calculation projects ecoWise's return at **1.53X** over the period 2004 to 2050, meaning the company is expected to generate approximately $1.53 for every dollar invested. Currently, revenue streams are largely derived from the sale of biomass to Gardens by the Bay, and from by-products such as whole meal, recovered fats and oils, and dried spent grain. If ecoWise can identify more revenue sources, its future returns could be further increased. For instance, the proposed production of pectin powder from orange peels, which is currently on hold, highlights ecoWise's potential to create more economic returns beyond what was estimated.

What's Next

As part of its upcoming expansion, ecoWise plans to complement its existing operations with food waste collection, enabling the conversion of waste into value-added products such as whole meals and recovered fats and oils. This initiative supports Singapore's drive toward a more circular economy, particularly in addressing the growing challenge of food waste. As of 2023, food waste was the sixth-largest waste stream by volume, with a recycling rate of just 18% (NEA, 2024), with the majority incinerated or sent to landfills. Improper handling of food waste can contribute to odour issues and pest infestations (NEA, 2025). ecoWise's proposed expansion represents a timely and impactful solution to enhance food waste management and resource recovery in Singapore.

3.3.3 Earthnote

Headquarters Shenzhen, China	**Geography Focus** China, East Asia	**Founding Year** 2023
Biofuel Generation 4th Generation	**Products** Bioethanol (to make SAF), Biochar, Biocoke (to produce green steel)	

Earthnote specialises in converting sweet sorghum into high-value products such as biochar, biofuels, and renewable energy. With its high biomass conversion efficiency, sweet sorghum can be processed into multiple forms of clean energy, including biogas and biochar. Its short growth cycle, rapid regenerative capacity, and wide adaptability to diverse soil and climatic conditions enhance its commercial viability. Moreover, sweet sorghum is considered an environmentally friendly energy source, as the carbon dioxide it absorbs during its growth nearly offsets the emissions released during its combustion.

Earthnote's production process starts with selective breeding to enhance the sorghum strain, ensuring only the highest-quality varieties are cultivated to maximise yield and efficiency. The left image of **Figure 19** shows the sweet sorghum cultivated by Earthnote, which is tall and typically reaches heights of 4 to 5 metres.

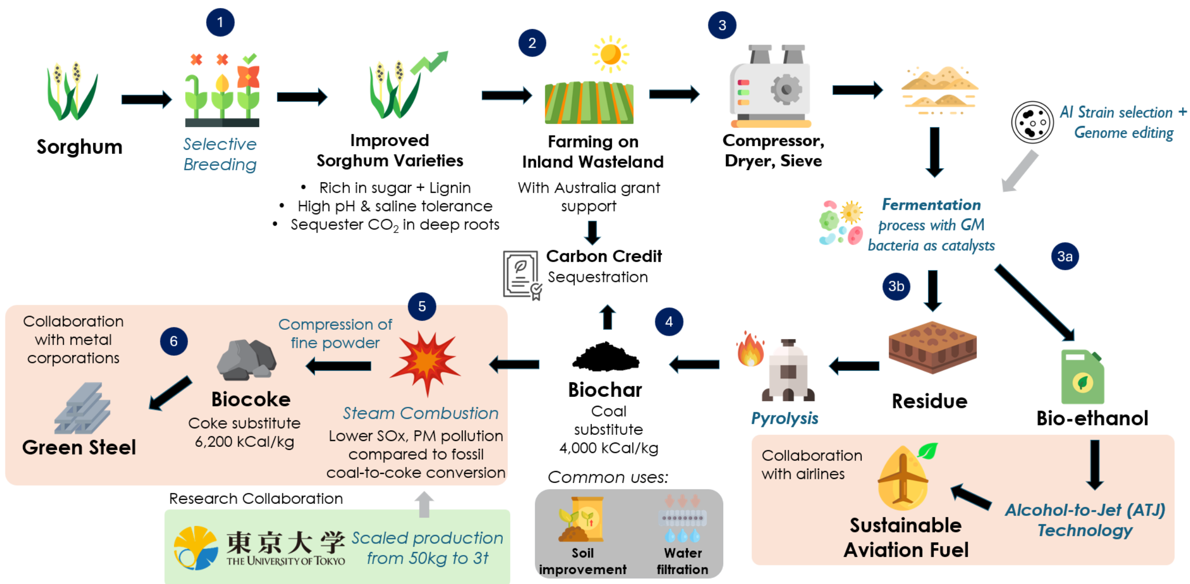
***Figure 19**. Tall, sweet sorghum variety with high sugar content cultivated by Earthnote (Left); Biochar produced via pyrolysis (Right)*

Source: Earthnote, enhanced using ChatGPT

The sorghum's deep root system enables carbon sequestration, allowing Earthnote to generate and monetise carbon credits based on this environmental benefit. Once harvested, the sorghum undergoes compression, drying, and sieving, followed by a fermentation process that uses genetically modified bacteria as a catalyst. This step results in bioethanol and a porous by-product. The bioethanol is then processed using Earthnote's Alcohol-to-Jet (ATJ) technology to produce SAF. Earthnote collaborates with companies like Renewable Developments Australia and airlines such as Air China and Air New Zealand to supply SAF, helping them meet their sustainability targets.

The by-product will undergo pyrolysis to produce biochar, as shown in the right image of , which is commonly used to improve the soil quality and for water filtration. This biochar can be further processed through steam combustion to create biocoke, a low-carbon alternative to conventional coke. Earthnote, in collaboration with a spin-off company from the University of Tokyo, has partnered with leading metal producers such as Rio Tinto and Nippon Steel to supply biocoke to produce green steel, supporting decarbonisation efforts in the metals industry. Unlike traditional steelmaking, which relies on coking coal and emits large volumes of carbon dioxide, green steel is produced using low-carbon alternatives like biocoke, resulting in significantly lower greenhouse gas emissions. **Figure** ***20*** outlines the entire process, illustrating how Earthnote transforms sweet sorghum into renewable energy, bio-based materials, and industrial decarbonisation solutions.

Figure 20*. Sorghum to renewable energy and bio-based products process chain*



Source: Earthnote and compiled by authors

Step 1: Selective breeding is applied to improve the sorghum's energy and carbon content, making it more suitable for bioenergy applications.
Step 2: The optimized sorghum is cultivated. Its deep root system promotes carbon sequestration, enabling the generation of carbon credits alongside biomass production.
Step 3: After harvesting, the sorghum will be compressed, dried, and sieved. It then goes through fermentation, which uses genetically modified bacteria as a catalyst to yield the following:

a. Bio-ethanol, an alcohol that is refined into SAF through the Alcohol-to-Jet technology, supporting the aviation sector's decarbonisation journey.
b. A porous solid residue, which will be further processed.

Step 4: This residue is subjected to pyrolysis, producing biochar. This biochar is commonly used for soil improvement and water filtration.
Step 5: The Biochar can be compressed into fine powder and converted into biocoke via steam combustion. This steam combustion method results in lower sulfur oxide (SO_x)and Particulate Matter (PM) pollution compared to traditional coal-to-coke processes.
Step 6: The resulting biocoke serves as a fossil coke substitute in steelmaking, contributing to the production of green steel in collaboration with metal industry partners.

Impact

The following section showcases Earthnote's key contributions to the UN SDGs and demonstrates how its innovative biochar solutions align with global priorities such as clean energy (SDG #7) and sustainable industrial development (SDG #9).

Affordable and Clean Energy

7 AFFORDABLE AND CLEAN ENERGY

Earthnote converts biomass waste like crop residues into renewable biofuels, offering alternative energy sources instead of fossil fuels.

Industry, Innovation and Infrastructure

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Earthnote develops a scalable AI-driven pyrolysis reactor to optimise biochar production for the industries.

Life On Land

15 LIFE ON LAND

Biochar produced by Earthnote can be used to restore degraded soil to enhance biodiversity on land.

Partnerships for the Goals

17 PARTNERSHIPS FOR THE GOALS

- Earthnote collaborates with airlines and supplies SAF to help them meet sustainability goals.
- Earthnote partners with metal corporations to produce green steel and help in their decarbonisation journey.

What's Next
Earthnote aims to advance its biochar innovation through three key pathways. First, the company will focus on developing high-efficiency, low-cost biochar production technologies to enhance output quality and scalability. Second, it will optimise coal-biochar blending strategies to improve energy efficiency and reduce emissions during the coking process. Third, Earthnote will explore new industrial applications for biochar, such as blast furnace injection and direct reduction process, to expand biochar's utility across the industrial sector.

In summary, these case study partners exemplify the innovation, resilience, and impact potential of emerging biofuel producers. Across different regions and stages, they show strong commitments to sustainability, technology, and scalable models, highlighting the need for continual process innovation to boost efficiency. The cases validate the valuation methods introduced earlier and affirm the commercial viability and positive externalities of biofuel production. Together, they underscore how targeted financing and supportive capital structures accelerate progress and market adoption.

4 Key Risks Faced by Biofuel Producers

The prior chapter has highlighted additional business line opportunities that biofuel producers can leverage to diversify their revenue streams and achieve cost savings. However, producers should also recognise that alongside these opportunities come key risks that must be carefully managed to ensure long-term viability.

