InformBio
Integrated Framework for Mapping, Modelling and Monitoring Ireland's Bioeconomy

An Roinn Talmhaíochta, Bia agus Mara
Department of Agriculture, Food and the Marine

InformBio National Bioeconomy Foresight Study

UNLOCKING IRELAND'S BIOECONOMY:

A 2050 NATIONAL STRATEGIC FORESIGHT REPORT

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EXECUTIVE SUMMARY

In 2018, the Irish government published its National Bioeconomy Policy Statement, recognising the role of the bioeconomy as a sustainable economic model and building on the developments of the European Commission's 2012 Bioeconomy Strategy. Since then, the bioeconomy has gained momentum at European and national level. This has been reflected in updates to the European Strategy in 2018 and again in 2025, as well as the publication of Ireland's first Bioeconomy Action Plan 2023-2025.

Significant investment has taken place at EU level, with over €5 billion being leveraged through the Bio-based Industries Joint Undertaking (2014-2020) and the Circular Bio-based Europe Joint Undertaking (2021-2027) initiatives to mobilise public and private funding. In Ireland, the government has invested over €57 million in the bioeconomy, supporting a range of pilot and demonstration initiatives across the sector. These investments help to resolve technological challenges associated with scaling up emerging technologies, whilst also improving stakeholder awareness, confidence, and capacity for wider commercial deployment.

This Foresight Report has been developed by the InformBio project to take stock of the current bioeconomy situation in Ireland and explore the vast untapped potential of Ireland's bioeconomy towards 2050, with a specific focus on meeting future climate and sustainability targets. InformBio is funded by the Department of Agriculture, Food and the Marine. The use of strategic foresight is a key tool for supporting robust decision-making in the midst of uncertain futures. The report attempts to answer a number of key questions which are summarised below and discussed in more detail throughout the chapters.

Chapter 2 of this reportfocuses on exploring the status quo or "Where we are now?". This research evaluated the strengths of Ireland's raw biomass material by utilising a Bioresource Mapping Tool to investigate over 200 primary and secondary biomass streams that cover over 50 million tonnes dry matter of raw materials generated annually, whilst also considering locations, fates, and compositions to assess suitability for future use. The resultant open access resource highlights the biomass potential of Irelands agri-food, forestry and marine sectors.

The next stage of the work answered, "What can be done?", exploring the future possibilities for using these resources within a circular bioeconomy in Ireland. This step considered a wide range of potential technological solutions for developing bio-based value chains based on these resources. Following a screening of potential value chains, five were selected for a deeper analysis using detailed analytical frameworks including life cycle assessment and techno-economic assessment to understand their environmental and economic viability. The results showed that these bio-based value chains can be a very effective mechanism for improving environmental sustainability. In addition to reducing greenhouse gas emissions compared with fossil-based alternatives and other unsustainable incumbent value chains, they can also contribute to more efficient resource use, reduce dependence on finite fossil resources, enhance circularity, and generate wider environmental benefits across the value chain. These value chains can, however, face challenging economic returns and may require targeted policy support in the short term, such as rewards for mitigation to improve their viability. Over the longer term, many of these value chains are also developing integrated cascading approaches aimed at producing higher-value products, which will help to strengthen the economic performance and long-term competitiveness of these value chains.

Following this, the report addressed the question, "What could the future look like?", through strategic foresight assessment of different futures using the OptiGOB model, which is designed to explore potential configurations of Ireland's agriculture, forestry, and other land use (AFOLU) sectors. Taking account of Ireland's Climate Action Plan target of achieving a climate neutral economy by 2050, the research compared a bioeconomy-focused Irish future (BE) – incorporating the scaled value chains explored in the previous chapter – with a business as usual (BAU) pathway over a 2050-time horizon, considering both environmental sustainability and resilience. Under the BAU pathway, net emissions are projected to increase to 29.7 Mt CO_2e by 2050, leaving the sector far adrift of national and international regulatory targets. In contrast, the BE pathway was able to achieve climate neutrality by 2050. This scenario considered ambitious afforestation, drastically reducing AFOLU emissions while

contributing new biomaterial supply to avoid emissions from concrete, steel and fossil energy, and considered ambitious expansion of technical carbon dioxide removals (Bioenergy with carbon capture and storage, Bioenergy with Carbon Capture and Sequestration, and/or biochar). Additionally, the bioeconomy pathway achieved significant reductions in environmental externalities, including air and water quality, compared to BAU by 2050 relative to 2020, while substantially increasing high nature value land. Importantly, the bioeconomy pathway achieved these environmental impacts reductions whilst increasing total protein output by 47% (via green biorefineries, crop protein, and more milk output) and increasing domestic bioenergy five-fold. Considered within the context of different Shared Socioeconomic Pathways used to reflect the range of uncertain possible futures, a risk screening across nine factors (including commodity price volatility, insolvency, and climate impacts) revealed that the bioeconomy pathway is less exposed to risk, and therefore more resilient, across the range of possible futures.

Finally, the report considered, "How do we get these futures", and provides details of engagement with stakeholders to ascertain perspectives on what will be required to bring these bioeconomy value chains into reality, while also detailing project perspectives on policy steps that could be introduced to support deployment. The report also highlights the need to set targets and measure progress towards a circular bioeconomy. In this context, the report provides details on a new Bioeconomy Monitoring Framework which has been designed within the InformBio project, and which will support efforts to track progress across a range of targeted indicators aligned with different pillars of Ireland's Bioeconomy Action Plan.

While achieving the bioeconomy futures detailed in this report requires a fundamental shift and degree of risk for farmers and other actors, it is evident from this report that the risks involved are much lower than the severe risks of not transitioning to a circular bioeconomy at all. Overall, the report provides a strong evidence-base that the bioeconomy can be critical to help Ireland to achieve climate neutrality, and could ultimately achieve a more resilient, sustainable, and vibrant rural economy.

Further details and access to full project reports can be found at the **InformBio Project Website** and **InformBio Zenodo repository**.

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ACRONYMS

ABBREVIATION	DEFINITION
AD	Anaerobic Digestion
AFOLU	Agriculture, Forestry, and Other Land Use
BAU	Business As Usual
BBVCs	Bio-Based Value Chains
BE	Bioeconomy-Focused Irish Future
BECCS	Bioenergy with Carbon Capture and Sequestration
BEP	Break-Even Price
Bio ERA	Bio Based Feedstock Environmental Risk Assessment
BMT	Bioresource Mapping Tool
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CRCF	Carbon Removal Certification Framework
CSO	Central Statistics Office
DAFM	Department of Agriculture, Food and the Marine
DCEE	Department of Climate, Energy and the Environment
DM	Dry Matter
EPA	Environmental Protection Agency
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gas
GIS	Geographical Information System
GOBLIN	General Overview for a Back-Casting Approach of Livestock Intensification
HNV	High Nature Value
LCA	Life Cycle Assessment
LCOB	Levelised Cost of Biomethane
LPC	Leaf Protein Concentrate
LULUCF	Land Use Land Use Change & Forestry
NPV	Net Present Value
OPEX	Operating Expenditure
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal
PF	Primary Feedstock
PF—liquid	Liquid Primary Feedstock
PF—solid	Solid Primary Feedstock
SEAI	Sustainable Energy Authority of Ireland
SF	Secondary Feedstock
SF—liquid	Liquid Secondary Feedstock
SF—solid	Solid Secondary Feedstock
SSPs	Shared Socioeconomic Pathways
tDCR	Technical Carbon Dioxide Removal
tDM	Tonnes of Dry Matter
TEA	Techno-Economic Assessment
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change

1. INTRODUCTION

The European Commission has placed the bioeconomy as a key component of its plan to transition to a sustainable economy since the introduction of its first Bioeconomy Strategy "Innovating for Sustainable Growth" in 2012. This strategy prompted a growing interest in the development of bio-based feedstocks, technologies, and products as alternatives to fossil-based materials and energy, providing a pathway to help Europe to meet its sustainability targets while also driving innovation and economic opportunities.

This strategy was updated in 2018 to sharpen its focus on sustainability, circularity, and the need to operate within safe ecological limits (European Commission, 2018). Specifically, it recognised biomass limitations and the need for careful resource management to avoid over-exploitation. To achieve this, the updated strategy discussed the need to acquire more data and develop systemic analysis to enhance the knowledge base and understanding of specific bioeconomy areas including biomass availability and status and resilience of terrestrial and marine systems. It also pointed to forward-looking activities including modelling, foresight exercises and scenarios to improve this knowledge base and emphasised the need for sustainability and circularity to be at the heart of the bioeconomy (European Commission, 2018). The 2018 strategy was revised and updated again in 2025, emphasising a greater focus towards industrial deployment, market scale-up, competitiveness and resilience (European Commission, 2025). The strategy update once again indicates that the bioeconomy will rely on foresight activities informing its sustainable development and again committing to strengthen modelling and data via the Commission's **Knowledge Centre for Bioeconomy**. To strengthen data related to the developing bioeconomy, the European Commission also launched an **EU Bioeconomy Monitoring System** in 2020, an action outlined in the 2018 strategy. This system helps to track the bioeconomy's progress towards sustainability in the EU and covers a range of pertinent indicators covering economic, environmental and social dimensions of the bioeconomy.

At the national level, Ireland has been gaining momentum in developing its own circular bioeconomy. The government launched a Bioeconomy Policy Statement in 2018, presenting an ambition to be a global leader for the bioeconomy through a co-ordinated approach that harnesses Ireland's natural resources and competitive advantages. Crucially, the policy aims to maximise these opportunities while proactively monitoring and avoiding unintended consequences.

The document also emphasises that harnessing the bioeconomy will allow Ireland to look beyond mere target compliance and carbon mitigation, ultimately embedding sustainable economic development into the country's core economic model as we transition to a low carbon and circular economy (Department of An Taoiseach, 2018).

The government then published a Bioeconomy Action Plan 2023-2025. The action plan is built on several pillars and includes more comprehensive commitments and 33 actions to support scaling Ireland's sustainable bioeconomy (DECC & DAFM, 2023). The action plan sets out guiding principles including; sustainability, cascading, precautionary, food-first and area-based local and regional development. Among its actions is Action *1.3 Support the development of a bioeconomy observatory for a sustainable and circular Irish bioeconomy* and *Action 3.1 Promote the bioeconomy as a key tool to deliver on our emissions reduction targets for 2030 and 2050*, which includes a sub action to ensure bioeconomy development is considered in modelling, foresight, and scenario planning to resolve multiple pressures on land and sea for mitigation, nature protection and supply of biomass for food systems and the bioeconomy.

Within this policy context, InformBio has been funded by the Department of Agriculture, Food and the Marine. InformBio aims to support preparations for a bioeconomy observatory for a sustainable and circular bioeconomy by developing an Integrated Framework for the Mapping, Modelling and Monitoring of Irelands BIOeconomy. The project approach involves mapping and analysing Ireland's sustainable raw material base and bio-based value chain opportunities; strategic foresight modelling of bioeconomy scenarios to understand their potential to help Ireland meet its sustainability targets; and monitoring the impact of the bioeconomy in the form of a prototype bioeconomy monitoring system. The activities of the project are presented in Figure 1.

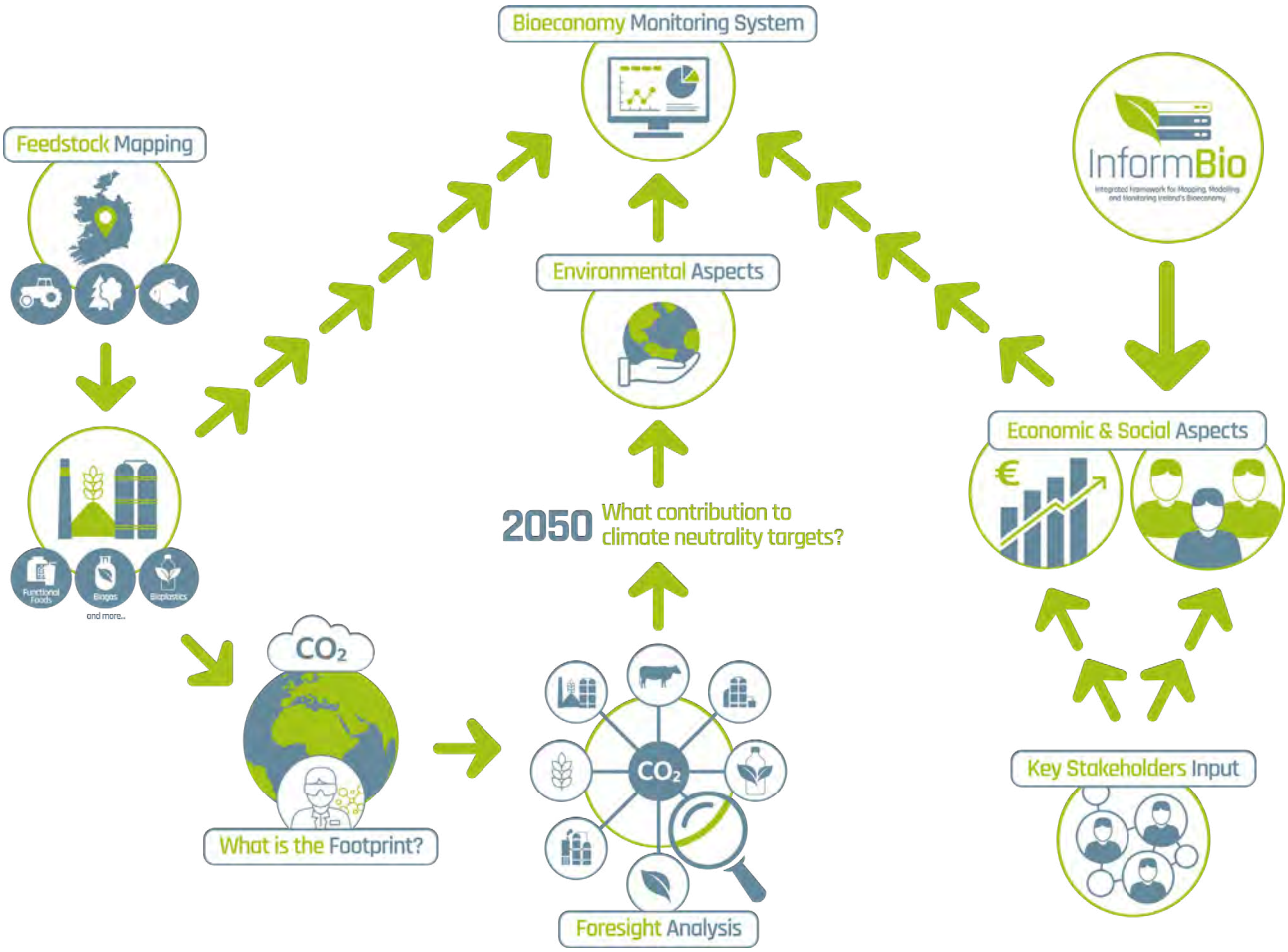


Figure 1.