This chapter discusses the major risks that biofuel producers may encounter while establishing biofuel business lines. These risks present potential challenges to the operations and financial health of biofuel producers. Furthermore, some of these risks might affect the attractiveness of producers to prospective financiers, as the level of business risks directly influences financiers' confidence and valuation. Here, we focus on identifying key categories of risk and examining how these risks emerge across the various stages of biofuel product development.

4.1 Product Development Cycle

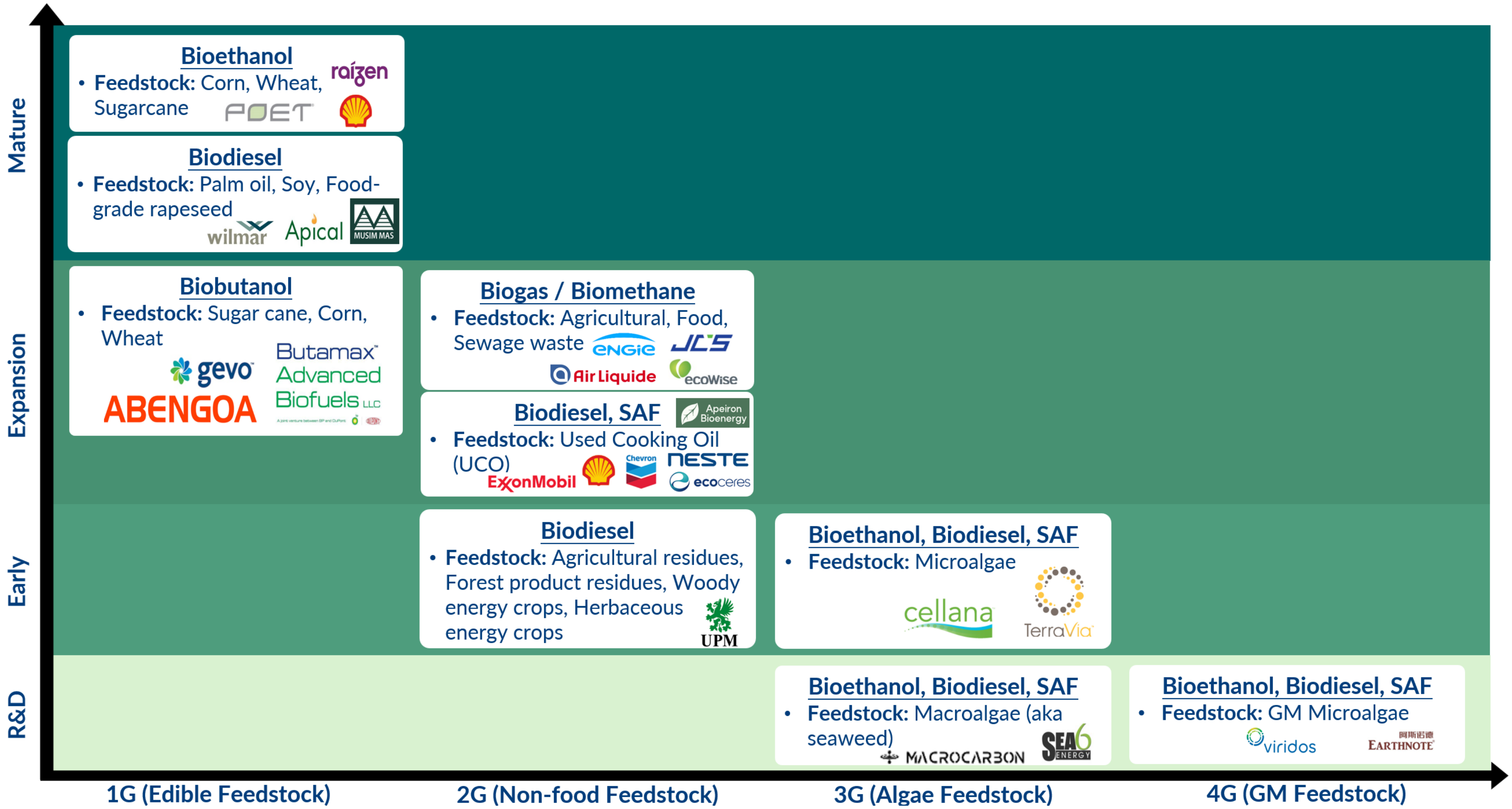
Biofuel companies typically progress through four product development stages: R&D, early, expansion, and mature. The **R&D** stage centres on validating technology, designing processes, and assessing feasibility. At the **early stage**, companies pilot their technology and begin engaging the market, aiming to demonstrate product–market fit and reduce commercial uncertainty. **Expansion** follows successful validation, with efforts focused on scaling production, improving operations, and entering new markets. **Mature** companies generate stable revenues, have broader market reach, and pursue strategic growth through acquisitions, diversification, or capital market access.

Based on existing literature, we identified typical product development stages across major biofuel generations, differentiated by feedstock. **Figure 21** below visualises the identified stages and highlights representative companies and key technical barriers to commercialisation that products in the R&D and early stages face. It also lists the dominant feedstock–product combinations, though it does not capture every emerging variant. For instance, recent R&D efforts in enzymatic catalysis for 1G and 2G biofuels may offer cost, yield, and environmental advantages. These innovations remain at an early stage but represent progress beyond current commercial baselines.

4.2 Revenue Stability Risk

Revenue stability risk is **the uncertainty associated with the fluctuations in demand and pricing of biofuels.** Just as feedstock costs are essential for financial viability, stable revenue streams are required for biofuel business line to achieve maturity. Given the long payback periods and high capital expenditure typical of biofuel projects, revenue stability is critical for a producer's financial sustainability. While the absolute level of revenue depends on the competitiveness of the biofuels and by-products in

Figure 21. *Product Development Stages for Different Biofuel Generations and Common Products*



Sources: (Carriquiry et al., 2011), (E4tech, 2024), (European Federation for Transport and Environment, 2024), (González-Gloria et al., 2021), (IEA, 2020), (Kargbo et al., 2021), (Kowalski et al., 2022), (Kumar & Singh, 2019), (Muthan et al., 2022), (Negi, 2024), (Raj et al., 2021), (Ribeiro et al., 2011), (RSB & Agroicone, 2021), (Ryan, 2021), (Shokravi et al., 2022), (Sims et al., 2010), (Su et al., 2017), (Surbarna, 2024) the downstream market, revenue stability is dependent on the business strategy choices of the producer and how its revenue streams are structured.

A key reason for revenue volatility is **the close link between biofuel and global fossil fuel prices.** The market price of biofuel tends to be closely associated with fossil fuel prices, as biofuel is perceived as a substitute energy source, even when production costs of biofuel remain fixed. This structural linkage exposes biofuel producers to the same macroeconomic and geopolitical shifts that could influence global oil markets. As a result, fluctuations in fossil fuel prices are transmitted directly into biofuel prices, creating revenue volatility that is largely outside the control of producers. To counter this, the biofuel producer could attempt to de-link its product price from fossil fuel prices by finding a product design that offers additional unique selling points that fossil fuel does not offer and are able to be priced by potential buyers. Government's policies could also play a role here to provide a price and demand floor through demand mandates, as will be discussed further in chapter 6.

Another driver of revenue volatility is **the consistency of revenue streams**. Firms with recurring revenue streams such as those secured through fixed-price offtake agreements or long-term partnerships could face lower revenue volatility compared to those dependent on opportunistic or one-off sales as they would be better insulated from short-term market fluctuation. As such, agreements and partnerships that can lock in prices could be preferable, and the ability to secure offtake agreements would determine the producer's exposure

While we have highlighted how different by-products could be sold as alternative revenue streams, not all these by-products enjoy broad and established markets. The more niche by-products, in particular, could face **limited demand due to their smaller market size and specialised applications**. This further increases uncertainty around revenue contributions from non-biofuel products.

Apart from stability of external demand, revenue volatility could also be affected by **variability in own's production yields**. In practice, the actual conversion yields of feedstock to biofuels might differ from the assumed efficiency levels used in financial projections due to unexpected breakdowns, poor maintenance of equipment, or simply non-ideal operational performance of machinery and labour. This amplifies revenue volatility by creating uncertainty around the amount of volume available to be sold as revenue, especially in early development stages where processes are less refined and proven.

4.3 Feedstock Risk

Feedstock risk refers to **the uncertainty surrounding the availability, cost, and supply of the raw materials used to produce biofuels**. Feedstock provides the backbone for any biofuel business lines, whether it is an upstream or downstream process. Having a consistent source of feedstock, with as little price volatility as possible, is key to unlocking a scalable and financially stable business model. It is important to note that lower feedstock risk means that feedstock cost is lower – level of feedstock risks reflects the predictability of feedstock costs over a period of time.

The sources of volatility in **the availability and price of feedstock sourced** can significantly differ depending on the feedstock sourced. For 1G biofuels which relies on food crops, there is direct competition between the feedstock's usage for biofuel or food. This exposes biofuel producers to agricultural commodity cycles, where the yield is affected by weather changes, seasonality of harvest cycles, and fluctuations in the cost of agricultural input. As a result, producers depending on 1G feedstocks face significant exposure to food market and agricultural volatility, which could affect both their availability and price.