InformBio Approach

Box 1: Strategic Foresight Definition

Strategic foresight is the structured evaluation of alternative futures based on relevant scientific, technical and socio-economic knowledge and insight. It differs from economic forecasting that tends to extrapolate recent trends, by deliberately considering a wider range of plausible outcomes. As such, strategic foresight does not aim to predict the future but rather examines critical vulnerabilities or opportunities that could manifest under different futures. This provides evidence needed for robust decision making in the midst of uncertainty – an inescapable reality for long-term strategic decision making necessary for land use policy.

Ireland has significantly increased it's funding for bioeconomy research activities over the last number of years. In 2023, O'Connor et al. (2023) published the synthesis report *Circular Bioeconomy Outlook Study: 2030-2050 in Support of Climate Action*, Sustainable Food and Biobased Systems. The report references that €57 million had been allocated for bioeconomy research. This, along with subsequent funding, has been allocated to research at different Technology Readiness Levels (TRL) levels including fundamental research (TRL 1-3), pilot activities (TRL 4-5) and demonstration activities (TRL 6-7). This includes funding for a number of pilot and demonstration activities including biorefining, biochar, and bioenergy activities. The work of InformBio helps to assess the scalability of such technologies and simulate the ability of these technologies to deliver quantifiable mitigation impacts in line with national targets. This modelling activity forms a fundamental part of this Foresight report. In addition, the foresight report captures some of the techno-economic challenges associated with these technologies, including recommendations for their implementation.

The structure of this report is summarised in Figure 2. *Chapter 2 Where are we now?* begins with a status quo review focused on assessing Ireland's bioresource availability, composition and flow to understand the fundamental basis for developing Ireland's bioeconomy and a summary of InformBio's mapping of over 200 potential feedstocks.

Chapter 3 What can be done? builds on Chapter 2 by considering the potential deployment of bio-based value chains considering Ireland's raw material base. This summarises a wide range of potential value chains for Ireland's bioeconomy considered within the project and a screening process to select 5 specific future bio-based value chain deployment scenarios for more in-depth analysis using environmental life cycle assessment and techno-economic assessment. *Chapter 4 What could the future look like?* uses a backcasting approach using the OptiGOB (GOBLIN-based, General Overview for a Backcasting approach of Livestock Intensification) land-balance model which helps to project the impacts of outscaling of these technologies over different future scenarios and time horizons, to quantify the potential impact on future sustainability, including national greenhouse gas emissions. Finally, *Chapter 5 How do we get to these futures?* provides recommendations for outscaling based on foresight and stakeholder inputs including PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) analysis. The chapter also presents a new Bioeconomy Monitoring Framework developed within the InformBio project which will be used to provide a status quote update of Ireland's bioeconomy against key environmental, social and economic indicators. The approach allows us to take stock of the current situation while using analytical frameworks and scenario-based modelling to make projection on future outcomes and steps towards achieving these.

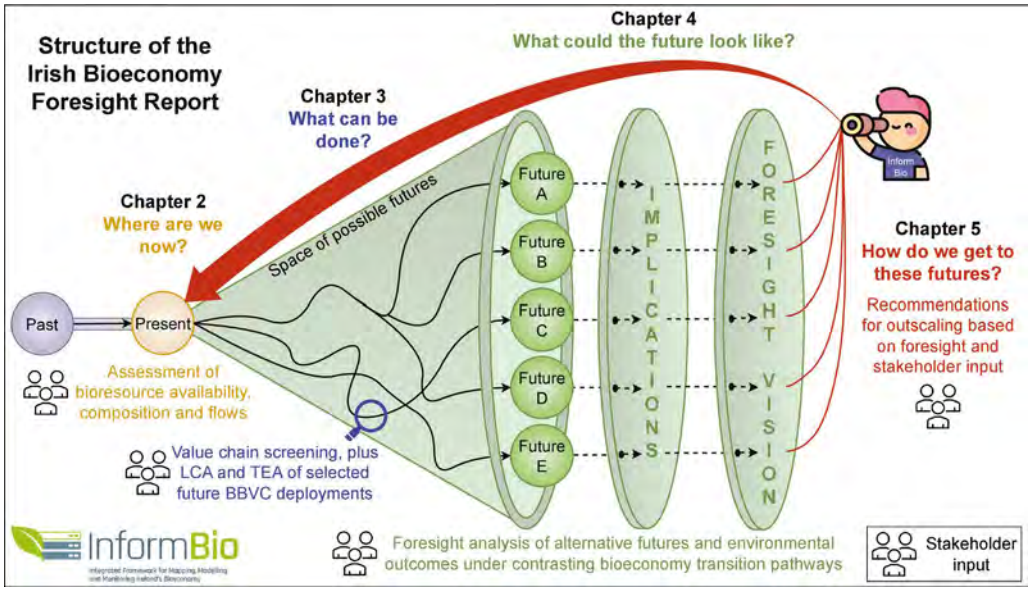


Figure 2.

Structure of InformBio Irish Bioeconomy Foresight Report

2. WHERE ARE WE NOW?

The current EU bioeconomy policy framework and the subsequent national policy background aim for a sustainable and circular Irish bioeconomy that will help boost the Irish economy, reduce national emissions, and integrate sustainable development into Ireland's economic framework. Irish and EU bioeconomy policy frameworks support research activities focused on sustainable biomass availability in order to ensure a bioeconomy operates within ecological limits and to support the development of an evidence-informed bioeconomy observatory.

In this context, the InformBio project has performed an assessment of *biological raw materials* to quantify, characterise, and map 221 primary (PF) and secondary (SF) feedstocks (See Box 2 for definitions), covering both solid and liquid streams in Ireland for use within the bioeconomy.

The feedstock analysis informs the question "Where are we now?" by shedding insights into the status quo and fundamental biomass basis for developing a bioeconomy in Ireland.

Box 2: Definitions

Feedstock: A raw material that goes into a process or plant as input to be converted into a product (Digital Europa Thesaurus, 2024). Biomass regardless of its value (waste, by-product, co-product, input) is considered feedstock.

Primary feedstock (PF): Biomass for which agriculture crops, silviculture fields, fish, or livestock are grown, caught, or raised. Moreover, this includes biomass used as input for industrial or other processing to generate main products. Examples of primary feedstocks are grains, meat, dairy, timber, beverages, etc.

Secondary feedstock (SF): Biomass that is obtained from a production process that does not aim to produce this form of biomass as a primary product. Secondary feedstocks can be grouped into by-products, co-products, and waste. Examples are straw or barley spent grain from brewing.

Bioresource: non-fossil biogenic resources which can be used by humans for multiple purposes: to produce food, products and/or energy (Pitcairn et al., 2017).

Fate: The current use of the outputs of a process. This applies to both primary and secondary feedstocks. Feedstocks may have several uses; therefore, fate is provided in percentages (%).

Besides the quantification of feedstocks at county level, validated by almost 40 interviews with key stakeholders, the InformBio project collected literature on chemical composition of feedstocks (macro- and micronutrients), current uses (fates), estimations of feedstock pricing, and bioresource availability (See Box 2); which are included in the **"Bioresource Mapping Tool (BMT)"** an open-access database (also included in the **InformBio Zenodo Repository**. Moreover, Geographical Information System (GIS) maps were created to visualise quantification of feedstocks at county-level and Sankey Diagrams were prepared to represent feedstocks' fate as material flow visualisation aids, complementing the BMT.

The work draws on multiple databases, peer reviewed literature, and expert interviews. The overall methodology followed for this assessment is explained in Figure 3. More details about the methodology can be found in Girón-Domínguez et al. (2026) and in the **InformBio D2.1 BMT**, and the **InformBio D2.2 Report** series. This methodology provides a replicable blueprint for future studies in Ireland and other EU member states. Results support stakeholders in identifying viable raw materials for bio-based value chains (BBVCs), where feedstock availability is as critical as processing technology or economic value (See section 3 for more details in BBVCs).

Figure 3.

Overall InformBio Methodology for the Quantification of 221 Feedstocks as Biological Raw Materials at County Level. Adapted from Girón-Domínguez Et Al. (2026) and InformBio D2.2 Report.

The outputs from this assessment may require future updates, refinement (See Box 3), and expansion as new data become available, so foresight, planning and innovation aimed at optimising bio-based feedstock utilisation in Ireland can be evidence informed.

Box 3: Limitations of the Feedstock Mapping

- Feedstock availability estimates are theoretical, not accounting for technical, economic, or legal constraints.
- Uncertainty arises from:
  - variable conversion factors,
  - data gaps,
  - limited sector-specific information.
- Results should therefore be interpreted with caution.

To support the sustainable growth and diversification of Irish feedstocks and avoid unintended environmental impacts, the InformBio project developed the Bio-based feedstock Environmental Risk Assessment (Bio-ERA) Framework, a rapid upstream sustainability screening tool. Building on a desk-based assessment and stakeholder validation, a study identified new and under-utilised crops, and biogenic CO_2 as potential future feedstocks for Ireland's circular bioeconomy. The Bio-ERA Framework applies consequential life-cycle thinking to enable early-stage identification of environmental risks associated with increased feedstock demand, supporting informed decision-making before investment lock-in occurs (Figure 4). Further details can be found in Bishopet al. (2025).

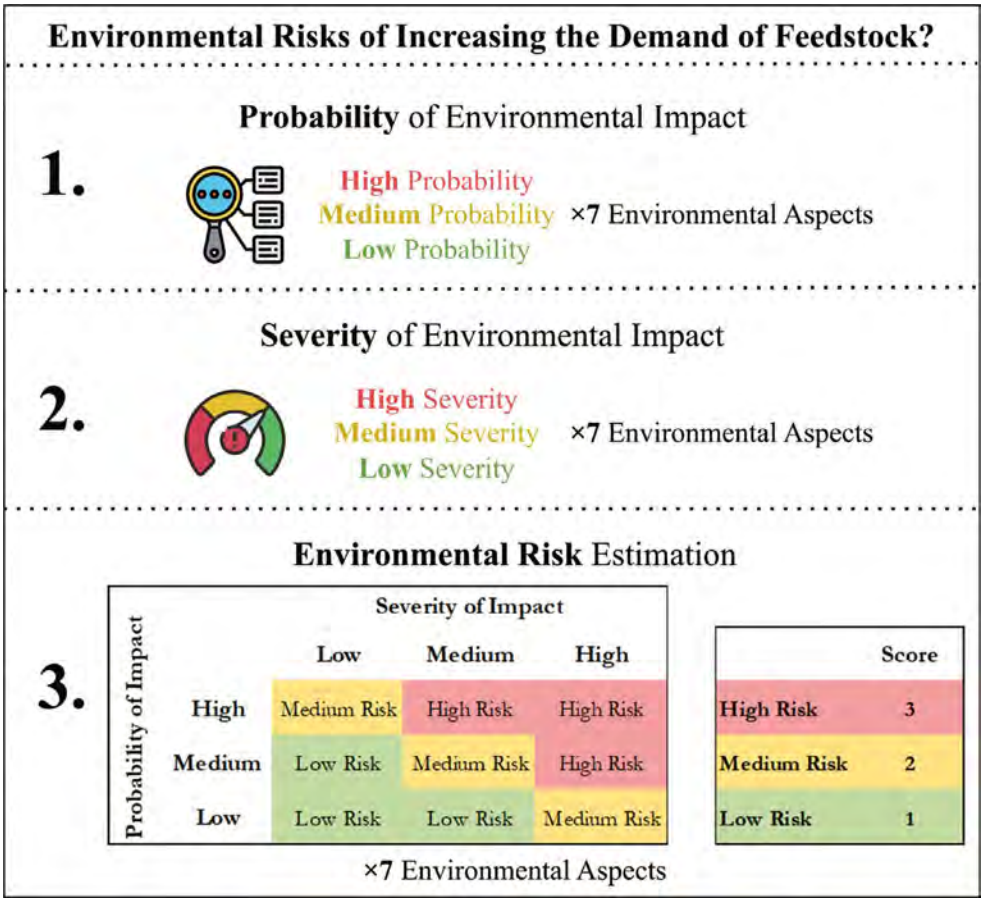


Figure 4.

The Bio ERA framework, structured into three discrete steps. Source: Bishop et al. (2025).

2.1 Summary of Results

A total of 221 feedstocks were mapped (207 solid feedstocks and 14 liquid feedstocks), including 85 primary feedstocks (PF) and 138 secondary feedstocks (SF). Approximately 49 million tDM of total solid feedstocks studied were identified in Ireland. This included approximately 43 million tDM of PF and 6 million tDM of SF across all sectors. In parallel, liquid feedstocks identified totalled to around 58 billion M^3, consisting of around 18 billion M^3 of PF and approximately 39 billion M^3 of SF. See Table 1 for detailed quantification regarding feedstock types and categories.

Table 1.

Estimated quantities of feedstocks (tDM And M^3) by type and category details

Physical State of Feedstock	Type of Feedstock	Category of Feedstock	Estimated Arisings (tDM)	Total (tDM)
Solid	PF	Grass	27,051,322	43,671,711
		Livestock (meat and milk-derived products)	6,224,152	
		Energy crops and plants	3,837,687	
		Forestry	3,669,809	
		Tillage	2,517,547	
		Horticulture	244,103	
		Pulses	64,013	
		Marine	63,078	
	SF	Manure	2,153,066	6,219,221
		Forestry	2,212,664	
		Straw from tillage	1,162,243	
		Other secondary feedstocks from tillage	250,956	
		Slaughterhouse arisings from livestock	177,794	
		Horticulture	163,037	
		Pulses	32,152	
		Drink industry and organic waste	45,904	
		Marine	16,816	
		Energy crops and plants	4590	
Solid feedstocks total (tDM)				**49,890,932**
Physical state of feedstock	**Type of Feedstock**	**Category of Feedstock**	**Estimated Arisings (M^3)**	**Total (M^3)**
Liquid	PF	Drink industry	850,060,000	18,502,893,200
		Dairy industry	17,652,833,200	
	SF	Drink industry	1,725,926,982	39,671,552,749
		Dairy industry	37,945,625,766	
Liquid feedstocks total (M^3)				**58,174,445,949**

Although secondary solid feedstocks were significant, their total mass represented only a small proportion of solid primary feedstocks (PF—solid) at national level. In contrast, the dairy and drinks sectors generated very large volumes of liquid secondary feedstocks (SF—liquid) due to high water content.

As depicted in Figure 5, there was heterogeneity in the geographical distribution of feedstock quantities and typologies. The southwest and southeast dominated in both solid and liquid biomass volumes. These heterogeneous regions could present opportunities for bioeconomy-led regional development.

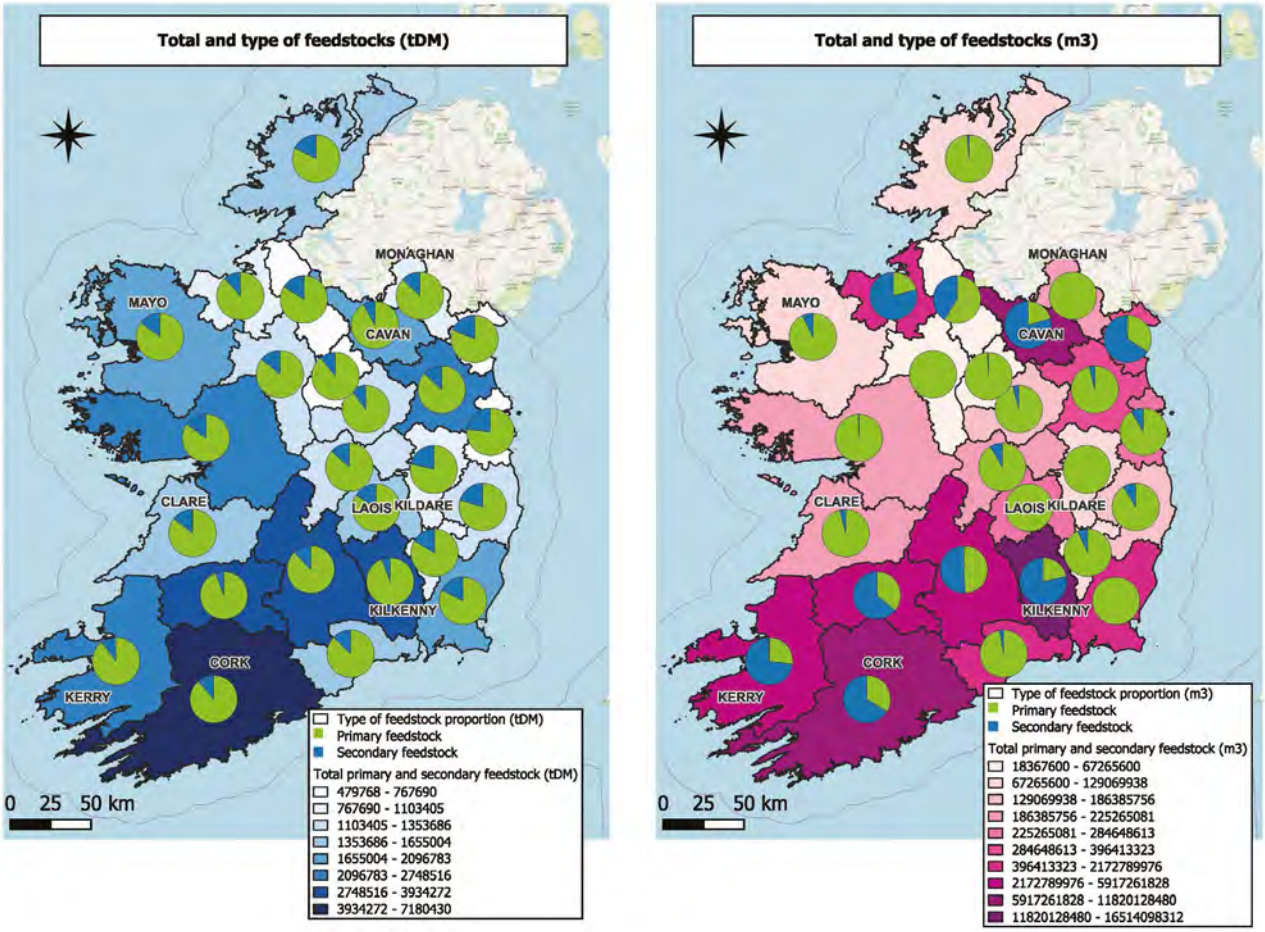


Figure 5.

County-level quantification maps with the total volumes of primary and secondary feedstocks. On the (left), solid feedstocks in tonnes of dry matter (DM). On the (right), liquid feedstocks in cubic meters (M^3).

Counties such as Cork and Tipperary have high quantities of solid and liquid PF and SF. Kerry, Kilkenny and Limerick have high quantities of PF—solid, PF—liquid, and SF—liquid. Galway and Meath produce large quantities of PF—solid and SF—liquid, while Wexford and Mayo have high quantities of SF—solid. Sligo, meanwhile, have high quantities of SF—liquid.

The east coast and midlands showed lower quantities and limited diversity of feedstocks. However, counties classified as having lower quantities still possess substantial absolute volumes of feedstocks, highlighting that low relative availability does not imply absence of biomass resources.

High feedstock quantity does not necessarily imply high feedstock diversity across counties. County Cork is an exception, as it exhibited both the highest quantities and the widest diversity of PF and SF. Livestock systems in Cork generated large volumes of SF directly and indirectly, including slurry, whey, wastewaters, and slaughterhouse by-products.

Grass from grasslands was the predominant primary solid feedstock in nearly all counties and is assumed to be almost fully utilised as animal feed. Outputs from this study suggest a potential substantial grass surplus, possibly driven partly by overproduction and inefficiencies in utilisation, aligning with literature which reported gaps between grass grown and grass used highlighting underexploited biomass potential at farm level (see Figure 6 for details). Therefore, for BBVC development, continuous monitoring and spatial mapping of grass production are essential to identify surplus zones suitable for circular bioeconomy applications such as grass biorefineries.

Assessing the bioeconomy potential of forests is critical to determining which biomass fractions can be sustainably retrieved. Forestry residues constituted the dominant category of secondary solid feedstocks, including natural forest biomass and wood processing residues. Despite low mass contribution, certain forestry residues (bark and pine needles) had high economic potential due to their valuable biochemical compounds. Sustainable valorisation assessments of forestry

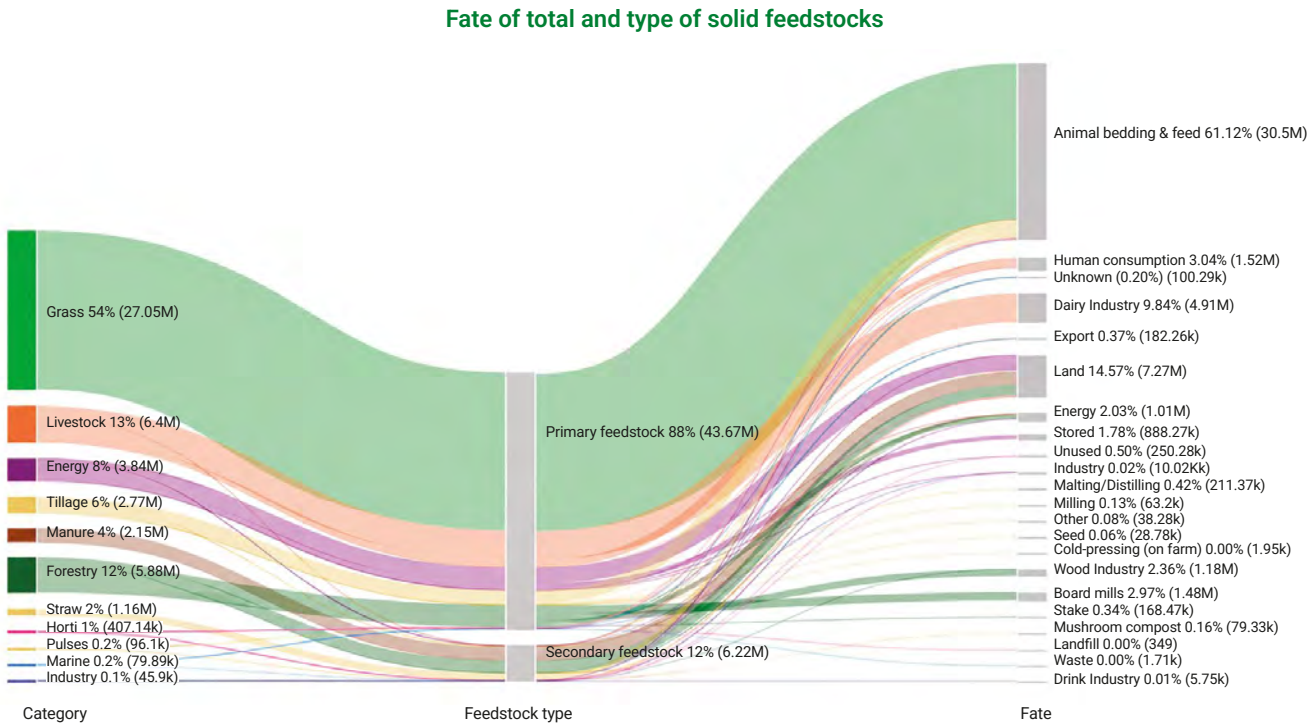


Figure 6.

Sankey diagram depicting fates of the total solid primary and secondary feedstock by category. Quantity details are expressed in tonnes DM.

secondary feedstocks will be required to enable the creation of value chains that balance economic value generation with ecological protection.

Manure and slurry were identified as the second most abundant secondary solid feedstock, although quantities are likely underestimated due to data limitations related to non-housing periods. At the time of the study, most slurry was returned to land, with only minimal use for energy generation, despite evidence from existing research highlighting its significant valorisation potential through anaerobic digestion, although with high capital investment requirements.

Straw from tillage farming represented another abundant secondary solid feedstock in Ireland. Most straw was used for animal bedding, with smaller proportions returned to land or used in mushroom compost, although emerging innovations such as mixing wheat straw with brewers' spent grain to produce high-quality compost, or using wheat straw in bio-based packaging to enhance biocomposite durability, indicate potential higher value applications that could both reduce environmental impacts and increase the economic value of existing straw streams.

The Irish dairy sector exhibited high recovery rates, meaning that only limited SF—liquid was treated as waste, with most arising as dairy wastewater rather than process intermediates (see Figure 7 for more details in feedstock utilisation). Research highlighted multiple valorisation pathways for these streams, including microbial fermentation, duckweed and algae cultivation, biofertilisers, and bio-product generation, while cascade systems combining anaerobic digestion and biomass cultivation demonstrate practical circular economy solutions for dairy wastewater.

SF—liquid such as those from the drinks industry have high potential for BBVCs and biorefineries due to their rich content of proteins, minerals, nitrogen, vitamins, and enzymes. Their utilisation within a circular bioeconomy can reduce upstream environmental burdens compared to primary feedstocks, while their spatial concentration highlights the importance of locating processing infrastructure close to high availability regions to maximise environmental and economic benefits.

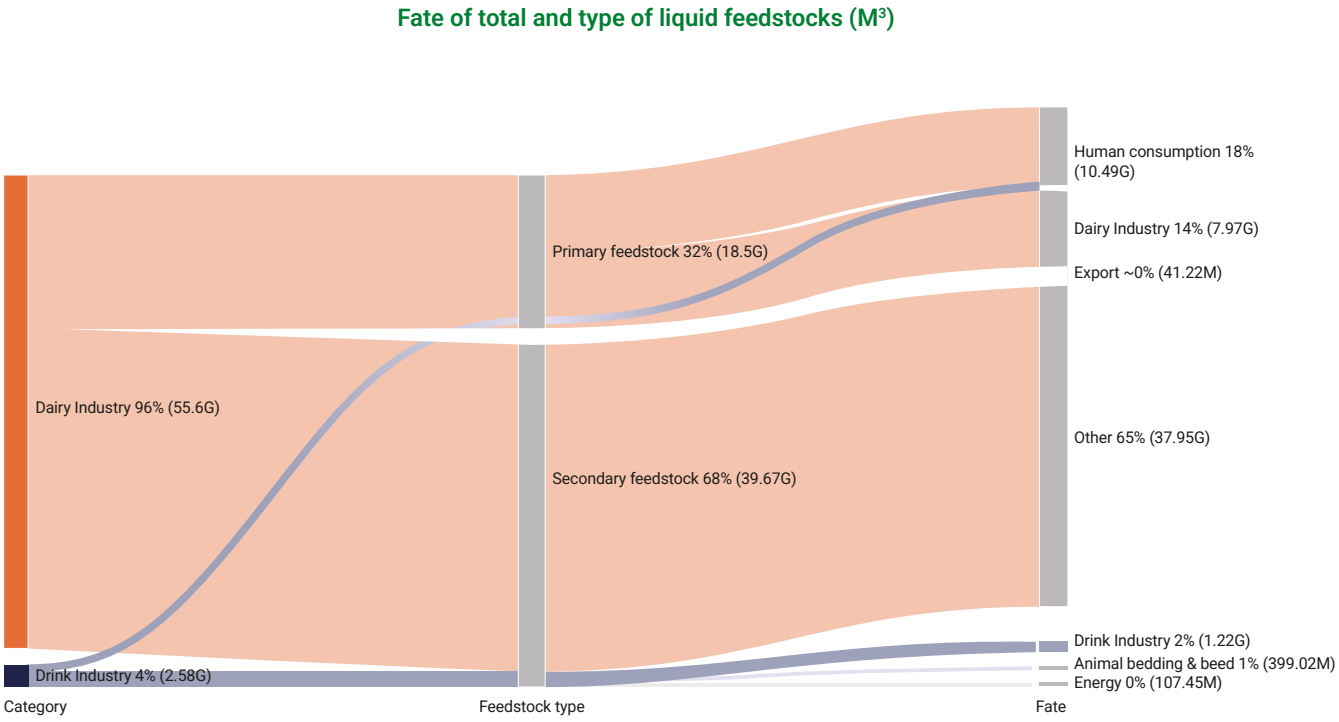


Figure 7.

Sankey diagram depicting the total fate of liquid primary and secondary feedstocks by category. Quantity details are expressed in M³.

Cascade systems are interesting approaches for BBVC development; they enable the integration of bioenergy generation within broader BBVCs, improve overall resource efficiency while prioritising higher value material uses in line with the bio-based value pyramid (Stegmann et al., 2020). InformBio's county level assessments indicated substantial renewable energy potential across Ireland, supporting national commitments from the National Biomethane Strategy (2024) (DCEE & DAFM, 2024), which targets up to 5.7 TWh of biomethane by 2030 through an agri-led, farmer-centric pathway.

Finally, the InformBio mapping assessment provides a foundational framework for future feedstock mapping and BBVC development, with tailored secondary feedstock ratios and spatial data that can be updated as new statistics become available. The results of the InformBio mapping assessment can be found in report format in the InformBio D2.2 Report series.