On the contrary, 2G biofuels depend on **the availability of waste and agricultural residues** whose availability are often fragmented and inconsistent in supply. Securing large scale volumes of residues could require aggregating waste from numerous small suppliers, each with variable supply patterns. This introduces variability not only in feedstock cost but also complicates efforts to guarantee stable long-term supply. Furthermore, if the feedstock waste used is associated with agricultural activities such as corn stovers or rice husks, 2G biofuels' feedstock procurement would also be susceptible to the seasonality of agricultural commodity cycles.

While newer 3G and 4G biofuels are less dependent on agricultural commodities, **operational inputs such as water, nutrients, and fertilizers** are still needed. As such, feedstock cost is still affected significantly by the market price of these inputs, which are linked to broader market prices like energy prices and supply chain constraints. However, at the current scale, 3G and 4G feedstocks are often cultivated in-house which reduces its exposure to changes in global market prices.

4.4 Capital Expenditure (CAPEX) Risk

CAPEX risk refers to **the financial uncertainty associated with the large upfront investments needed to build and expand biofuel facilities.** These expenditures carry the possibility that returns may fall short of expectations due to cost overruns, delays, or underutilisation of assets. Technological changes may also render assets obsolete before their full value can be realised, further amplifying the risk.

Advanced biofuel projects, particularly those in the 2G, 3G, and 4G, are highly capital-intensive and often face significant financial challenges. These risks extend from the R&D stage through to the early and expansion stages. During the R&D stage, producers face substantial upfront costs to acquire **specialised equipment, set up pre-treatment facilities, and build refinery infrastructures**. Even beyond this stage, projects are vulnerable to **delays arising from permitting issues, supply chain bottlenecks, or construction delays**, all of which increase financing costs and postpone revenue generation.

4.5 Technological Risk

Technological risk refers to **the uncertainty regarding the performance, scalability, and reliability of the production technologies**. Many advanced biofuel technologies remain at the pilot or testing stage, relying on novel technologies that have not yet been fully proven at a commercial scale due to the technical challenges encountered when scaling up.

Scaling up technologies like pyrolysis and hydrothermal liquefaction poses difficulties, including reactor instability, catalyst degradation, and the complexity of handling heterogeneous feedstocks. **These technical bottlenecks** often lead to lower-than-expected yields, reduced efficiency, and higher production costs. For non-biofuel producers seeking to diversify into the biofuel sector, integrating advanced biofuel processes into existing infrastructure will add more complexity and costs. Additionally, the technology also risks **becoming obsolete** as competing innovations may reduce the long-term relevance of such biofuel technologies.

4.6 Policy Risk

Policy risk is **the uncertainty that a business or project faces due to changes, delays, or inconsistencies in government policies, regulations, or subsidies that affect the economic viability of the industry**. In the biofuel sector, this risk could be very critical because the industry is heavily shaped by mandates, subsidies, and tax incentives. How dependent a producer is on policies to support its operations and reduce the 4 above risks would determine the level of policy risk it bears.

Regulatory changes, such as shifts in renewable fuel standards, blending mandates, or emission targets, can instantly cut or boost the demand for biofuel. A sudden reduction in the required blending percentages can reduce the demand for biofuels. Equally important is the presence of subsidies or incentives, which often determine whether projects are financially viable. Any withdrawal, reduction, or delay in such support can directly threaten project cash flows.

Trade policies and geopolitical factors also shape risk exposure. Import tariffs, or any sudden changes in international trade relations, can restrict export markets and destabilise the revenue streams. For biofuel producers that rely heavily on exports, such measures can undermine profitability overnight, especially if the destination countries adopt stronger self-sufficiency policies. Furthermore, geopolitical disruptions in agricultural supply chains, shifts in energy security policies, or outright trade disputes from geopolitical conflicts can trigger great volatility in feedstock prices. This makes biofuel businesses particularly sensitive to the existing policies.

4.7 Synthesis of Key Risks for Biofuel Producers

Building on the preceding discussion on the five key business risks faced by biofuel producers, **Table 12** illustrates how the current relative level of these risks shifts across different stages of development, with a comparison of risk levels between conventional 1G biofuels and newer advanced generations, 2G to 4G.

***Table 12**. Risk Matrix of Business Risks*

Business Risk	Generation	R&D	Early	Expansion	Mature
Revenue Stability Risk	**1G**	Medium	Medium	Medium	Low
	2G - 4G	High	High	High	Medium
Feedstock Risk	**1G**	High	High	High	High
	2G - 4G	Low	Medium	High	Medium
CAPEX Risk	**1G**	Low	Medium	High	Low
	2G - 4G	Medium	High	High	Low
Technological Risk	**1G**	Low	Low	Low	Medium
	2G - 4G	High	High	High	Medium
Policy Risk	**1G**	Medium	High	High	Medium
	2G - 4G	Medium	High	High	Medium

Source: Compiled by authors

In the current landscape, the **downstream revenue stability** of 1G biofuels could be expected to be higher than newer generations due to the demand mandates such as blending requirements. This provides a pathway for more offtake agreements especially when they are already mature, which helps to lock-in prices and de-link price from unexpected movements in fossil fuel prices.

On the other hand, newer generation biofuels producers, whose demand is not created by policies as of this point, **would need to identify demand opportunities themselves**. With limited demand policy support with exceptions for SAF, newer generations' revenue streams remain more vulnerable to volatility. Furthermore, due to the longer existence of 1G biofuels, the by-products of 1G biofuels have more established markets as compared to that of newer generation biofuels, allowing for easier diversification. However, as we highlighted in chapter 3, there are opportunities available to newer generation biofuels that might have yet to be tapped, and we hope that these could be leveraged more effectively to help improve the revenue stability across the four development stages.

Feedstock risks tend to be high for 1G biofuels due to their usage on food-based crops, which compete directly with agricultural demand for food. This leads to 1G feedstock's price to be closely correlated with agricultural cycles. Regardless of development stage, the need to source food-based feedstock would expose them to price and quantity volatilities that are outside of their control.

In contrast, newer biofuel generations can possibly have feedstock streams that are independently procured and less tied to commodity markets, thereby reducing their direct exposure to agricultural price volatility. However, they face a different form of feedstock risk, that is the challenge of integrating multiple, smaller-scale feedstock supply streams. As production scales from R&D to expansion, the need to secure a wider network of reliable suppliers and integrate them to match production schedules become more complex, leading to increasing feedstock risk whose extent is proportional to the amount of feedstock they need to source. A more stable, well-structured feedstock supply stream is a sign of maturity that newer generations biofuel producers should aim for.

Due to the established technologies and infrastructures of 1G biofuels, the likelihood of under-performance of **CAPEX** tends to be low at the R&D stage. However, as the company expands, CAPEX risk could rise due to the larger amount of capital at stake, if the newly added plant is unable to capture sufficient demand to match its expanded capacity.

On the other hand, newer generation biofuels face **higher CAPEX risks** from the beginning due to the uncertainty of success of its more novel processes. Even if the infrastructures and technology are effective when validated in the R&D stage, scaling introduces new challenges and might not provide the same level of efficiency as what was observed in the R&D stage, exposing them to higher CAPEX failure risk.

Similarly, **technological risk** for 1G biofuel producers is relatively low during their development cycle, given the reliance on established and proven processes. However, as these technologies mature, the risk of obsolescence increases, particularly with rising competition from newer generations of biofuels. In contrast, newer generations face high technological barriers early on, as they depend on developing and commercializing unproven processes. Yet, once scalability is achieved, these newer technologies are expected to become increasingly competitive over the long term.

Since biofuels' supply and demand remain largely shaped by **policies**, we do not anticipate major differences in level of **policy risk** between generations. The policy environment necessary to support growth—such as subsidies, mandates, and regulatory support—applies in a similar way across all generations of biofuels.

Overall, while the early stages may appear daunting, companies that can sustain operations passed the expansion phase will see their overall risks decline, reaching lower levels at maturity. The transition from high to lower risks underscores the long-term rewards of perseverance. For financiers, this progression underscores the importance of early de-risking strategies, as successful projects that survive the expansion phase evolve into stable, lower-risk investments with strong potential for sustainable returns.

5 Financing Landscape for Biofuel

The financing landscape for biofuel producers reflects the risks outlined in the previous section. While innovators can access early support through philanthropic funding, grants, and to some extent venture capital**, the most critical hurdle emerges when projects begin to scale**. At the expansion and mature stages, capital requirements rise sharply, yet **concessional capital and government policies are often insufficient** to bridge the financing gap. Although mature firms eventually attract debt and equity once revenues are established, many producers fail to transition between early growth and full commercial scale.

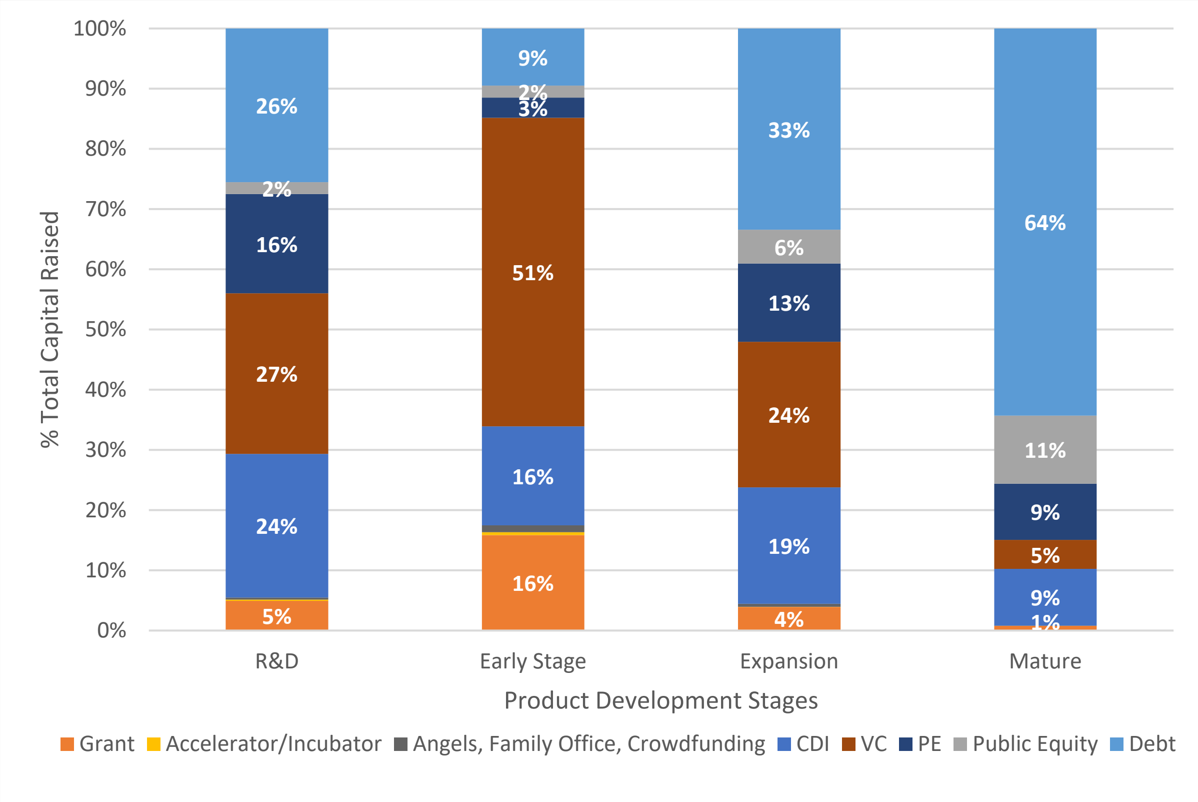
This chapter draws on the insights from PitchBook's dataset of **3,405 capital-raising activities** by **1,342 producers worldwide between January 2015 and June 2025**. We define 'Capital Raised' as primary inflows to producers, such as grants, philanthropic contributions, Corporate Direct Investments (CDI), Venture Capital, growth/expansion Private Equity, public equities (IPO and follow-ons), concessional loans and bonds. These transactions expand the company's balance sheet, directly supporting business activities such as R&D expenditure and CAPEX. Since the purpose is to study the challenges faced by producers to grow their business, we exclude M&A and Buyouts, as these transactions generally represent changes in ownership between investors and do not inject new funds into the company, unless explicitly structured with a primary infusion. For similar reasons, we exclude recapitalisations and debt refinancing, which do not provide additional capital for growth.

The results show that sources of capital shift across development stages, in line with the evolving risk profile described in the previous chapter. Using a weighted average of the capital composition at each stage and the risk–return ranking of each instrument, we derive the risk–return profile for biofuel businesses across stages. The results indicate that **the risk-return trade-off is below the Capital Market Line**, showing the financing gaps faced by producers especially when scaling. While expansion and mature companies attract more capital, **the industry still requires further policy support and de-risking mechanisms** to enable more investments for producers to reach commercial scale.

5.1 Financing Sources

Based on our analysis, **the composition of financing sources differs significantly across development stages**, reflecting the evolving risk–return profile of biofuel producers. **Figure 22** illustrates the breakdown of financing instruments across stages, and **Table 13** provides the corresponding percentage shares. Together, these results highlight the structural shift from equity-heavy financing in the early phases toward debt as firms move closer to maturity.

***Figure 22** Breakdown of Financing Sources for Biofuel Business*



Source: Pitchbook

***Table 13** Breakdown of Financing Sources for Biofuel Business*

Product Development Stages	Grant	Accelerator/ Incubator	Angels, Family Office, Crowdfunding	CDI	VC	PE	Debt	Public Equity
R&D	4.9%	0.2%	0.4%	23.9%	26.7%	16.5%	25.5%	2.0%
Early Stage	15.9%	0.5%	1.1%	16.4%	51.3%	3.3%	9.5%	2.0%
Expansion	3.9%	0.0%	0.5%	19.3%	24.2%	13.0%	33.4%	5.6%
Mature	0.8%	0.0%	0.0%	9.5%	4.8%	9.3%	64.3%	11.3%

Source: Pitchbook

- **R&D stage**: The three main sources are **venture capital (27%), debt (26%), and corporate direct investment (24%)**. While it is not surprising to see a reasonable level of VC capital at this early stage, the presence of debt here suggests that some projects may be backed by parent firms or supported through asset-backed structures, but this remains limited in scope. As for corporate direct investment (CDI), most of these corporates are oil & gas and airline companies. The overall picture is one of fragmented support, with no single dominant source.

- **Early stage**: Financing is dominated **by venture capital (51%), with grants and corporate direct investment (16% each)** also playing a role. This reliance on venture funding reflects growing investor interest in promising technologies, but it also highlights vulnerability, since producers are dependent on one type of investor behaviour. Venture capital typically operates with shorter investment horizons, which may not fully align with the longer development timelines required in the biofuel sector.

- **Expansion stage**: Financing becomes more balanced. **Debt is the largest source (33%)**, followed by **venture capital (24%)** and **corporate direct investment (19%)**. This indicates that some producers at this stage begin to access more conventional instruments, but the level of debt remains small compared with the scale of capital needed for biorefineries.

- **Mature stage**: **Debt dominates**, accounting for **64%** of total financing, while **public equity (11%)** and **private equity (9%)** are also significant. This reflects the greater confidence of lenders and capital markets in producers with proven operations and stable revenue streams.

The progression shows a clear shift: from fragmented funding in **R&D stage**, to venture-driven growth in **early stage**, to partial diversification at **expansion stage**, and finally to debt-based financing once **maturity stage** is reached. The most difficult transition appears between early and expansion, when capital requirements increase sharply but access to lower-cost debt is still constrained.

5.2 Risk and Return Profile for Biofuel Business

One way to observe the financing gap is through the risk–return trade-off across different sources of capital. We assign values from one to three for both risk and return, where 3 represents the highest level and 1 the lowest. Values are assigned to 3 cases, base case, which reflects the average of the possible range, and best and worst cases for investors, which represents the higher and lower bound of the possibilities. This simple framework helps illustrate the financing gaps facing at different stages.

Table 14 *Risk and Return Ranking for Each Source of Capital*

Case	Metric	Grant	Accelerator/ Incubator	Angels, Family Office, Crowdfunding	CDI	VC	PE	Debt	Public Equity
Base	**Risk**	2.0	3.0	3.0	2.5	3.0	2.5	2.5	2.5
	Return	0.5	2.0	3.0	2.0	3.0	2.0	1.0	2.0
Best	**Risk**	2.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0
	Return	1.0	2.0	3.0	2.0	3.0	2.0	1.0	2.0
Worst	**Risk**	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	Return	0.0	2.0	3.0	2.0	3.0	2.0	1.0	2.0

Source: Compiled by authors

Grant (Risk 2, Return 0-1) Grants are non-repayable, so their direct financial return is typically zero. However, a score of 1 may be justified because many grants are conditional on meeting research milestones, policy objectives, or development targets, and their successful use can generate spillover benefits for the wider industry. By supporting early innovation and strengthening the sector's overall life cycle, grants create indirect value even if they do not yield financial upside in the conventional sense. Risk is set at 2, as projects often fail to deliver these outcomes, even though the funder's loss is capped at the grant amount.

Accelerator/Incubator (Risk 3, Return 2) Accelerators operate more like seed-stage venture investors, providing small amounts of funding alongside structured programmes, usually in exchange for equity. Incubators, often linked to universities or government programmes, provide non-dilutive support such as facilities and mentorship, recovering costs through fees or sponsorship. Combined, we assigned this category with high risk and moderate return.

Angels, Family Office, Crowdfunding (Risk 3, Return 3) Angels, family offices, and crowdfunding investors also assume high risk in exchange for high potential returns. Angels typically invest personal wealth at stages where companies are too early for institutional venture capital, while family offices and crowdfunding platforms may follow a similar pattern. Most of them seek equity returns. Their exposure is financially similar to early-stage venture, high business failure rate with the possibility of outsized rewards, hence a risk–return profile of three and three.

Corporate Direct Investment (Risk 2-3, Return 2) Corporate direct investment reflects a more strategic rationale. Corporates such as oil majors, airlines, and agribusiness players invest in biofuels to secure feedstock, meet compliance targets, or capture long-term sustainability synergies. The risk rating sits around 2.5, depending on the stages of the investees, resembling those of VC and PE. Returns are moderate, typically around two, since the motivation is as much strategic as financial, and outcomes are rarely comparable to venture capital-type multiples.