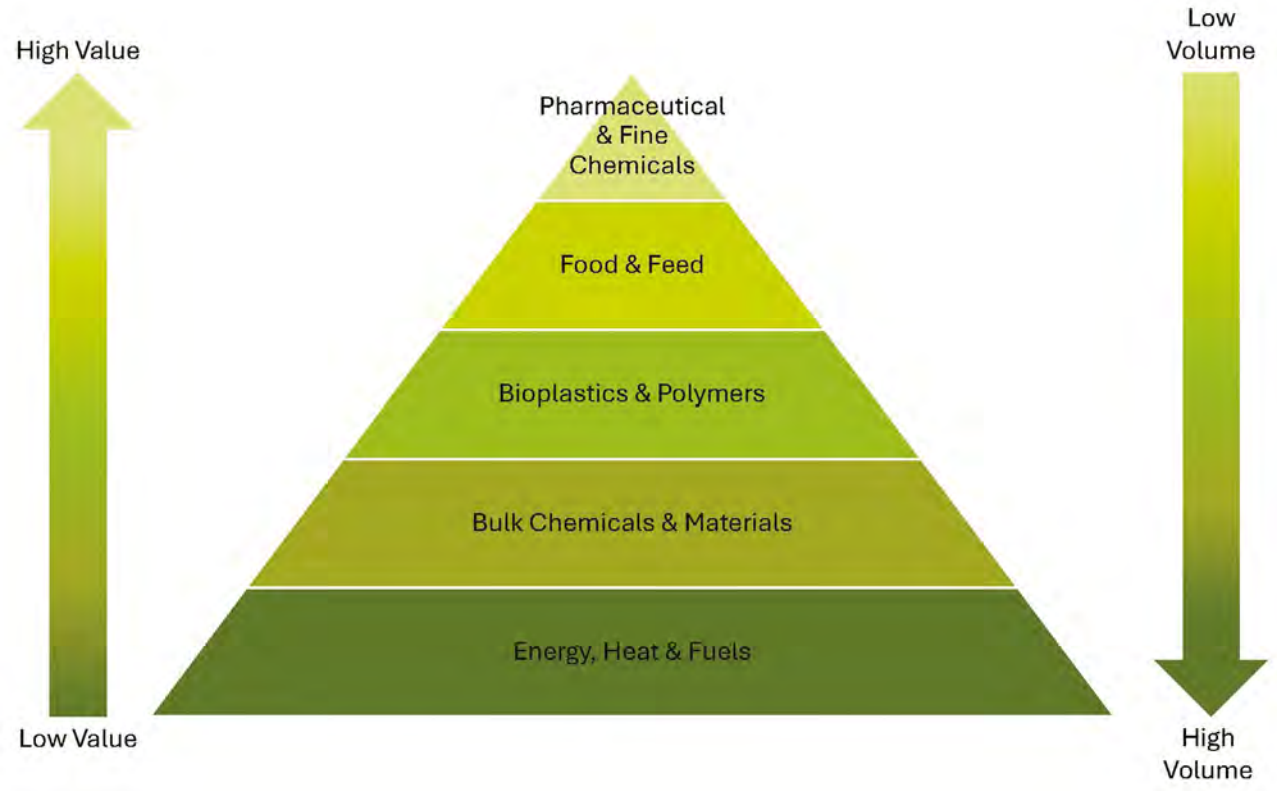


Figure 8.

Bio-Based Value Pyramid. Adapted from Stegmann Et Al. (2020).

3. WHAT CAN BE DONE?

The bioeconomy represents a significant yet underutilised environmental and economic opportunity for Ireland, encompassing all sectors and systems that depend on biological resources to produce bio-based energy, products, and services.

A sustainable bioeconomy is widely recognised as a practical pathway toward achieving the UN Sustainable Development Goals (Ronzon & Sanjuán, 2020), and Ireland has formulated a long-term vision to expand this sector in alignment with national objectives for climate action, the circular economy, global competitiveness, and rural development (DECC & DAFM, 2023). To ensure this vision is viable over the long term, emerging BBVCs must demonstrate both rigorous environmental sustainability and commercial economic feasibility. This chapter explores the environmental and economic opportunities that can be realised through the development of selected value chains within the Irish bioeconomy, considering the Irish feedstock base identified in the previous chapter.

3.1 Prioritising Ireland's Bioeconomy Potential

3.1.1 THE SCREENING AND SELECTION PROCESS

To identify feedstock-specific deployment opportunities within Ireland's bioeconomy, a catalogue of 68 BBVC opportunities was compiled as part of the **InformBio D3.1 Report**. These opportunities were identified through an extensive review of recent and ongoing European research projects, as well as emerging commercial developments across the bioeconomy sector. For each BBVC, the catalogue details the relevant feedstocks, conversion technologies, products and applications, alongside assessments of TRLs, market deployment conditions, key stakeholders, and associated environmental and social considerations.

The identified 68 BBVC opportunities were strategically clustered according to their primary feedstock type to align with Ireland's biomass availability. This sectoral organisation included:

- **Agriculture (25 BBVCs):** This was the largest category, including a wide range of agricultural feedstocks, from fresh and silage grass to dedicated energy crops like hemp, willow, and miscanthus. It also included cereals, pulses, and various agricultural residues, wastes, and by-products.
- **Forestry (11 BBVCs):** Focusing on both primary wood and secondary wood residues.
- **Marine (13 BBVCs):** Covering seaweed, microalgae, and marine waste.
- **Agro-industrial side streams (15 BBVCs):** This sector addresses high-potential waste streams from livestock (e.g., wool, slurry, animal by-products), dairy (wastewater and whey), breweries, and distilleries.
- **Domestic waste (3 BBVCs):** Focusing on the organic fractions of municipal solid waste and food waste.
- **Carbon capture and utilisation (1 BBVC):** Exploring the conversion of biogenic carbon dioxide into useful chemicals and biopolymers.

A summary of the vast array of potential BBVC opportunities for Ireland's bioeconomy based on the initial review is presented in Figure 9 on the following page, adapted from Lange's (2022) biorefinery colour-coded classification.

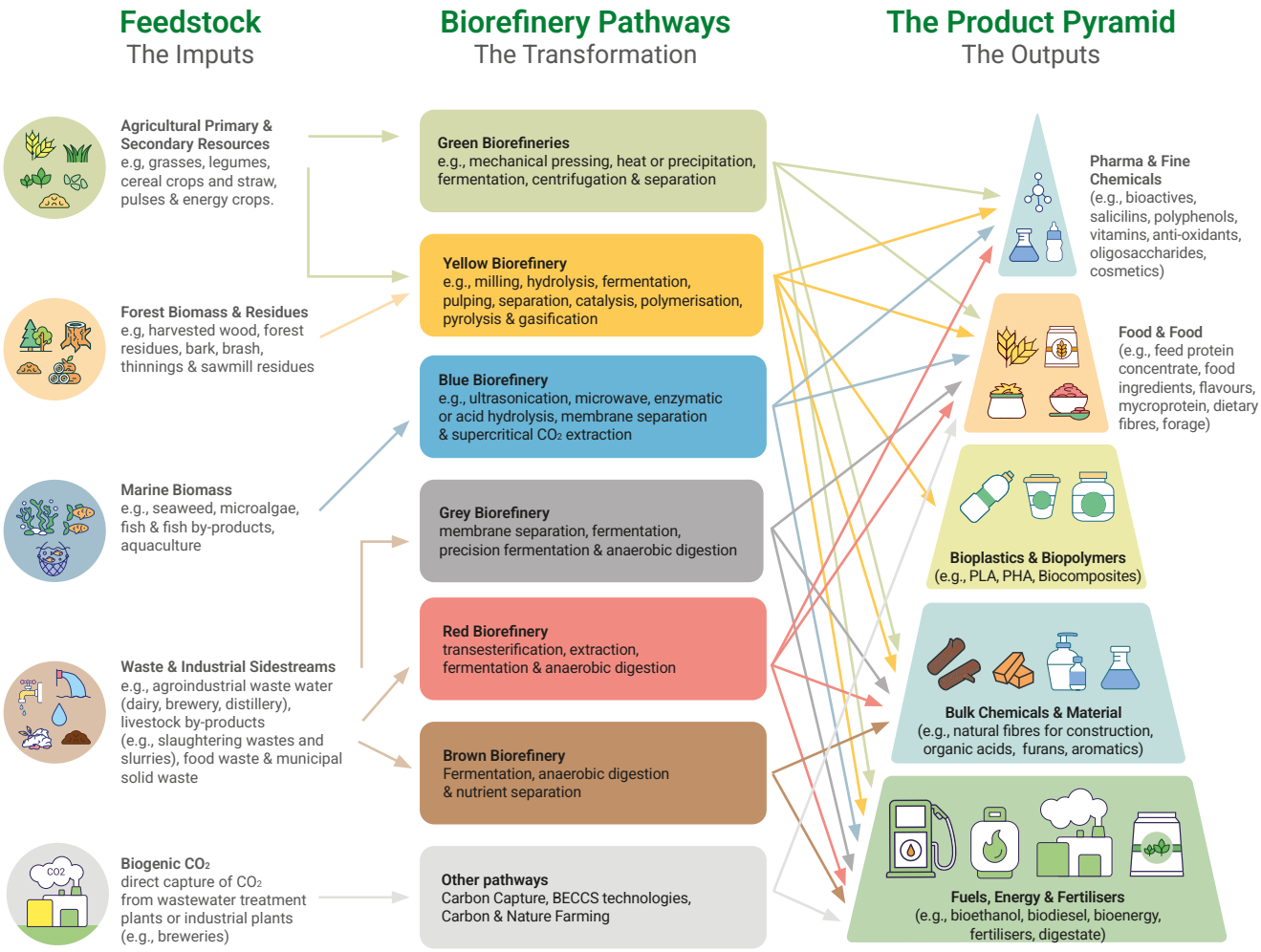


Figure 9.

The bioeconomy value web: from sustainable feedstocks to high-value products.

3.1.2 STAKEHOLDER-DRIVEN PRIORITISATION

Given the vast scope of potential bioeconomy opportunities, it is neither practical nor strategically meaningful to deeply assess the environmental and economic potential of every possible technological pathway. Consequently, the InformBio project initiated a structured screening process to rank the most promising BBVCs for the Irish context, as part of the **InformBio D3.2 Report**.

To move from this broad catalogue to a prioritised shortlist, the project evaluated each value chain against ten carefully selected criteria. These criteria were designed to provide a multi-dimensional view of impact, covering environmental, economic, and social dimensions, alongside technical feasibility and alignment with overarching national policy objectives (Table 2).

A core component of the InformBio methodology was the integration of stakeholder perspectives to ensure that the prioritisation reflected the priorities of the Irish bioeconomy ecosystem (Figure 9). This was achieved through a ranking exercise, where key stakeholders ranked the ten evaluation criteria based on their perceived importance. These rankings were subsequently translated into specific weighting factors, which reflected the relative priority of each criterion in the final analysis (Table 2).

Table 2.

Definitions and stakeholder-derived weighting factors for the ten screening criteria used to prioritise Irish bio-based value chains

Screening Criteria	Stakeholder Weighting
Scalability of BBVC	0.166
Displacement of emission intensive products and energy	0.166
Potential to realise a cascading BBVC balancing high and low value products	0.134
Avoidance of conflict with important competing/existing uses of biomass	0.107
Near term viability (TRL)	0.106
Potential of BBVC to provide social benefits (e.g., job creation, less exposure to agrochemicals, increase quality of life, food security, etc.)	0.090
Potential of BBVC to support carbon sequestration	0.083
Potential of BBVC to deliver other additional economic benefits not previously considered (e.g., rural development / increase of income / reduce supply costs such as fertilisers creation/ development of new value chains, etc.)	0.069
Potential of BBVC to deliver other additional environmental benefits not previously considered (e.g., biodiversity conservation / ecosystem services / soil health / ecosystem regeneration, etc.)	0.059
Alignment with EPA Circular Bioeconomy Outlook Study 2030-2050	0.021

Following this, each of the **68 BBVC case studies** was scored by the research team as having high, medium, or low potential for each of the ten criteria. These qualitative ratings were then processed through a weighted sum model, where the criteria weighting factors were multiplied by the corresponding scores and summed to generate a final, objective rank for every value chain in the catalogue. The complete set of value chains can also be viewed in case study form via a **"BBVC screening tool"** online by feedstock and TRL.

Figure 10.

Stakeholder workshop to identify prioritised BBVCs.

3.1.3 THE PRIORITISED SHORTLIST

The screening process resulted in a shortlist of the highest-ranking BBVCs, which were deemed most suitable for Ireland's specific opportunities and challenges. These value chains included:

- Grass to protein feed and energy
- Grass to bio-based materials and energy
- Agriculture residues to biochar
- Wood and residues to bio-products
- Slurry, straw, and woodchips to energy, biomethane, and biofertiliser
- Municipal solid waste to bio-products

3.1.4 ADVANCED ASSESSMENT OF THESE BBVCS

Building on the prioritised list, a project deliverable, **InformBio D4.1 Report**, reviewed the body of international studies that have applied attributional Life Cycle Assessment (LCA) to these prioritised chains. A critical conclusion of that literature review was that while attributional LCA provides useful baseline footprint impacts, it often lacks the depth required to capture broader system-wide effects and indirect impacts that can arise from prospective deployment. Consequently, the ***InformBio D4.1 Report*** recommended a shift toward more expanded assessment methodologies to provide a comprehensive view of environmental sustainability.

This informed the project's **InformBio D3.3 Report**, which examined the environmental and economic potential of five priority bioeconomy opportunities identified from the screening process: grass biorefineries, wood waste to biochar, cascading use of wood residues to wood products and bioenergy with carbon capture and storage (BECCS), large- and small-scale anaerobic digestion (AD) multi-input systems, and food waste-specific AD. That report provided results from Techno-Economic Assessment (TEA) evaluating the commercial viability of these options, alongside advanced LCA exploring the potential environmental impacts of their deployment in Ireland.

These analyses were further complimented by a detailed stakeholder mapping exercise to identify the actors critical to successful implementation, as well as a market assessment of the resulting bio-based products.

To ensure the strategic viability of Ireland's bioeconomy, this foresight report chapter synthesises the results presented in ***InformBio D3.3 Report***. The combined LCA and TEA approach allows for a simultaneous evaluation of commercial profitability and environmental sustainability under specific scenario configurations, providing a robust evidence base for policy and investment decisions.

Box 4: Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA)

LCA is a systematic methodology used to quantify the environmental impacts associated with a product or service throughout its entire lifespan, from raw material extraction through production, use, and end-of-life management. LCA covers a broad spectrum of environmental concerns including global warming potential, acidification, eutrophication, resource depletion, and fossil energy use, among many others. LCA can be applied using different methodological approaches depending on the study objective:

- **Attributional LCA** quantifies the environmental burdens directly associated with a system as it exists, typically using historical or average data and allocation procedures to address multifunctional processes. This approach provides a descriptive snapshot of environmental performance. In this report, an expanded boundary attributional LCA is applied to the grass biorefinery LCA.

- **Consequential LCA** is a forward-looking LCA approach which assesses the environmental consequences of a potential decision. It considers not just direct impacts but also indirect effects arising from market-induced responses, supply chain shifts, and policy interventions. This report applies consequential LCA to wood residue biochar and the AD studies to evaluate the system-wide implications of adopting these technologies in Ireland.

- **Dynamic LCA** introduces an explicit temporal dimension to account for the timing of emissions and removals via annual emission inventories and time-dependent characterisation factors. This was essential for the cascading wood into BECCS BBVC, where long-term carbon storage and gradual sequestration was important aspects to capture.

TEA evaluates the technical and economic performance of a process to determine its commercial viability. It combines process modelling with economic analysis to estimate capital and operating costs and assess financial performance under defined operating conditions. Process simulation tools are used to develop mass and energy balances, estimate material and utility requirements, and determine equipment sizing. These outputs form the basis for estimating key economic indicators, including:

- **Capital Expenditure (CAPEX):** The overall upfront investment required to construct and establish the facility, including equipment, installation, engineering, and contingency costs.

- **Operating Expenditure (OPEX):** The recurring costs associated with operating the process, including raw materials, utilities, labour, maintenance, and waste management.

- **Net Present Value (NPV):** The present value of future cash flows generated by the project, discounted over its lifetime, used to assess overall profitability.