Venture Capital (Risk 3, Return 3) Venture capital represents the archetypal high-risk, high-return model. VCs invest in R&D and early stage firms, accepting high failure rates in exchange for the possibility of exceptional exits through IPOs or acquisitions. In biofuels, the risk is further heightened by capital intensity, long lead times, and policy dependency, but the return potential remains high if a technology achieves scale. This justifies the classic profile of three for both risk and return.

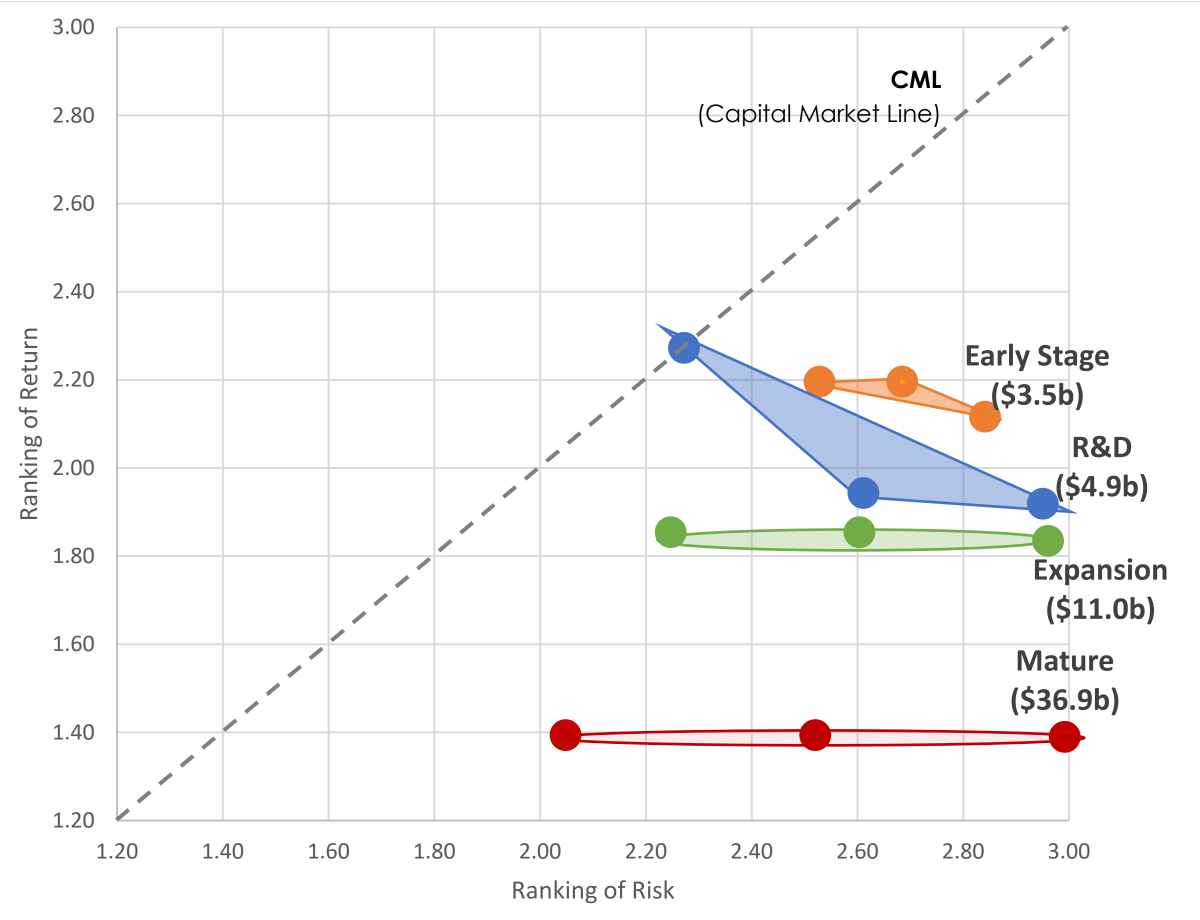
Private Equity (Risk 2-3, Return 3) Private equity, by contrast, operates later in the lifecycle. Biofuel firms that attract PE funding are typically in the expansion phase, building large-scale plants and proving commercial viability. The risk level is moderate-to-high, around 2.5, due to execution risk and heavy reliance on external policy incentives, but lower than venture capital since the business model is more developed. Returns are correspondingly moderate, around two, driven by operational efficiency, leverage, and structured exits rather than breakthrough multiples.

Debt (Risk 2-3, Return 1) Debt include publicly issued bonds, commercial loans, and private debt instruments. They have higher seniority than equity in liquidation. Compared to other instruments, debt instruments offer lower risk-adjusted return (Blackrock, 2024). In biofuels, lenders face significant policy and feedstock risks that make repayment less predictable than in conventional industries, pushing risk level to medium to high. Its returns remain capped at interest and fees, fixed by contract, meaning it cannot scale with project success.

Public Equity (Risk 2, Return 2) Public equity sits between private equity and venture capital. Listed biofuel firms are highly sensitive to fossil fuel price cycles and regulatory shifts, making their risk moderately high. However, liquidity and market depth reduce the downside relative to private markets. Returns are moderate, with potential upside if policy tailwinds and energy prices align, but unlikely to match the extreme multiples of venture capital.

Using the capital weights in **Table 13** and the risk-return scores in **Table 14**, we calculated weighted averages for each development stage. **Figure 23** presents these profiles across best, base, and worst cases for investors, with shaded areas showing outcome ranges and the dashed line representing the Capital Market Line (CML).

Figure 23 *Risk & Return Profile for Biofuel Business and the Capital Raised since 2015*



Source: Pitchbook and compiled by authors

All stages sit below the CML, meaning biofuel financing offers lower returns for the level of risk taken for investors, given the concession private capital investors provide to the industry. **Expansion and mature stages are furthest from the line**, highlighting the highest level of concessionally provided by the market. Their deviation from the CML shows the least attractiveness to investors, exposing clear financing gaps faced by producers. **R&D stage and early stage producers are closer to CML**, offering relatively better trade-offs.

R&D Stage (blue cluster): Financing at the R&D stage is highly fragmented, combining grants, corporate direct investment, and limited venture capital. **Grants** require minimal financial returns (0–1) as compared to its risk ranking, **serving primarily as a de-risking mechanism for early-stage innovation.** Although venture and corporate investment introduce higher return potential to the stage, the overall cluster remains positioned below the Capital Market Line (CML). Returns are modest relative to risks, reflecting the inherent uncertainty and extended development cycles characteristic of this stage. The total capital injection here stood at **$4.9 billion**.

Early stage (orange cluster): Early-stage businesses demonstrate the strongest alignment with the CML, indicating optimal investor perception of risk-reward balance. **Venture capital dominates this space**, achieving a (3,3) risk-return ranking that reflects VCs' natural appetite for high-risk, high-return opportunities. **The stage also records the highest number of deal activities across the stages**. However, despite offering better risk-adjusted returns compared to R&D, the higher risk deters most investor classes beyond venture capital. Consequently, total capital raised remains relatively modest at **$3.5 billion** compared to other stages, demonstrating that while numerous investors support promising technologies at this stage, deployment amounts are insufficient to finance the transition to commercial scale.

Expansion stage (green cluster): The expansion stage is **characterized by debt and corporate direct investment dominance**. Debt instruments rank 2–3 for risk and 1 for return, reflecting capped upside potential and exposure to credit risk. This positioning places the cluster below the CML, creating a flat risk-return profile that explains why **expansion represents a critical bottleneck**. While producers require substantial capital to construct biorefineries, the lower risk-return trade-off makes the case for concessional capital to step in to support the growth. Although capital raised increases significantly to **$11.0 billion** at this stage, the expansion phase's capital-intensive nature creates a persistent financing gap that limits industry growth.

Mature stage (red cluster): Mature-stage financing gravitates toward debt (2–3 risk, 1 return) and public equity (2–3 risk, 2 return). This cluster occupies the lower end of the risk-return spectrum, reflecting constrained investor rewards. Despite attracting the largest capital flows at **$36.9 billion**, this profile demonstrates lender and market preference for scale and established revenue streams rather than innovation potential.

In summary, this chapter examines how sources of capital and risk–return profiles shift across biofuel development stages, reflecting the risks outlined in Chapter 4. Although a variety of investors participate, the sector as a whole remains below the Capital Market Line. The evidence shows that industry relies on concessional capital, especially in the form of debt, CDI and grants.

Closing these gaps will require more than financial structuring. Philanthropic funding and grants remain vital in the R&D and early stages, where risks are highest and commercial returns are uncertain. As projects move toward expansion and maturity, concessional capital and government policies become decisive in shaping demand, reducing uncertainty, and attracting sustained private investment. Fundamentally, these fundings should provide to address the risks described in Chapter 4 to help the industry grow and derisk. We will discuss these policy mechanisms in greater detail in the next chapter, focusing on how regulation and market design can better align incentives and support biofuels' path toward large-scale commercialization.