- **Payback Period:** The time required for cumulative project revenues to recover the initial capital investment.

3.2 Environmental and economic sustainability assessments of prioritised Irish BBVCs

3.2.1 SCOPE AND DATA PROVENANCE

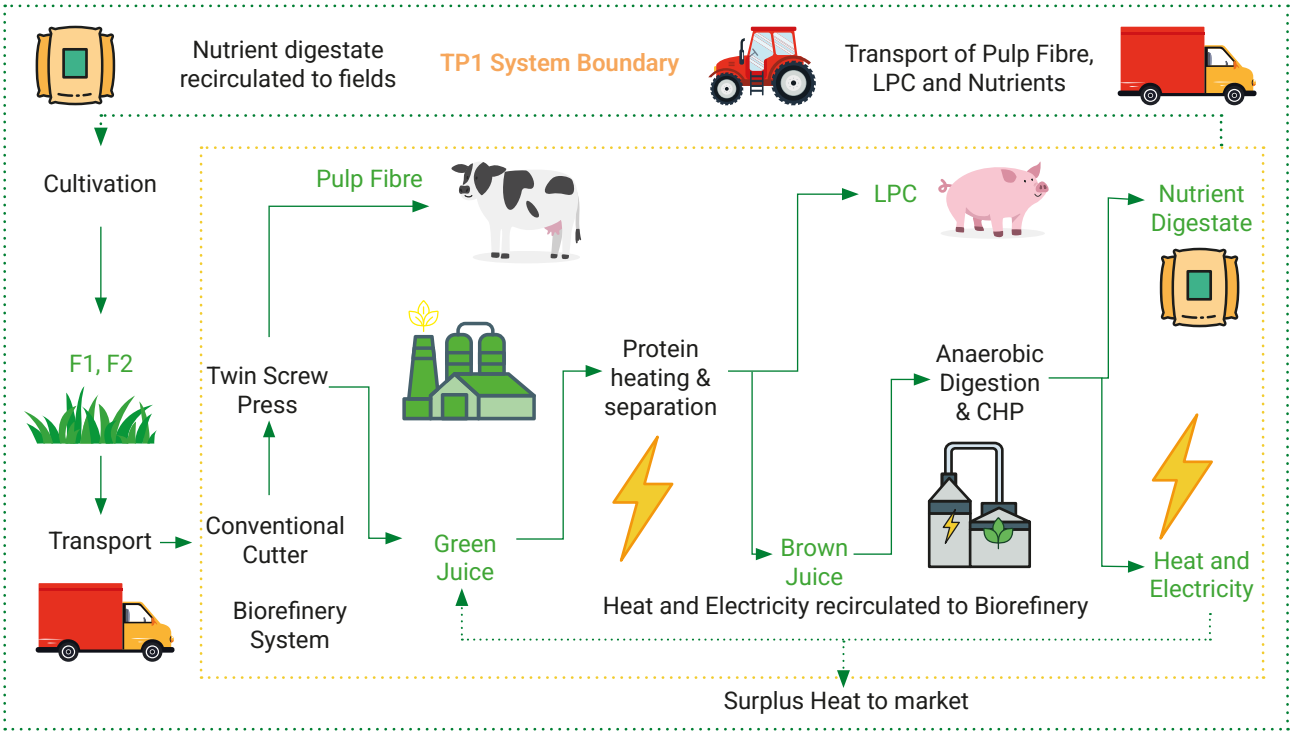
The following sections summarise the detailed technical and environmental assessments of the five top priority BBVCs identified for Ireland in the ***InformBio D3.2 Report***: (a) grass biorefinery, (b) wood waste to biochar, (c) wood residues to particleboard and BECCS, (d) large- and small-scale AD, and (e) food waste AD. These LCA and TEA assessment summaries are synthesised from the findings presented in the ***InformBio D3.3 Report***. The results have also been disseminated through several peer-reviewed international journals, including **Science of the Total Environment** (Gaffey et al., 2024); **Sustainable Energy Technologies and Assessments** (Martínez-Arce et al., 2025); and **Communications Earth & Environment** (Bishop et al., 2026), with additional manuscripts currently under peer-review.

To ensure transparency and facilitate further analysis, detailed underlying data, including system diagrams, full LCA results, and itemised capital and operating cost evaluations, are hosted in an online repository linked to the ***InformBio D3.3 Report.*** Stakeholders can access the full suite of TEA and complete LCA results along with other InformBio reports via the **InformBio Zenodo repository**.

3.2.2 GRASS BIOREFINERY

3.2.2.1 GRASS BIOREFINERY BBVC CASE STUDY

Ireland possesses a vast biological resource in its grasslands, which cover 54% of the national land area and produce approximately 27 million tonnes of dry matter annually from pasture and silage (Girón-Domínguez et al., 2026). The grass biorefinery concept aims to valorise this biomass into a diversified portfolio of value-added products, including leaf protein concentrate (LPC) for use as a high-protein animal feed ingredient, fibre press cake for fodder (alternatively for bio-based materials), and biogas for energy generation. In this BBVC case study, two distinct grass biorefinery technology pathways were evaluated (Figures 11A and 11B): a conventional one-stage maceration system and a novel high-efficiency multi-stage maceration system (Gaffey et al., 2024). These processes both involved mechanical shredding, wet fractionation via screw press, and heat precipitation followed by centrifugal separation to extract protein, followed by AD of the residual "brown juice" to generate energy. The multi-stage maceration system involved extra steps of re-processing the initial solid fibre fraction through blending with water or recycled juice, secondary wet cutting, mechanical disintegration of dry matter, and a secondary pressing operation to increase protein yields. Within these two technology pathways, two feedstock scenarios were considered, for four scenarios total, and included perennial ryegrass-only or a grass-clover mixture. This multi-output approach is designed to maximise resource efficiency and provide a domestically produced alternative to imported protein feed crops.



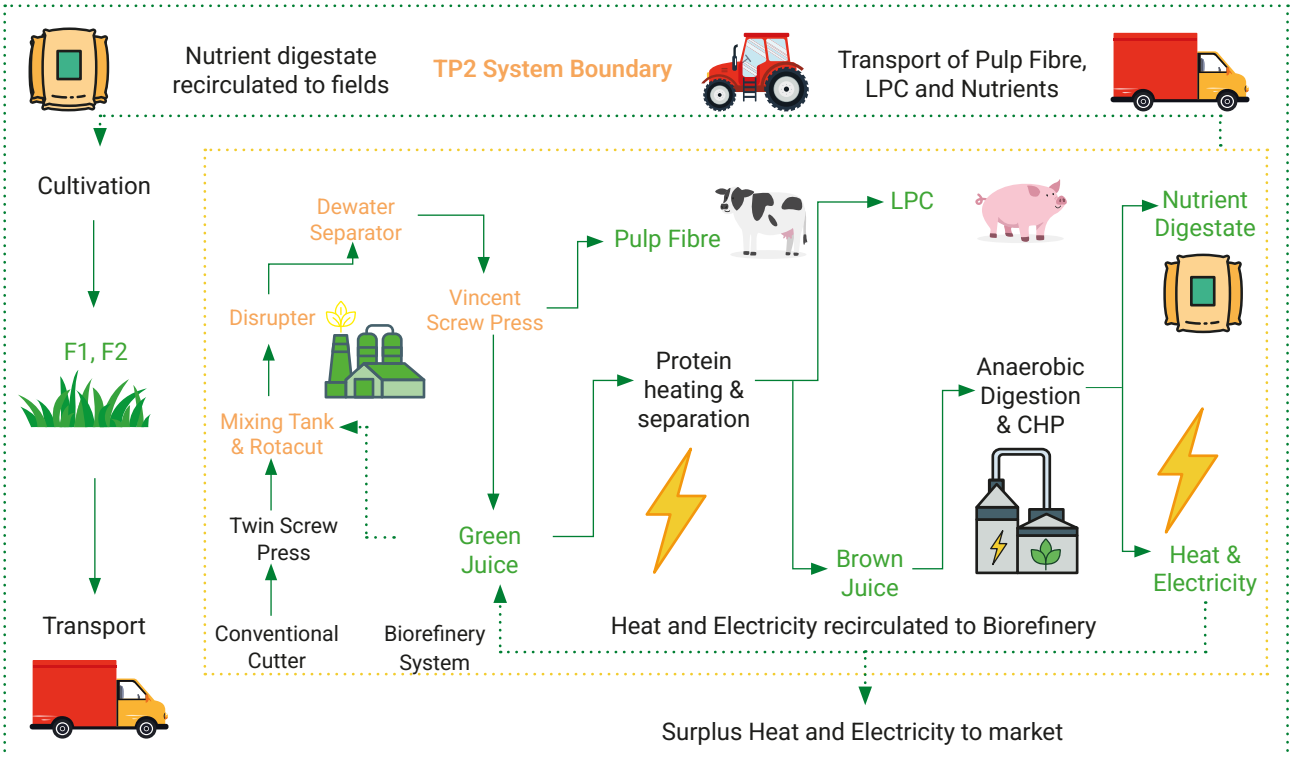


Figure 11A. & 11B.

System Boundaries for the two green biorefinery BBVCs. Technology Pathway 1 (11A) presents a conventional biorefinery route to produce leaf protein concentrate (LPC), with TP2 (11B) presents a novel multi-stage maceration system for LPC production.

3.2.2.2 ENVIRONMENTAL PERFORMANCE

The environmental sustainability of the explored grass biorefinery BBVCs was assessed using an expanded boundary attributional LCA, which benchmarked grass biorefinery-derived LPC protein against imported soybean meal. Overall, the leaf protein concentrate produced from the modelled grass biorefinery systems had an improved environmental performance across all modelled impact categories when compared to soybean meal, irrespective of the system configuration.

In the case of climate change, the emission intensity was 57–85% lower compared with SBM. However, the selection of GBR feedstock and technology pathway has a strong influence on environmental intensities for the crude protein produced. Scenarios utilising a grass-clover mixture consistently outperformed perennial ryegrass monocultures across all categories, including climate change, acidification, and non-renewable energy use. Specifically, grass-clover systems produced between 560 and 851 kg CO_2 eq. per tonne of crude protein, compared to 1393 and 1650 kg CO_2 eq. per tonne of crude protein from perennial ryegrass only. However, these still represented a drastic reduction compared to the 3780 kg CO_2 eq. per tonne of crude protein associated with imported soybean meal.

Beyond climate change, the biorefinery scenarios demonstrated significant advantages in other environmental metrics, notably achieving 54–88% lower acidification burdens and 74–89% lower freshwater eutrophication levels compared to soybean meal. For example, the most efficient grass-clover scenario generated only 1.40 mol H+ eq. for acidification and 0.044 kg P eq. for freshwater eutrophication, while soybean meal results were substantially higher at 6.47 mol H+ eq. and 0.383 kg P eq., respectively. Within the baseline scenarios, the combined grass-clover and a novel multi-stage maceration process performed best across all impact categories, minimising artificial fertiliser inputs, improving biorefinery energy self-sufficiency, and increasing protein yield, leading to reduced land and feedstock requirements.

This shift signifies a major environmental opportunity for Europe to reduce its heavy reliance on protein imports, where it is currently less than 5% self-sufficient in soya (European Commission, 2018a). By unlocking more protein from land already in use for livestock, green biorefineries enhance regional protein resilience and could potentially decrease total land requirements for animal feed by an estimated one-third (Sanders et al., 2020).

3.2.2.3 ECONOMIC PERFORMANCE

While the environmental case is strong, the TEA indicates that the evaluated configurations, producing LPC as the primary product and press cake and biogas as co-products face significant economic challenges under current market conditions. Economic performance was assessed using the Net Present Value (NPV) and Break-Even Price (BEP). The NPV represents the present value of all future cash flows over the project lifetime, while the BEP is the minimum selling price required for total revenues to cover total costs. In the base case grass-clover scenario, where LPC price is benchmarked with SBM, the project generated an NPV of –€26 million, indicating that it is not financially viable. The corresponding BEP of €955/t is substantially higher than the assumed market price for LPC. Sensitivity analysis identified grass cost, operating expenditure, LPC selling price, and product yield as the most influential factors affecting profitability. In an alternative scenario, a 50% capital grant, combined with a 25% reduction in feedstock price, brings the BEP of LPC down to €575 per tonne, which is higher than the current basic market value for soybean meal, but in line with a 2022 Danish study which places a green premium on LPC (either as a non-GMO protein or organic protein alternative to soybean mean meal) ranging from €460 to €750 (Andrade & Ambye-Jensen, 2022).

The results suggest that improving the competitiveness of the grass biorefinery value chain focused the relatively low value outputs of animal feed and biogas alone will require complementary policy and market interventions. Measures to increase biogas or biomethane co-product incentives, reduce grass costs (e.g., by improving farmer integration in the model), tax less sustainable protein imports, or lengthen the processing season to accommodate winter feedstocks, would also help to improve the viability of the model. The recent publication of the EU's Protein Action Plan which reference protein concentrates from grass and supporting activities aimed at increasing locally produced soy alternatives for developing protein concentrates, could be an important opportunity to support favourable conditions for LPC and other local protein alternatives (European Commission, 2026).

In the medium term, there is also significant room for increasing the value of the grass biorefinery co-products, with several research demonstration initiatives currently underway focused on optimising the fractionation of green protein for animal, and functional white protein for human consumption or the co-production of prebiotics,

biomaterials or high value ingredients for food or feed additive market. Such developments are also highlighted in literature (dos Passos & Ambye-Jensen, 2024; Menon et al., 2024). Previous green biorefinery projects have indicated the importance of producing even relatively small volumes of such high value co-products alongside feed products to maximize the potential of these value chains. Research is currently being undertaken to improve feedstock flexibility in grass biorefinery systems so that processing can take place for a longer period of the year, further enhancing viability. More research is also being undertaken to improve biomass harvesting and supply chain logistics which can further reduce costs and enhance product quality (Rural BioReFarmeries). These measures could support the commercialisation of grass biorefineries and Ireland's transition to a resilient and sustainable circular bioeconomy.

3.2.2.4 MARKET OUTLOOK

Market indicators, however, are favourable; the grass biorefinery system's primary product, leaf protein concentrate, contains approximately 47% crude protein and offers a locally produced alternative to imported soy. This supports protein resilience against volatile markets and advances sustainability in Ireland and the EU, aligning with the EU Farm to Fork strategy and a global soy protein market projected to grow from USD 10.0 billion in 2024 to USD 18.4 billion by 2033 (Imarc, 2025). The system's co-products hold similar market relevance. Fiber press cake improves livestock nutrition and reduces reliance on conventional silage, lowering agricultural emissions while capitalising on a global animal feed market forecast to reach USD 859.6 billion by 2034 (Feed & Additive Magazine, 2025). Meanwhile, residual brown juice is converted via anaerobic digestion into biogas for heat and power. This feeds into a global biogas market expected to grow from USD 140.9 billion in 2025 to USD 191.9 billion by 2032 (Fortune Business Insights, 2025b).