6 Implications for Policymakers in Supporting Biofuel Business

This chapter examines the cost dynamics of biofuels in comparison with other renewable energy sources, with a focus on the policies that can support biofuel commercialization. A key dimension of this comparison is the **Levelized Cost of Energy (LCOE)**. Although LCOE has steadily declined for most renewable technologies, biofuels continue to struggle with **higher cost structures** due to feedstock volatility and technological barriers. **Targeted policies** are therefore essential to close this gap. Instruments such as **subsidies, tax incentives, and blending mandates** can mitigate operational risks, enhance price competitiveness, and secure a stable demand base that enables producers to scale. Ultimately, the chapter highlights the **policy gaps** that must be addressed to move biofuels closer to cost parity with other renewables.

6.1 The Impact of Technological Limitations on LCOE

Biofuel technologies, especially the latter generations, have not yet achieved the cost breakthroughs seen in other clean energy sources. Most biofuel generations perform well in lab trials or pilot plants, but technical bottlenecks and cost overruns at larger scales (e.g., feedstock handling issues, reactor inefficiencies, and lower yields than expected) prevent them from achieving widespread commercialisation. For instance, cellulosic ethanol, a second-generation biofuel made from the non-food parts of plants, was once touted as imminently scalable. However, it has seen several high-profile commercial plant failures or underperformances in the 2010s, underscoring the difficulty of moving from pilot to full scale. (Pavlenko, 2018)

The LCOE for biofuels and bioenergy (e.g., biofuel-based power or heat generation) has thus **remained relatively high** compared to other clean energy sources. Unlike solar and wind power, which have seen dramatic cost declines over the last 10 years due to technology innovation and economies of scale, biofuel-related energy costs have remained largely stagnant. For instance, the median LCOE for bioenergy is roughly USD 92 per MWh, whereas solar power is USD 51 per MWh and onshore wind USD 58 per MWh (Timilsina, 2020). In fact, bioenergy's costs have not seen comparable improvement; IRENA (2025) reported a **minor increase of 1% in bioenergy LCOE** between 2010 and 2024, compared to the 70–90% reduction for solar and wind over the same period.

Table 15 summarizes the LCOE for various clean energy technologies. Biofuels remain at the high end of the cost spectrum among clean energy sources throughout the period from 2010 to 2024, implying that the **technology has not advanced enough to drive down the LCOE** to the levels of other renewables or even to compete with conventional energy on cost.

***Table 15**. The LCOE of various clean energy technologies (in USD/MWh)*

	Biofuel/ Bioenergy	Solar	Offshore Wind	Onshore Wind	Geothermal	Hydro
Minimum	41.40	14.11	55.97	27.42	29.22	16.60
Maximum	188.69	157.32	273.62	119.51	108.64	141.52
Median	92.41	50.70	130.81	58.43	56.90	49.74
Weighted Mean in 2010	86	417	208	113	55	44
Weighted Mean in 2024	87	43	79	34	60	57
Historical Change	+1%	−90%	−62%	−70%	+9%	+30%

Source: The minimum, maximum, and median LCOE values were derived from Timilsina (2020). The historical LCOEs for the year 2010 and 2024 were taken from IRENA (2025).

One reason for this stagnancy lies in the **nature of biofuel production**. Industrial biofuel production often relies on various feedstock types and multiple steps in a complex process, whose costs are not as easily lowered as manufacturing solar photovoltaic panels or wind turbines. According to the International Energy Agency (IEA, n.d. -b), emerging biofuels like cellulosic ethanol or SAF cost twice or thrice more per unit energy than fossil fuels on average. Even optimistic projections see those costs possibly declining by 27% over the next decade, leaving a gap that still needs to be bridged. Without intervention, then, the LCOE of biofuel will likely remain higher than other clean energy sources for the foreseeable future.

Crucially, this cost disadvantage exists *before* considering any government support. In the absence of policy support, investors and producers have little incentive to deploy biofuel projects that cannot compete on pure price. Even in countries with sizable biofuel industries, market forces alone have not closed the cost gap. For example, the United States and Brazil, two of the world's most established biofuel markets, have each reached plateaus and even faced setbacks in scaling later biofuel generations despite the strong initial growth of the first-generation fuels. The U.S. Renewable Fuel Standard (RFS), which mandated rising biofuel production, had to repeatedly slash its cellulosic biofuel targets because the industry failed to produce the intended volumes (Pavlenko, 2018). In Brazil, nationwide ethanol blending and the RenovaBio program have successfully expanded biofuel use, but the resultant growth needs to be sustained through more support. For instance, Brazil launched a new Sustainable Aviation Fuel program from 2027 to 2037 to spur innovation (Anselmi and Dupont, 2025). Without either a technological breakthrough or significant government intervention, biofuels' LCOE may remain high relative to other clean energy sources, necessitating a closer look at what types of policies can help close the cost gap.

6.2 Key Government Policies to Address High LCOE

To overcome the cost and risk hurdles facing biofuels, governments all over the world have deployed a range of policy measures. Broadly, three categories of policies have been identified as most critical to lowering the effective LCOE of biofuels in the future:

subsidies, mandates, and direct tax incentives. Each type targets different aspects of the LCOE; subsidies lower operational risks by sharing financial burdens, direct tax incentives improve the price competitiveness for producers and incentivize purchases for buyers, while mandates spurs market activities even when the LCOE is relatively higher, providing more certainty for producers.

6.2.1 Subsidies

This policy category **directly reduces the capital or operating expenditures (CAPEX or OPEX)** for biofuel producers, addressing significant related risks (e.g., feedstock cost volatility) that hamper **cost competitiveness**. Such subsidies typically take the form of either direct cash grants or price-based support mechanisms. The aim is to buffer producers against high upfront investments and ongoing costs unique to biofuels.

History shows that subsidies have been instrumental in scaling up other clean energy sources. Taking the example of solar energy, the Section 1603 grant programme, introduced under the American Recovery and Reinvestment Act in 2009, awarded US $25 billion in direct cash grants for solar investments through 2016, substantially lowering upfront capital costs and accelerating deployment of photovoltaic capacity (U.S. Department of the Treasury, 2018). In Europe, Germany's Renewable Energy Sources Act (EEG) provided feed-in tariff (FiT) scheme that guaranteed fixed payments for 20 years from the date of commissioning. It was first implemented in 2000 and mostly phased out in 2014, which supported the deployment of nearly 50 GW of capacity by 2016. (Clean Coalition, 2023)

Attempts to replicate this success for biofuel are evident in the various standard policy tools such as capital grants and price subsidies. On a global scale, grants are provided by many countries to spur the growth in advanced biofuels, such as EU Innovation Fund and U.S. Department of Agriculture's Advanced Biofuel Payment Program. In addition to grants for advanced biofuels, price subsidies are also implemented for more established products such as biodiesel. One notable example is Indonesia's Palm Oil Plantation Fund Management Agency (BPDPKS) which subsidizes the price differences between cost of palm oil-based fuel and fossil fuels. The fund is financed by the export levies collected from palm oil, aiming to promote domestic production and consumption (Reuters, 2024b). The subsidy addresses revenue stability risk, lowering the effective cost of production and thereby the LCOE that Indonesian biofuel producers require to break even.

6.2.2 Tax Incentives

Tax incentives like tax credits, rebates, and exemptions **directly boost the producer's bottom line** by either reducing upfront investment cost or rewarding output.

Tax credits for producers

Tax credits for producers are government incentives that reward producers for each unit of renewable fuel generated, or for capital and operational investments in biofuel facilities. The objective is to make biofuel production more financially viable and competitive with fossil fuels by **offsetting costs**, thereby **improving margins**. One common approach is a production tax credit. For example, under the Clean Fuel Production Credit, the U.S. offers a $0.20 per gallon tax credit for biofuels and $0.35/gal for SAF (DOE, 2025). This effectively lowers the cost per unit for producers by paying them for each gallon produced. Investment tax credits, which refund a percentage of capital investment, have also been used. Between 2012 and 2016, the state of Florida offered producers investment tax credits covering up to 75% of all capital, operation, maintenance, and R&D costs incurred associated with the production, storage, and distribution of biodiesel, ethanol or other renewable fuel, with a cap at $1 million annually per producer and $10 million annually for all producers (DOE, 2016).

Tax rebates for consumers

Tax rebates for consumers are government incentives designed to lower the effective cost of purchasing or using biofuels. Instead of directly subsidising producers, these rebates **reduce the financial burden on end-users**, stimulating demand for biofuels. By **improving affordability** and **market uptake**, consumer tax rebates indirectly encourage producers to expand supply and achieve economies of scale. Some countries simply reduce or waive fuel taxes on biofuels to make them more competitive at the pump. For instance, Brazil has a long-standing policy of lower excise taxes on ethanol and biodiesel compared to gasoline or diesel, which has recently been locked in for 20 years from 2022. Many EU member states likewise implemented tax exemptions for biofuels. Similarly, India reduced the Goods and Services Tax (GST) on ethanol supplied for blending with petrol from 18% to 5%, effectively acting as a tax rebate for consumers by lowering pump prices (PIB, 2021).

These tax measures enhance the price competitiveness of biofuels by either **cutting production cost (via tax credits to producers)** or **end-user cost (via fuel rebates)**. Such tax incentives encourage more investment in the sector, which over time can lead to technology improvements and cost reduction, thereby narrowing the LCOE gap.