3.2.2.5 STAKEHOLDER INTEGRATION

Successful implementation in Ireland requires a coordinated stakeholder ecosystem to de-risk investment and secure feedstock supply. Dairy, beef, and sheep farmers are essential as biomass suppliers, but they must be convinced of the socio-economic benefits, potential "green premiums" or supporting policies to justify changing their current enterprises. Agricultural cooperatives play a pivotal role by facilitating capital investment and providing feedstock and market access, as demonstrated by pioneering initiatives like Biorefinery Glas.

Feed manufacturers (for monogastric feed) can support commercialisation by incorporating LPC into livestock feed, validating its performance, and creating stable demand through long-term supply agreements. Additionally, technology providers and engineering firms are needed to scale process designs, while policymakers must establish supportive regulatory frameworks and funding mechanisms to bridge the current profitability gap. Strategic co-location of grass biorefineries with existing AD plants is also recommended to reduce transportation costs for brown juice and improve overall system circularity.

3.2.3 WOOD WASTE TO BIOCHAR

3.2.3.1 BIOCHAR BBVC CASE STUDY

Ireland generates approximately 1.2 million tonnes of wood waste annually (Girón-Domínguez et al., 2026), comprising sawmill residues such as sawdust, bark, and offcuts. This BBVC evaluates the conversion of these low-value lignocellulosic residues into carbon-rich products via two biochar thermochemical pathways: torrefaction and pyrolysis. Torrefaction is a continuous, lower-temperature process (250–300°C) designed to produce "bio-coal" pellets, a solid biofuel with energy properties similar to hard coal. In contrast, pyrolysis is a higher-temperature (around 600°C) process that yields high-grade biochar suitable for material applications, alongside bio-oil and syngas. In this case study, the biochar was used as a concrete additive with long-term carbon storage potential. These two systems were modelled at a scale of 50,000 tonnes of fresh wood waste per year. While both processes utilise internal syngas combustion in a combined heat and power unit to satisfy a portion of their internal energy requirements, under the specific modelled conditions, they both required additional external electricity and heat to operate. Here, an avoided counterfactual assumed that the wood resides would otherwise undergo waste incineration with energy recovery, resulting in additional marginal heat and electricity generation when the waste wood was diverted to the BBVC pathways.

3.2.3.2 ENVIRONMENTAL PERFORMANCE

A consequential LCA revealed that both BBVCs delivered significant net environmental benefits. Under modelled conditions, torrefaction and pyrolysis achieved net climate change mitigation of -40,444 tonnes CO_2 eq. and -15,544 tonnes CO_2 eq., respectively. For torrefaction, these benefits were largely driven by the displacement of approximately 19,058 tonnes of smokeless hard

coal, avoiding an estimated 52,409 tonnes of fossil CO_2 emissions from coal combustion.

Although pyrolysis achieved a lower overall net climate change benefit of -15,544 tonnes of CO_2 eq., it provided genuine carbon dioxide removal (CDR) through the long-term sequestration of 21,977 tonnes of biogenic CO_2 stored in concrete. Additional climate benefits arose from the substitution of heavy heating oil with bio-oil, avoiding approximately 10,274 tonnes of fossil CO_2 emissions, while also reducing SOx emissions due to the bio-oil's near-zero sulphur content.

Fossil resource use differed markedly between the scenarios: torrefaction achieved a net saving of -220,037 GJ, whereas pyrolysis generated a net burden of +154,106 GJ, indicating that in our scenario the heavy oil substitution wasn't great enough to offset the additional energy demands of the system. Both pathways generated net acidification benefits, with impacts reduced by -41,121 and -58,813 mol H+ eq. for torrefaction and pyrolysis, respectively. For terrestrial eutrophication, torrefaction again demonstrated substantial net savings (-160,983 mol N eq.), largely due to avoided hard coal extraction, while pyrolysis resulted in a small net burden (+27,008 mol N eq.) associated with increased marginal energy production.

3.2.3.3 ECONOMIC PERFORMANCE

The NPV and BEP financial indicators from the TEA showed that both modelled systems would currently face substantial financial barriers in the Irish market without established carbon finance markets. The base-case NPV for the pyrolysis and torrefaction projects excluding the value of carbon credits was –€32 million and -€82million respectively. As biochar is eligible for high-value

carbon removal credits, which are experiencing strong market demand, a sensitivity analysis was undertaken to determine the carbon credit price required for each system to break even. The financial analysis estimated BEPs of €180/t CO_2-eq for the pyrolysis system and €175/t CO_2-eq for the torrefaction system. High value biochar carbon credits are projected to exceed €200/t CO_2-eq (International Biochar Initiative, 2024) by 2030, as such, both systems could become financially viable under a sufficiently developed and robust carbon credit market. The sensitivity of different scenarios also showed that the profitability of the two systems was largely dependent on feedstock price, OPEX, prices of products and CAPEX. For the two systems evaluated, pyrolysis demonstrated greater economic potential due to its multiple revenue-generating co-products, while torrefaction offered logistical advantages and was better suited to decentralised applications. Overall, both processes highlighted the necessity of carbon finance mechanisms, supportive policy structures (including CAPEX grants), and integration into high-value markets to unlock economic viability.

3.2.3.4 MARKET OUTLOOK

A market assessment identified strong global growth prospects for biochar and its co-products, driven by increasing demand for sustainable materials, renewable energy sources, and carbon-negative technologies. The global biochar market, valued at USD 763.5 million in 2024, is projected to grow at a compound annual growth rate (CAGR) of 13.6%, surpassing USD 2 billion by 2032 (Fortune Business Insights, 2025a). This growth is supported by expanding applications in agriculture, construction materials, and carbon credit markets. Europe, in particular, is experiencing rapid uptake of biochar technologies, supported by green construction initiatives and climate-smart agricultural practices.

The bio-oil market is also expected to expand significantly, increasing from an estimated USD 99.5 billion in 2023 to USD 207.9 billion by 2030, representing a CAGR of 11.3%, reflecting its versatility in heating, power generation, and renewable fuel production (Grand View Research, 2024). Similarly, the global syngas market, estimated at approximately 246 billion Nm³/h in 2024, is forecast to exceed 629 billion Nm³/h by 2032 (Fortune Business Insights, 2025c). This expansion highlights the increasing role of syngas in hydrogen production, synthetic fuel synthesis, and chemical manufacturing.

3.2.3.5 STAKEHOLDER INTEGRATION

The successful development and deployment of a wood waste-to-biochar BBVC depends on the coordinated engagement of a diverse stakeholder ecosystem. Biomass suppliers, including forestry operators, sawmills, wood processors, and manufacturers generating wood residues, play a fundamental role in ensuring a consistent and sustainable feedstock supply. Technology developers and equipment providers are essential for delivering efficient, scalable pyrolysis and torrefaction solutions that can convert biomass into high-quality biochar and other value-added products.

Market uptake is driven by end users across sectors such as construction, agriculture, horticulture, and energy, where biochar can be utilised in applications ranging from low-carbon construction materials to soil enhancement and carbon sequestration. End-of-life managers, including composting, waste management, and agronomic service providers, are also critical for ensuring the effective application and integration of biochar into circular economy systems.

Policy makers and regulatory bodies will play a central role in creating enabling market conditions through certification frameworks, carbon account and natural capital accounting methodologies, financial incentives, and public procurement policies that support low-carbon materials and technologies. In parallel, infrastructure and logistics partners are required to facilitate feedstock collection, storage, transportation, and integration with existing energy and industrial systems.

3.2.4 WOOD RESIDUES TO PARTICLEBOARD AND BIOENERGY WITH CARBON CAPTURE AND STORAGE

3.2.4.1 CASCADING WOOD USE BBVC CASE STUDY

Large-scale CDR is essential to limit global warming to below 2°C and offset residual emissions from hard-to-abate sectors (IPCC, 2022). Bioenergy with Carbon Capture and Storage (BECCS) offers a unique opportunity to generate renewable energy while also delivering permanent CDR. This BBVC case study focused on the management of sawmill wood residues, a substantial biogenic carbon stock in Ireland that integrates effectively with existing bioenergy infrastructure. Two primary pathways were evaluated: the direct conversion of these residues to bioenergy and a “cascading” model where residues are first used to manufacture particleboard before eventual end-of-life recovery for bioenergy after 30-years (Bishop et al., 2026).

Here, a multi-scale dynamic LCA approach was used that combined detailed, time-based carbon accounting of different BECCS pathways with models of forest growth and carbon storage. First, the climate impacts were modelled for a single flow of sawmill wood residues used for bioenergy, either directly or after being used to make particleboard, both with and without carbon capture and storage (CCS), evaluated under several discrete future decarbonisation scenarios.

Then, the analysis was expanded to consider a continuous annual flow of wood residues over time. This allowed the modelling to account for the gradual deployment of CCS technologies, progressive decarbonisation across the wider economy through time, and changes in forest carbon stocks over time. Finally, these BECCS pathways were compared with an alternative scenario in which forest harvesting stopped and forests were left to grow to maximise carbon storage (Figure 12).

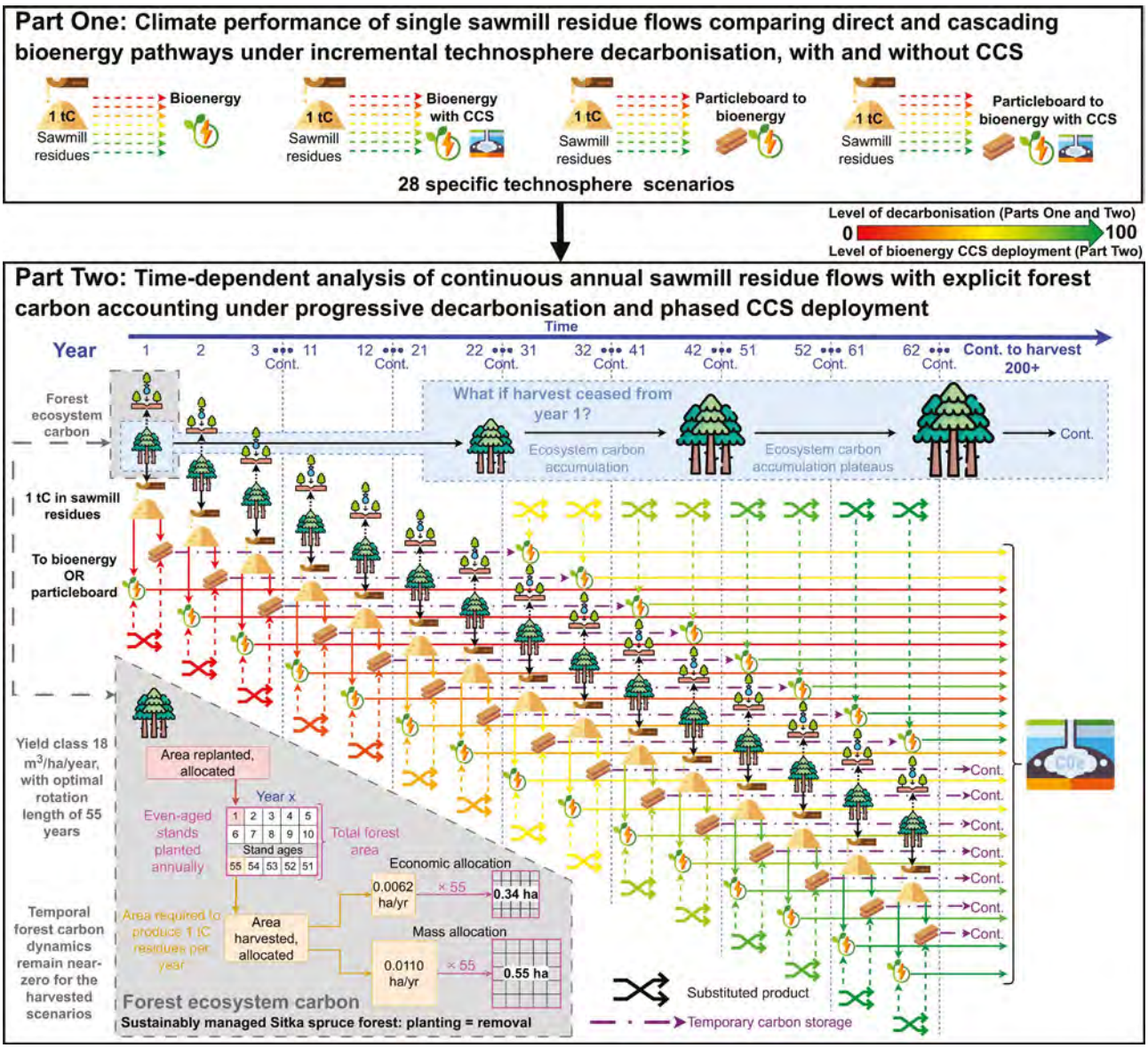


Figure 12.

Overview of study design for cascading wood use into Bioenergy with Carbon Capture and Sequestration (BECCS).

3.2.4.2 ENVIRONMENTAL PERFORMANCE

The research demonstrated that BECCS, specifically when using sawmill wood residues, provides a robust and enduring pathway for global cooling across all decarbonisation scenarios. The study highlighted that BECCS value chains consistently outperform bioenergy without CCS, regardless of the level of decarbonisation. This superiority is maintained even though BECCS processes have lower energy efficiency compared to non-CCS bioenergy. This climate advantage is driven by the permanent transfer of approximately 3,300 kg of CO_2 to geological storage for every tonne of carbon contained in the sawmill residues directed to BECCS. Crucially, all bioenergy and BECCS BBVCs maintained their climate change mitigation efficacy even in a fully decarbonised economy where fossil fuel substitution benefits cease, provided that forest carbon stocks are maintained through sustainable management.

The study further revealed that a cascading wood use strategy yields superior near-term climate benefits. By delaying final combustion, this temporary carbon storage approach effectively "buys time" for CCS infrastructure to be deployed, drastically improving the emissions profile of the same flow of wood waste that would otherwise have been combusted 30 years earlier when CCS deployment levels were lower. This approach also facilitates immediate material substitution credits (via displacement of more carbon-intensive materials). Though these credits cease as the economy becomes fully decarbonised, simultaneous attainment of complete deployment of BECCS ensures continuous climate change mitigation.

The study also identified critical crossover points where cascading and BECCS BBVCs surpasses the climate performance of leaving forests unharvested. While unmanaged forests can offer greater near-term cooling, their sequestration strength plateaus as they mature, and the stored carbon remains vulnerable to increasing climate-driven disturbances such as wildfires and disease. In contrast, transferring biogenic carbon into geological stores via BECCS offers a more resilient and permanent CDR solution.

Finally, the findings underscore that the timing of emissions and removals is a vital factor in climate outcomes, which is often misrepresented by traditional static LCA methods – with traditional static LCA producing more optimistic results than dynamic LCA. Consequently, the study concluded that long-term climate stabilisation requires immediate policy investment to accelerate permanent CCS storage infrastructure and incentivise cascading wood strategies.

3.2.4.3 ECONOMIC PERFORMANCE

BECCS offers a promising pathway for achieving durable negative emissions, but it comes with high capital and operational costs primarily due to the need for CO_2 capture, transport, and long-term geological storage infrastructure. Due to the lack of commercially available data, an economic review instead of a full TEA was undertaken to evaluate the potential viability of BECCS in Ireland. A wide range of cost and scalability estimates exist for BECCS reflecting the different factors across the whole chain such as feedstock cost, logistics, plant capacity factor and the characteristics of the captured CO_2. Conventional TEAs from international bioenergy BECCS projects found that costs varied widely across different pathways with previous specific European case studies quoting between €54 to €102/tCO_2 and a break-even carbon credit price of €117/tCO_2 to make BECCS financially viable (Emenike et al., 2021; Kuparinen et al., 2023; Rickels et al., 2021). The variation is more pronounced across different regions with recent studies providing much higher abatement cost estimates of approximately €220-€520/tCO_2 (Heimann et al., 2025). The bioenergy revenue will not be able to offset the costs; therefore BECCS heavily relies on carbon pricing.

The carbon credit markets for removals are not as developed as avoidance markets; however, their prices are significantly higher, with BECCS credits valued at approximately €325 /tCO_2 in 2025 (Allied Offsets, 2026; Johnstone et al., 2026).

The European Commission's Carbon Removal Certification Framework (CRCF) establishes the first EU-wide certification system for permanent carbon removals, providing an important foundation for future compliance and voluntary carbon markets (European Commission, 2024). Though the current EU compliance market i.e. Emission Trading System (ETS) does not cater for carbon removal mechanisms, it is anticipated that BECCS economic performance will improve as policy for removals mature (Johnstone et al., 2026). In the short term, government credit guarantees or other demand-pull supports will be required for deployment of BECCS (Zetterberg et al., 2021). Government incentives, robust CCS infrastructure development, and cascading biomass use strategies are necessary to maximise both economic and environmental returns from BECCS (Coalition for Negative Emissions, 2021).

3.2.4.4 MARKET OUTLOOK

The global BECCS market was valued at approximately USD 210.68 million in 2023 and is projected to reach USD 742.73 million by 2030, growing at a CAGR of 19.84% from 2024 to 2030 (Grand View Research, 2025). The broader CDR market is expected to expand significantly, with projections suggesting it could reach USD 50 billion by 2030 and exceed USD 250 billion by 2045 (Research and Markets, 2025). BECCS is gaining attention globally, with companies like Drax Group, Microsoft Corp. and Shell investing in large-scale projects (MSCI Carbon Markets, 2023). Stockholm Exergi's project positions Sweden as a leader in BECCS deployment in Europe (DGB Group, 2025).

3.2.4.5 STAKEHOLDER INTEGRATION

Successful deployment in Ireland requires coordinated action across a broad stakeholder ecosystem, including the forestry and sawmill industry, technology providers, and energy end-users. The most significant barrier to implementation is the lack of robust CO_2 transport and geological storage infrastructure, which must be addressed to enable initial project financing. Policy frameworks must evolve beyond simple renewable energy subsidies to provide long-term, predictable incentives for high-integrity carbon removals under the EU Carbon Removal Certification Framework. Strategically, the integration of cascading biomass use is recommended to maximise both the economic value of the wood resource and the total cumulative climate benefit. By positioning wood waste biorefineries as cornerstones of the green industrial value chain, Ireland can contribute significantly to international CDR targets while strengthening its circular bioeconomy.

3.2.5 LARGE- AND SMALL-SCALE ANAEROBIC DIGESTION

3.2.5.1 AD BBVC CASE STUDY

Anaerobic digestion (AD) is a biological process where microorganisms decompose organic materials in the absence of oxygen, generating methane-rich biogas and a nutrient-rich digestate. It is considered a cornerstone of circular bioeconomy strategies for its ability to produce renewable energy and support nutrient recycling, directly aiding national net-zero targets. In Ireland, interest in AD is driven by the National Biomethane Strategy, which targets 5.7 TWh of biomethane production by 2030 to decarbonise the gas grid and agricultural systems (DCEE & DAFM, 2024). To evaluate this transition, consequential LCA of 61 prospective AD scenarios tailored to Irish conditions where explored (Figure 13). These scenarios explored 11 feedstock mixes: six large-scale industrial mixes derived from commercial project plans and five small-scale agricultural mixes consisting of grass-clover silage and cattle slurry. These were assessed under various technology configurations, including differences in biogas utilisation (grid injection vs. transport fuel), the inclusion of carbon capture and storage or utilisation, and advanced digestate treatments like ammonia stripping and struvite precipitation.

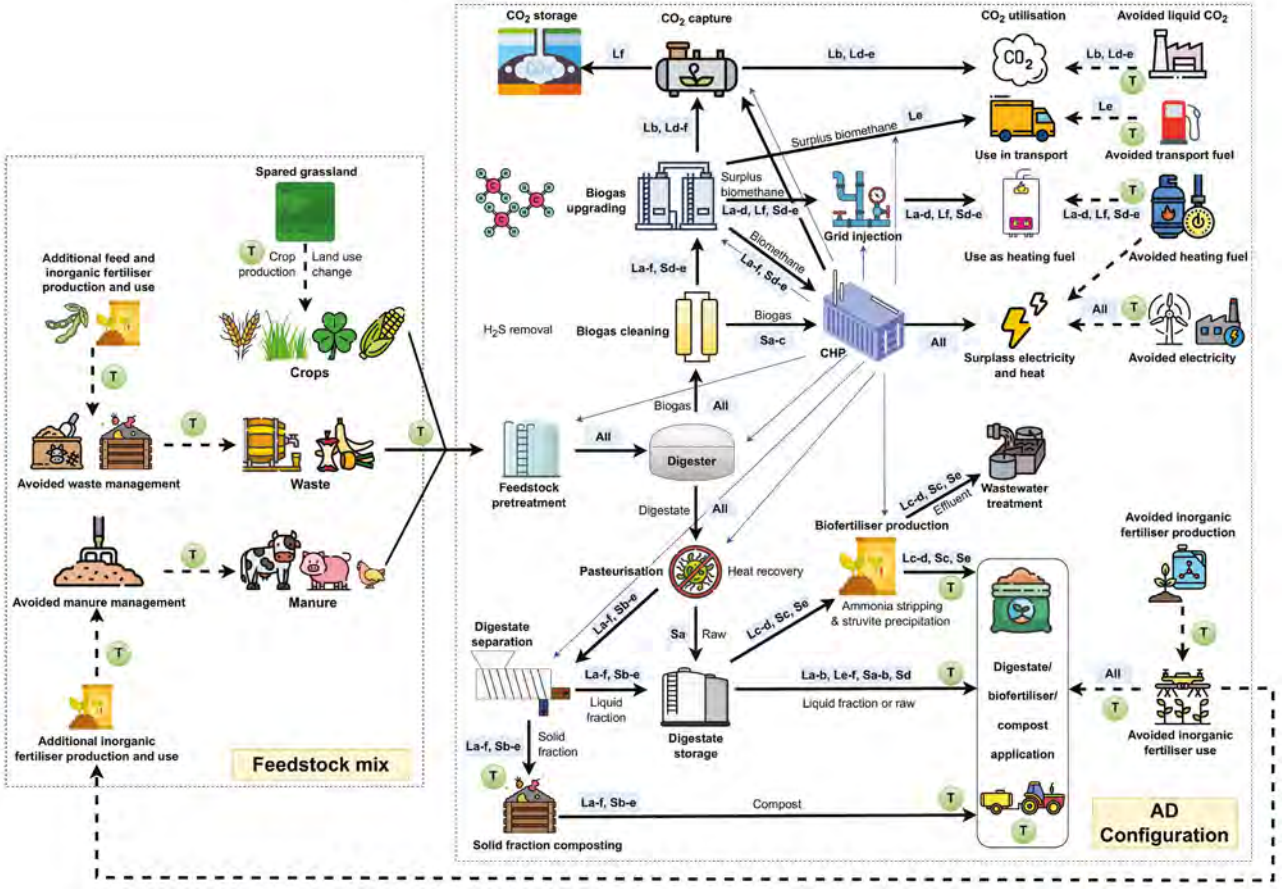


Figure 13.

Modelled Anaerobic Digestion BBVCs.

3.2.5.2 ENVIRONMENTAL PERFORMANCE

The environmental performance of AD in Ireland was fundamentally determined by the interaction between feedstock composition and plant configuration, which together explained nearly all observed variation in environmental outcomes. Statistical analysis demonstrated that, in large-scale systems, these two factors exerted a near-total influence on weighted single-score results, while in small-scale systems plant configuration played a comparatively greater role than feedstock composition.

Overall, large-scale integrated systems consistently achieved greater net environmental benefits per tonne of dry matter input than small-scale plants, primarily because they can deliver stronger climate change mitigation and fossil resource savings through biomethane substitution and the integration of carbon capture technologies.

The environmental benefits of AD systems were largely driven by substituted processes, particularly the displacement of marginal grid electricity, fossil natural gas, and mineral fertilisers. The best-performing scenario on a dry matter basis was L5b, a large-scale system incorporating carbon capture, highlighting the substantial potential of integrated biomethane and carbon management strategies for national energy decarbonisation.

However, the results also demonstrate that feedstock selection is a critical determinant of sustainability, with indirect and market-mediated effects significantly influencing environmental outcomes.

Feedstocks that displace high-value animal feed, such as brewery by-products, may generate substantial indirect burdens through increased demand for compensatory soybean production. This was evident in the L6 feedstock scenario, which achieved the greatest climate change mitigation potential but recorded the poorest overall single-score performance because of these upstream consequences. Similarly, the sustainability of crop-based feedstocks depends strongly on land-use dynamics, as cultivation
on spared grassland can support climate benefits, whereas indirect land-use change may substantially reduce environmental gains.

Despite the substantial benefits associated with substituted energy and fertiliser products, environmental hotspots remained consistently associated with feedstock provision and digestate management. Although diverting manure from conventional storage avoids certain emissions, it also creates a need for compensatory mineral fertilisers, contributing to freshwater ecotoxicity and fossil resource burdens unless these impacts are offset through efficient digestate utilisation. Methane leakage during upgrading and combined heat and power operation also remains an important contributor to climate change impacts.

The assessment further highlighted significant environmental trade-offs and the limitations of climate-centric evaluations. Technologies aimed at improving nutrient recovery, such as ammonia stripping and struvite precipitation, enhanced nutrient circularity and reduce local acidification burdens. However, their high thermal energy requirements reduce the amount of biomethane available for grid injection, thereby diminishing climate and fossil resource benefits and worsening overall single-score performance. Consequently, the results demonstrate the necessity of adopting a multi-impact assessment framework that considers a broad range of environmental indicators rather than focusing solely on greenhouse gas emission reductions.

3.2.5.3 ECONOMIC PERFORMANCE

The TEAs of the small-scale and large-scale AD systems focused more discretely on cattle slurry and grass silage inputs and indicated that, under current market conditions, neither configuration is economically viable. All baseline scenarios produced negative NPVs failing to reach breakeven over their project lifetimes. The levelised cost of biomethane (LCOB), representing the break-even production cost, ranged from €125 to €169/MWh for the large-scale scenarios, exceeding current market prices and highlighting the need for policy and market interventions. Sensitivity analysis identified CAPEX, OPEX, grass silage price and biogas/biomethane price as primary drivers of profitability.

Introduction of supports in the form of CAPEX grants, increased biomethane certificate prices, and carbon credit revenues significantly improved the economic performance of the large-scale AD systems, turning them to positive NPVs. Though financial performance improved under support mechanisms, small-scale AD systems remained economically unviable, highlighting the need for improved support and diversified revenue streams. For instance, improving digestate valuation or incentivising nutrient recirculation could possibly provide additional revenue streams and reductions in grass production costs which could, in turn, increase profitability.

The results indicated that a diversified policy mix is required rather than reliance on a single intervention. Small-scale AD could prioritise nutrient recycling and local agricultural integration, while large-scale plants will benefit from efficient biomethane production and grid injection. This reflects the Biomethane Strategy's approach of combining decentralised nutrient management with centralised energy delivery.

3.2.5.4 MARKET OUTLOOK

The biomethane market is experiencing significant growth as countries seek to decarbonise transport, heating, and industrial sectors. In 2024, the global renewable gas market was valued at approximately USD 35–40 billion and is projected to grow at an annual rate of 10–12%, reaching an estimated value of USD 60–70 billion by the mid-2030s (Markets and Markets, 2023). This expansion is being driven by renewable gas mandates, carbon pricing mechanisms, and strong policy support, particularly across Europe and North America, where biomethane and green hydrogen are increasingly incorporated into national energy strategies.

In parallel, digestate markets are also expanding. The global organic fertiliser sector is projected to exceed USD 14 billion by 2030, with an estimated compound annual growth rate of approximately 12% (MarkNtel Advisors, 2024). Digestate derived from AD systems offers an attractive circular-economy product by recycling nutrients and improving soil health. Growing interest in sustainable agriculture and reduced dependence on synthetic fertilisers further strengthens market potential.

3.2.5.5 STAKEHOLDER INTEGRATION

AD value chains involve a diverse network of stakeholders whose interactions influence the technical, economic, and environmental performance of both small- and large-scale AD systems. Effective collaboration among these groups is essential for successful project development and long-term operation. Feedstock suppliers, including arable farmers, livestock producers, and silage contractors, provide slurry, grass silage, and other organic residues required for biogas production. Reliable feedstock supply agreements are essential to ensure consistent availability and cost stability.

Technology developers, including AD equipment manufacturers and research organisations, contribute to improvements in digester design, gas upgrading technologies, and process control systems. These innovations support greater operational efficiency and enhanced biomethane yields. Plant operators and project developers, such as farm cooperatives, community energy groups, and private investors, are responsible for project construction, operation, maintenance, and performance monitoring. Their ability to secure financing and manage operational risks is critical to project success.

Energy offtake partners, including gas network operators and electricity suppliers, provide markets for biomethane and renewable electricity through feed-in tariffs, renewable gas certificates, and long-term purchase agreements. Their participation helps establish revenue certainty for AD projects. Infrastructure partners, including transport companies, slurry collection services, and gas injection operators, facilitate feedstock logistics and integration with energy networks.

Efficient infrastructure systems are necessary to minimise costs and improve supply chain performance.

Government departments, regulatory agencies, and environmental authorities establish renewable energy targets, safety regulations, environmental standards, and financial support mechanisms. Policy stability and clear regulatory frameworks are particularly important for reducing investment risks.

3.2.6 FOOD WASTE ANAEROBIC DIGESTION

3.2.6.1 FOOD WASTE AD BBVC CASE STUDY

Food waste is a significant concern due to the environmental burden of its management. Ireland generates 750,000 tonnes of food waste per year, with major contributions from households (26%), food manufacturing (25%), and the hospitality sector (22%) (Domínguez et al., 2026). This case study modelled a facility treating 50,000 tonnes of food waste annually, incorporating pretreatment, pasteurisation, mesophilic digestion, biogas upgrading by water scrubbing, and digestate separation by centrifugation (Martínez-Arce et al., 2025) (Figure 14). The assessment explored multiple scenarios, including base, best (+15%), and worst-case (-15%) financial configurations that varied revenue drivers such as biomethane output, selling prices, and gate fees. Furthermore, the study evaluated the influence of policy support mechanisms like carbon credits and the Renewable Heat Incentive, alongside environmental sensitivity analyses that varied fugitive methane emissions, utility energy sources, and digestate circularity configurations.