6.2.3 Mandates

Blending mandates and renewable fuel standards define a minimum share of biofuels in the energy mix, **guaranteeing market demand**. By assuring producers that a market exists for their product, mandates help biofuel facilities achieve **economies of scale** and **steady revenues**. The U.S. Renewable Fuel Standard (RFS) is a prime example of this category, legally requiring fuel suppliers to blend specified volumes of biofuels into gasoline/diesel, effectively creating a captive market. Likewise, the EU Renewable Energy Directive (RED) sets binding renewable energy targets (including transport fuels), pushing EU member states to use biofuels. Over 80 countries, including European Union members and the US, have such related policies to drive the biofuel demand, most commonly blending mandates, indicating how widespread this policy category has become (IEA, n.d. b).

Mandates do not directly lower production cost, but by reducing market uncertainty and expanding scale, they indirectly drive the LCOE down in the longer timeframe through learning-by-doing and investment in larger biofuel plants. They also provide a **demand "floor"** that can justify new advanced biofuel projects, which otherwise might be too risky. For instance, Indonesia has an ambitious B40 biodiesel mandate (40% palm biodiesel blend), which ensures domestic consumption. The government also supplements it with subsidies in the form of crude palm oil levy to cover the cost gap (USDA FAS, 2024), thus sustaining one of the world's largest biodiesel programs.

6.2.4 Roles of the Three Policies

In summary, policy support is indispensable to drive biofuels' LCOE down to competitive levels. Without policy, advanced biofuels would remain technologically and economically confined to pilot phases. However, with a strategic mix of subsidies, mandates, and tax incentives, governments can help biofuel technologies bridge the cost gap.

These three policies address varying parts of the industry and work hand-in-hand to provide the foundational ecosystem for biofuels' scalability. On **the supply-side**, subsidies reduce the operational risks by reducing the upfront R&D and CAPEX costs and operating expenses. Tax incentives for producers help to improve cost competitiveness, while tax rebates for end-user enhances price competitiveness of biofuel products, thereby **linking supply and demand**. Lastly, demand mandates create stable markets that provide **demand certainty** for producers. Therefore, these three policies should be **collectively implemented** and **not done in isolation** to each other.

As technologies mature, subsidies can then be gradually phased out, ensuring long-term sustainability of the biofuel sector. Thus, reducing the LCOE of biofuels will hinge on both technological advancement and proactive policy intervention. While achieving cost-competitive and scalable biofuel production remains a challenge, biofuels can overcome their current limitations and play a vital role in the clean energy transition with sustained and well-designed policies.

For more policy-related information, please refer to the appendix. **Table 16** summarises the current implementation stage of the three policies across selected nations and regions. Notably, Singapore currently lags behind the policy leaders in the space, having just started to implement an SAF mandate and tax rebates on ship operators using low-carbon fuels. Moving forward, **there is much space to expand the policy support for biofuels in Singapore**. If designed well, these measures in tandem can accelerate technological learning and offset costs in the interim, thus significantly addressing the higher LCOE of biofuels in the future.

Table 16. *Comparison of biofuel-related policies across selected countries and regions*

Legend: Actively implemented | Preliminary phase | No action

	Subsidies (Operational Risks)	Tax Rebates (Price Competitiveness)	Mandates (Market Demand)
United States	**Biofuel Producers Relief Payment Program:** Up to $700 million for eligible producers (USDA, 2021)	**Clean Fuel Production Credit:** $0.20/gallon for non-aviation fuel and $0.35/gallon for SAF (DOE, 2025)	**Renewable Fuel Standard (RFS):** Mandates blending requirements (EPA, 2025)
Brazil	**BNDES:** $1 billion grants for SAF and maritime biofuel projects (Carbon Pulse, 2024)	**Reinstated lower tax** for biofuels than fossil fuels in 2022, for 20 years (Barros & Teixeira, 2022)	**BNDES RenovaBio:** Reduce carbon intensity and create carbon credit market (CBIOs) (IEA, 2025)
European Union (EU)	**Innovation Fund**: €1.1 billion(1st call), €3 billion (3rd call) to support advanced biofuel projects (DG CLIMA, n.d.)	**Member State Tax Reductions/ Exemptions**: Not all member states offer tax benefits for biofuel use	**Renewable Energy Directive (RED II):** Legally binding EU-wide renewable energy targets of 32% by 2030 (EBA, 2025)
China	*Scaling back on biofuel subsidies*	–	**Ethanol Blending Mandate (E10):** Suspended (USDA FAS, 2020)
India	**Capital subsidy:** Up to 30% of the total project cost is funded to establish biofuel production plants (Advance Biofuel, 2025)	**Income tax rebates**, **Carbon credits**, **Green energy certificates**, **GST exemptions** (Advance Biofuel, 2025)	**Ethanol Blending Program (EBP):** Achieved 20% ethanol blending target by 2025-26 (News on Air, 2025)
Indonesia	**Price Gap Subsidies**: $1.2 billion subsidies for the price difference between biodiesel and fossil diesel (USDA FAS, 2024)	**Lower income tax, accelerated depreciation** , and **Carbon economic value scheme** (Carbon pricing) (OECD, 2015), (Mubarak, M.R., 2025)	**Biodiesel Blending Mandate:** Fully implemented B40 mandate, which blends 40% palm oil with 60% diesel and is targeting to roll out B50 mandate by early 2026 (Issac, 2025)
Singapore	–	**Maritime Singapore Green Initiative:** Tax rebates on ships operators using cleaner fuels only, not for producers (MPA Singapore, 2025)	**SAF Mandate:** 1% in 2026, 3-5% by 2030 (S&P Global, 2024)

Source: Compiled by authors; Note: For more policy-related information, please refer to the appendix.

7 Conclusion

To conclude, the transition towards a sustainable and secure energy future requires a suite of solutions, with biofuels serving as one of the critical pathways in this journey. The four generations of biofuel reflect a trajectory of innovation, each seeking to overcome the limitations of its predecessors. They offer the potential to reduce GHG emissions and diversify the clean energy supply. While it looks promising, the widespread adoption and commercialisation of biofuels remain constrained by technological, financial and policy challenges.

For producers, this whitepaper aims to provide more information on the different ways to strengthen business models, be it through diversifying their revenue streams, capturing value from the by-products, or adopting the circular business model. Concurrently, biofuel production is not without its business risks. The five business risks we discussed earlier in the whitepaper continue to pose challenges that can deter investment and slow growth. Recognising these risks and preparing strategies to mitigate them will be as important as identifying new revenue opportunities.

For financiers, we hope our whitepaper reveals the need to assess projects not only on their promise of returns but also on their risk management strategies.

Our analysis also reveals a persistent financing gap from private capital, as the risk-return profile of biofuel producers remain below the capital market line across all stages of development. As such, policy frameworks will play a critical role in bridging this gap by de-risking investments and mobilising more concessional capital flows into the sector.

Policy support has been critical in advancing biofuels, but gaps remain. Inconsistent mandates, shifting subsidies, and fragmented sustainability standards hinder investor confidence and limit the ability to secure long-term investments.

Looking ahead, we believe there are three key directions to help the biofuel industry reach its potential.

1) **Accelerating technology** through sustained investment in R&D to increase the efficiency and yield of current biofuel technology.
2) **Mobilising capital at scale** to help biofuel producers sustain through the various business stages.
3) **Strengthen the global policy framework** to ensure greater consistency and enforcement of sustainable standards to accelerate the adoption of biofuels.

Biofuels alone will not solve the climate crisis, but they are still vital in the fight against climate change. This is especially so in the hard-to-abate transportation sectors like aviation and shipping. With coordinated efforts from producers, financiers, policymakers, and consumers, biofuels can drive meaningful progress toward decarbonisation.

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Appendix - Biofuel-related Policies Across the World

United States

1. **Higher Blends Infrastructure Incentive Program (HBIIP):**
    a. The U.S. Department of Agriculture (USDA) administers HBIIP to increase the availability of higher ethanol and biodiesel blends. In August 2022, USDA began accepting applications for $100 million in grants to expand biofuel infrastructure (USDA, 2022). These grants cover up to 75% of project costs, with a maximum of $5 million per project, assisting facilities in converting to higher-blend fuels.
2. **Biofuel Producer Program:**
    a. Authorized by the Coronavirus Aid, Relief, and Economic Security (CARES) Act, this program allocated $700 million in December 2021 to provide economic relief to biofuel producers affected by the pandemic (USDA, 2021). The funds aimed to restore renewable fuel markets and support industry stability.
    b. Example: Department of Energy (DOE) Loan Guarantees: In October 2024, the DOE approved conditional loan guarantees totalling nearly $3 billion for two sustainable aviation fuel (SAF) projects (U.S. News & World Report, 2024):
        i. Calumet Inc: Received up to $1.44 billion to expand its Montana facility, aiming to produce approximately 315 million gallons per year of biofuels, primarily SAF (Sunny, 2024).
        ii. Gevo, Inc.: Secured up to $1.46 billion for a corn starch-to-jet fuel facility in South Dakota, marking the first commercial-scale U.S. plant to convert corn starch to SAF with carbon capture and renewable power (Sunny, 2024).

Brazil

1. **RenovaBio:**
    a. The National Biofuels Policy, RenovaBio, was introduced to decrease the carbon intensity of Brazil's transportation fuel matrix. It sets annual decarbonization targets and incentivizes biofuel producers through the issuance of Decarbonization Credits (CBIOs), which can be traded in financial markets. This market-based approach encourages the production and use of renewable fuels over fossil fuels.
2. **BNDES RenovaBio Program:**
    a. To support the objectives of RenovaBio, the Brazilian Development Bank (BNDES) established the BNDES RenovaBio Program, offering loans to biofuel producers to enhance energy-environmental efficiency. The program initially allocated BRL 1 billion (approximately USD 195 million) in 2021, with individual loans capped at BRL 100 million per production unit. In May 2022, BNDES doubled the program's budget to BRL 2 billion (around USD 390 million) to meet growing demand (Global Trade Alert, 2022). Companies that achieve specified CO_2 emission reduction

targets benefit from reduced interest rates, incentivizing sustainable practices.

b. Example: Usina Santa Adélia S.A.
    i. In May 2021, the Brazilian Development Bank (BNDES) approved a R$100 million (approximately USD 20 million) financing for Usina Santa Adélia S.A., a biofuel production unit located in Jaboticabal, São Paulo (BNDES, 2021). This funding, part of the BNDES RenovaBio Program, aims to enhance the company's energy-environmental efficiency, with incentives linked to achieving specific carbon emission reduction targets.

3. **Future Fuel Law:**
    a. Enacted in October 2024, the Future Fuel Law aims to attract investments in biofuels, including ethanol, biodiesel, sustainable aviation fuel (SAF), green diesel, biomethane, and carbon capture technologies. The law is expected to generate BRL 260 billion (approximately USD 47 billion) in investments over the coming years. It increases the mandatory ethanol content in gasoline to between 27% and 35% by 2030 and raises the minimum biodiesel content in diesel to 20%, benefiting Brazil's agribusiness sector (Government of Brazil, 2024).

<u>Singapore</u>

1. **Singapore Green Plan 2030:**
    a. All new harbour craft operating in our port waters to be fully electric, be capable of using B100 biofuels, or be compatible with net zero fuels from 2030 (SG Green Plan, n.d.-a).
2. **Maritime and Port Authority (MPA) Initiatives:**
    a. Marine Biofuel Standards: In preparation for a multi-fuel bunkering future, the MPA has developed the world's first provisional national quality standard for marine biofuels, specifically for biofuel blends of up to 50% (B50). This standard ensures the quality and safety of biofuels supplied within the Port of Singapore.
    b. The MAP pledged up to S$100 million over five years to promote clean and green shipping. This initiative includes incentives for adopting biofuels in maritime operations, supporting the reduction of environmental impact in shipping activities (SG Green Plan, n.d.-b).
3. **Sustainable Aviation Fuel (SAF) Adoption:**
    a. The Singapore Sustainable Air Hub Blueprint was launched on Feb. 19. It was developed by the Civil Aviation Authority of Singapore in consultation with industry and other stakeholders and aims to decarbonize the country's aviation sector. Under the blueprint, CAAS will work with aviation stakeholders to reduce domestic aviation emissions from airport operations by 20% by 2030 when compared to a 2019 baseline. The program aims to achieve net-zero domestic and international emissions by 2050 (Voegele, 2024).

   b. Airline Commitments: Singapore Airlines and its subsidiary, Scoot, have set a target to replace 5% of their total fuel requirements with SAF by 2030 (SIA/Scoot, 2023). This commitment underscores the airlines' dedication to reducing carbon emissions and supporting the development of a sustainable aviation ecosystem.

4. **Enterprise Financing Scheme:**
   a. Aligned with the Singapore Green Plan 2030, EFS-Green assists local companies in developing capabilities within the green economy, including biofuel projects. It offers various loan types, such as Developmental Capital Loans (up to S$3 million) and Fixed Asset Loans (up to S$30 million), to support green initiatives. The total borrower group limit exposure is S$50 million for EFS-Green and EFS combined (Enterprise Singapore, n.d.).
5. **SG Eco Fund:**
   a. Launched by the Ministry of Sustainability and the Environment, this S$50 million fund supports ground-up projects that advance environmental sustainability, including biofuel-related initiatives. It operates on a co-funding basis, providing up to 80% of supportable cost items, subject to a maximum of S$1 million (MSE, 2024).

<u>China</u>

1. **Ethanol Blending Mandate:**
   a. In 2001, China initiated pilot programs mandating the blending of 10% ethanol (E10) with gasoline in select provinces. By 2004, this mandate expanded to additional regions, with the government announcing plans in 2017 to implement a nationwide E10 mandate by 2020 (IEA, 2024-c). However, due to concerns over grain supply and other challenges, the nationwide rollout has been delayed.
2. **Production Subsidies:**
   a. Between 2008 and 2010, the government provided flexible subsidies to bioethanol producers, averaging approximately $0.20 per liter in 2008, $0.19 in 2009, and $0.17 in 2010 (Zhao, 2015). These subsidies aimed to offset production costs and encourage bioethanol output.
3. **Establishment of SAF Technical Center:**
   a. In July 2024, the Civil Aviation Authority of China (CAAC) inaugurated the country's first technical center dedicated to sustainable aviation fuel in Chengdu (Reuters, 2024a). This center is responsible for policy formulation, setting industry standards, and ensuring product quality control for SAF, aiming to decarbonize China's aviation sector.
   b. Investments in SAF Production: Chinese biofuel companies are investing over $1 billion USD to construct facilities that convert waste cooking oil into aviation fuel. These plants are projected to produce more than one million metric tons of SAF annually, addressing approximately 2.5% of China's current aviation fuel demand.

European Union

1. **The revised Renewable Energy Directive:**
    a. It establishes binding targets for the share of renewable energy in the transport sector, including maritime and aviation. By 2030, EU countries are required to either achieve a share of 29% of renewable energy in transport, or to reduce the emissions intensity of transport fuels by 14.5%, as well as a combined sub-target for renewable hydrogen and advanced biofuels of 5.5% (European Commission, n.d-a
2. **Innovation Fund:**
    a. The EU's Innovation Fund supports the commercialization of innovative low-carbon technologies, including advanced biofuels. It provides funding for large-scale projects that contribute to greenhouse gas reduction. For example, the fund has allocated substantial grants to biofuel projects across Europe, such as the construction of advanced biofuel production facilities.
    b. Details: Revenue of more than 38 billion Euros (40 billion USD) until 2030 from the EU Emissions Trading System, the Innovation Fund aims to create the right financial incentives for companies and public authorities to invest in the next generation of low-carbon technologies and give EU companies a first-mover advantage to become global technology leaders (European Commission, 2022).
    c. First call: grants of 1.1 billion Euros to 7 projects in energy-intensive industries, hydrogen, carbon capture, use and storage, and renewable energy (Open Access Government, 2022).
    d. Second call: 17 projects were selected under the second call for large-scale projects, meaning they have capital costs above 7.5 million Euros
    e. Third call: 3 billion Euros estimated

India

1. **National Biofuel Policy:**
    a. Aim to achieve a 20% ethanol blending target by 2030, promoting the use of biofuels derived from non-food feedstocks. In 2022, this target was advanced to 2025-26, reflecting the government's commitment to accelerating biofuel adoption.
2. **Viability Gap Funding:**
    a. To support the establishment of Second Generation (2G) ethanol biorefineries, the policy introduced a viability gap funding scheme amounting to ₹5,000 crore (approximately USD 675 million) over six years (PIB, 2018). This funding aims to make advanced biofuel projects financially viable.
3. **Tax incentives:**
    a. To stimulate biofuel blending, the government has expanded excise duty exemptions. In July 2022, the exemption for ethanol blended with gasoline was increased from 10% to 12%-15% (Reuters, 2022). For diesel,

a 20% portion of alkyl esters of long-chain fatty acids derived from vegetable oils now qualifies for the exemption.

b. The Goods and Services Tax (GST) rate for biodiesel supplied to Oil Marketing Companies (OMCs) for blending with diesel was reduced from 12% to 5% in October 2021, making biodiesel more cost-competitive (PIB, 2023).

<u>**Indonesia**</u>

1. **Biodiesel Blending Mandate:**
    a. B35 and B40 Programs: Indonesia has progressively increased its biodiesel blending mandates, with the B40 program (40% biodiesel blend) implemented nationwide in January 2025 to reduce carbon dioxide emissions by approximately 40 million metric tons (Sipahutar, 2024). The government plans to introduce the B50 mandate (50% biodiesel blend) by 2026 (Reuters, 2025).
2. **Oil Palm Plantation Fund Management Agency (BPDPKS):**
    a. This organisation provided IDR 28.01 trillion (approximately USD 1.7 billion) in incentives for the production of 8.42 billion litres of biodiesel in 2020; in 2021, it is expecting to provide IDR 45 trillion (approximately USD 2.8 billion) for the production of 9.2 billion litres (IEA, 2023-d).
3. **Indonesia Biofuel Producer Association:**
    a. To support the government's program in developing the usage of biofuels as the new energy in Indonesia, APROBI (Indonesia Biofuel Producer Association), which consists of biodiesel and bioethanol companies, builds a partnership with the Government and other parties regarding optimising the usage of biofuels in Indonesia, which is also being supported within international forums (APROBI, n.d.).