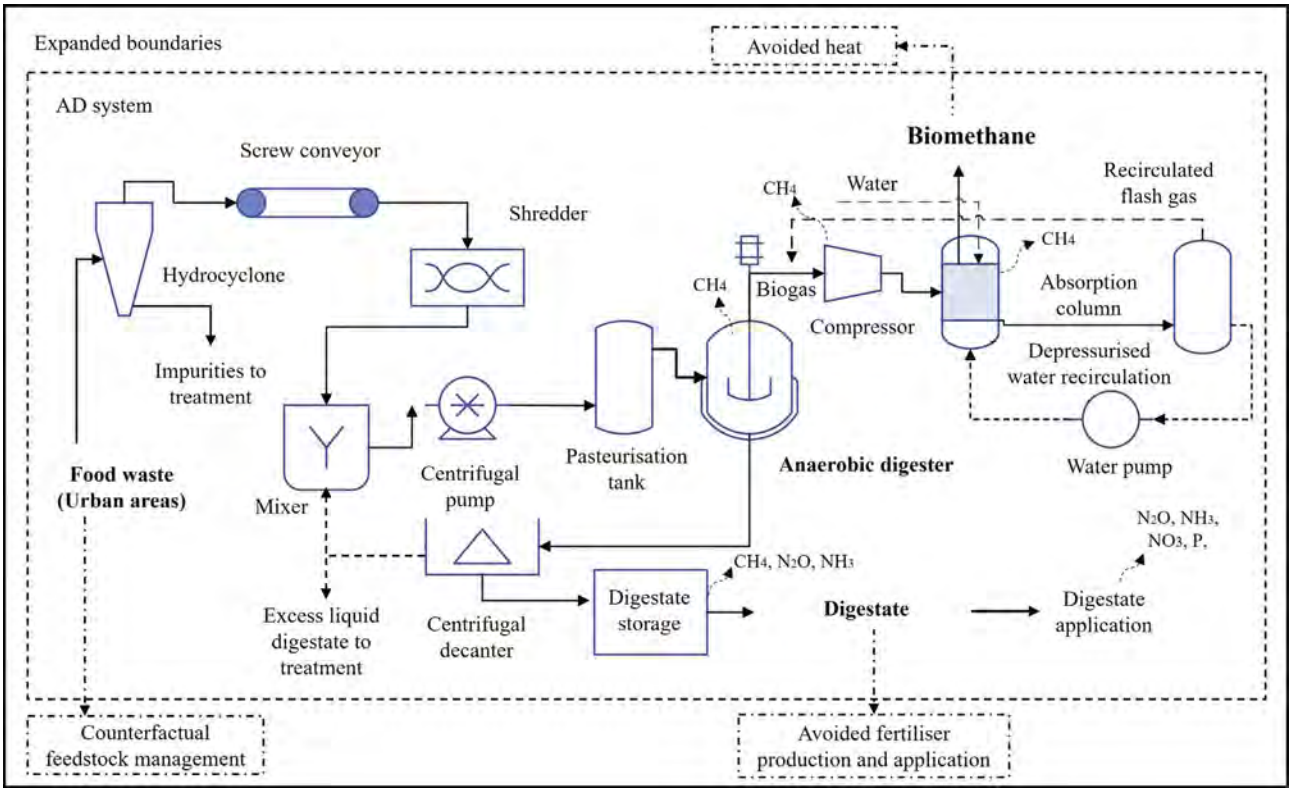


Figure 14.

Process flow diagram and system boundaries used for the techno-economic and environmental assessment of biomethane production from food waste.

3.2.6.2 ENVIRONMENTAL PERFORMANCE

The environmental LCA indicated that biomethane production from food waste generally offers a net climate benefit, though results are highly sensitive to operational factors. Under the base case scenario, the system achieved a mitigation potential of 46 kg CO_2 eq. per tonne of food waste treated. This performance improved significantly in the best-case scenario, reaching mitigation potential benefits of between 194 and 222 kg CO_2 eq./tonne depending on whether liquid digestate was recirculated or applied to land following the Nitrates Directive. Conversely, the worst-case scenario resulted in a net environmental impact of 167 to 204 kg CO_2 eq. / tonne, primarily driven by the use of coal-based energy, reduced fossil energy displacement, and high fugitive methane emissions.

A key finding was that uncontrolled fugitive methane emissions can entirely negate the climate benefits of AD. In high-emissions scenarios where leakage during biogas upgrading was not managed, the mitigation potential was lost, resulting in a net impact of 6 to 30 kg CO_2 eq./ tonne. Beyond climate change, the study highlighted environmental trade-offs in other categories; for example, while circular digestate management reduced freshwater eutrophication, it increased terrestrial eutrophication and acidification due to ammonia and nitrate emissions during land application.

Nutrient circularity through the application of liquid digestate was found to be feasible, requiring between 700 and 1,000 hectares of land annually for the model facility. Adhering to the Nitrates Directive closed periods (applying only 67% of surplus digestate) proved superior

to "bad practice" all-year application, which halved the fertiliser substitution value while increasing environmental burdens. These results emphasised that while AD offers substantial potential for climate mitigation and nutrient recycling, rigorous emission control and strategic digestate management are essential to ensure a net positive environmental outcome.

3.2.6.3 ECONOMIC PERFORMANCE

Under current market conditions, the TEA of a 50,000 t/yr food waste biomethane plant was not financially viable with an NPV of -€27 million. The LCOB was €249/MWh, substantially exceeded current biomethane market values and a gate fee of €69/tonne was required to breakeven. Sensitivity analysis indicated that gate fee revenues, CAPEX and utility costs were the dominant economic drivers, highlighting the importance of gate fees as a key market-based revenue mechanism. The analysis demonstrated that higher gate fees, together with policy support mechanisms such as biomethane incentives, capital grants and carbon credits, are necessary to achieve commercial viability under current market conditions. These findings reinforce the importance of integrated market and policy support for food waste biomethane production. Detailed economic analysis including the annualised costs and revenue is available from (Martínez-Arce et al., 2025).

3.2.6.4 MARKET OUTLOOK

As described in Chapter 3.2.5.5, biomethane has strong growth potential in Ireland, driven by national and EU policy commitments. Under the National Biomethane Strategy, Ireland aims to produce 5.7 TWh of biomethane by 2030, supplying approximately 10% of national gas demand. Current production is low (~0.075 TWh), creating a large supply gap and significant investment opportunities (DCEE & DAFM, 2024). Biomethane can be directly injected into the existing Gas Networks Ireland grid, offering flexibility for use in residential heating, industry, and transport (Compressed Natural Gas (CNG)/ Liquid Natural Gas (LNG) fleets). Demand is particularly strong in sectors where electrification is challenging (e.g., heavy transport, high-temperature industrial processes). However, production costs remain high (~249 €/MWh in our study vs. natural gas ~112 €/MWh), highlighting the need for policy supports such as Renewable Heat Obligations, carbon credits, and capital grants. If these mechanisms are well-calibrated, biomethane could emerge as a competitive, low-carbon substitute for imported fossil gas.

Digestate represents the second major output. From a plant processing 50,000 tonnes of food waste annually, around 40,000 tonnes of digestate are produced, including a liquid fraction and a solid fraction. Digestate can be applied directly as a biofertiliser, recycling nutrients such as nitrogen, phosphorus, and potassium back into agricultural soils. The market potential is significant given the EU's push to reduce reliance on imported mineral fertilisers, especially in the wake of price volatility linked to global energy crises. Digestate offers farmers a circular, locally sourced alternative that reduces costs and carbon footprints. However, the market faces regulatory and practical barriers: compliance with the Nitrates Directive, challenges in storage and spreading, and the need for quality assurance standards to build farmer confidence. Emerging innovations-such as nutrient recovery technologies (e.g., ammonia stripping) - could create higher-value fertiliser products from digestate, improving both its marketability and environmental performance.

3.2.6.5 STAKEHOLDER INTEGRATION

As discussed in Chapter 3.2.5.5, the majority of stakeholders within the food waste AD BBVC remain consistent with those identified for other AD systems. Nevertheless, food waste-specific AD requires additional engagement and coordination with waste-producing sectors, including municipal authorities, food manufacturers, retailers, hospitality businesses, and households, to secure enough source-separated organic waste and maintain feedstock quality.

4. WHAT COULD THE FUTURE LOOK LIKE?

4.1. Objective

Ireland's Climate Action and Low Carbon Development Act commits Ireland to achieving a climate neutral, biodiversity rich, and resilient economy by 2050. The Agriculture, Forestry, and Other Land Use (AFOLU) sector accounts for over 40% of national GHG emissions, and is a major source of water pollution, ammonia emissions, and biodiversity loss. The AFOLU sector will play a critical role in meeting the aforementioned targets, whilst facing growing demand for food, energy, and materials. Effective realisation of a just transition for AFOLU stakeholders, whilst delivering the multifaceted demands that society places on this sector, constitutes a "wicked problem", characterised by complex trade-offs across food security, economic stability, and environmental imperatives. Strategic foresight is a systems approach to explore plausible futures (Prager & Wiebe, 2021), providing evidence on transformative change that may not be well represented in the economic models often used to inform policy. Those models tend to focus on small perturbations to continuations of recent trends that are assumed to represent optimised equilibria, in contrast with multifaceted decision-making and non-linear, potentially volatile, risks facing AFOLU stakeholders (Stern, 2016). Here, we summarise the application of strategic foresight to evaluate a bioeconomy (BE) pathway, comprising scaled value chains described in Chapter 3, with business as usual (BAU), on a 2050-time horizon. This chapter compares the BE pathway against BAU in terms of sustainability and resilience, drawing on key indicators such as GHG emissions, ecosystem services, and risk exposure under uncertain future contexts.

4.2. Methodology

Two indicative pathways (BAU and BE) are derived from scenarios run for the Land Use Review and published in Styles et al., 2025. Full details can be found in those references for these pathways, which were co-developed with expert stakeholders in the policy and scientific domains. The BE pathway drew heavily from evidence generated in InformBio, scaling priority BBVCs identified in Chapter 3. The OptiGOB model (Duffy et al., 2026) was employed to evaluate food, energy and material outputs, GHG emissions, nutrient losses to air and water, and High Nature Value (HNV) land areas for the two pathways (Box 5).

This model was also used to scale cattle output in the BE pathway in order to achieve split-gas climate neutrality by 2050 (i.e. a 32% reduction in national emissions of the short-lived GHG methane, relative to 2018, alongside net zero CO_2 equivalent for the long-lived GHGs CO_2 and nitrous oxide).

Box 5:

OptiGOB is a decision-support tool that supports foresight by enabling systematic design and analysis of wide-ranging AFOLU scenarios. OptiGOB enables users to explore the environmental and productivity outcomes of alternative configurations and priorities for Ireland's AFOLU sector, for a selected target year extending out to 2100. Greenhouse gas emissions, land areas, potential high nature value (HNV) areas, food protein outputs, timber harvests, and bioenergy are estimated for baseline and target year(s). OptiGOB combines data outputs from the GOBLIN (General Overview for a Backcasting approach of Livestock Intensification) model for agriculture and land use, from FERS-CBM for forestry, and from the LCAD2.0 model for anaerobic digestion, to generate scenarios that respect biophysical constraints, including: (i) available areas of mineral and organic soils; (ii) user-defined climate neutrality targets; (iii) estimated agricultural productivity gains out to 2050 (e.g. milk yield per cow). Crucially, future land areas and emissions from agriculture depend on user-defined levels of ambition in the application of technically proven productivity and abatement measures. Emission calculation algorithms in the underlying models are aligned with methodology used to compile Ireland's greenhouse gas (GHG) emissions for UNFCCC reporting in annual National Inventory Reports.

Bioeconomy pathway parameterisation in OptiGOB was based on scaling out of priority BBVC identified in InformBio, in consultation with expert stakeholders during the Land Use Review 2. Here, this pathway is compared with Business as Usual (BAU).

Resilience screening was undertaken using quantitative outputs from OptiGOB (for the year 2050), and considering risks and opportunities under alternative future contexts represented by Shared Socioeconomic Pathways used in global integrated assessment modelling – completing the structured foresight analysis.

Table 3.

Key characteristics of, and indicative policy interventions needed to realise, the two AFOLU pathways evaluated in this chapter

Pathway	2050	Indicative policy interventions
Business as usual	Afforestation continues at circa 2 kha/yr 50:50 broadleaf:conifer Deforestation continues at 752 ha/yr High rate of forest harvesting No additional rewetting Dairy cow numbers increase to 1.8 million, suckler cow numbers remain similar (0.87 million) based on EPA projections Medium productivity increase Emissions intensity held constant Other activities and areas held constant	Existing subsidy supports of circa €2bn per annum directed towards existing farming systems – includes circa €0.6 bn for agri-environmental measures. Ongoing promotion of abatement measures through agri-advisory support. However, no additional regulation or strong policies such as agricultural emission pricing to drive abatement & diversification. Afforestation grants are financially attractive, but uptake remains low owing to various "lock ins" to current farming and farmer preference to keep options open for future land use.
Bioeconomy (split gas climate neutrality target)	Afforestation 16 kha/yr No deforestation Extended forest harvest interval 90% rewetting of drained peatland 90% rewetting organic soil under grass Frontier ag abatement measures Biomethane strategy implementation 2 Mt/yr technical CDR (cascading wood biochar and/or BECCS) Cattle numbers scaled to achieve split-gas target (10:1 dairy:suckler) High productivity increase for cattle Additional 100 kha protein cropping 180 kha grass-protein biorefineries 400 kha willow for tCDR	Carbon tax or cap & trade to constrain sectoral emissions and leverage diversification (including higher uptake of afforestation grants). Hypothecation to technological productivity and abatement measures ("sustainable intensification"), supports for protein and energy crops and a herd retirement (exit) scheme. Combined with low gross margins for beef cattle farms, this could drive suckler-beef destocking whilst preserving efficient dairy systems alongside expansion of protein and energy/ carbon farming. Land sparing by design – encourages uptake of afforestation grants and diversification on spared land. CAPEX and/or renewable energy and/or bioenergy mandates could drive AD and wood energy deployment. Extended to incentivise AD-integrated protein biorefineries and tCDR. This would need to be accompanied by an ambitious industrial bioeconomy development strategy to drive demand and supply chains.

Table 3 summarises key features of the two pathways, and indicative policy interventions likely to be needed to achieve them. In brief, the BAU pathway represents a continuation of existing trends, with a gradual increase in dairy cow numbers, low rates of afforestation and no additional peatland rewetting nor implementation of the Biomethane Strategy.

In contrast, the BE pathway includes a large reduction in suckler-beef cattle numbers, sustainable intensification of dairy production (stable herd size but more productive cows), 16 kha per annum of afforestation from 2030 onwards, full implementation of Ireland's Biomethane Strategy plus deployment of circa 180 kha of grass-clover for grass-protein biorefineries, an additional 100 kha of protein cropping and 400 kha of willow cultivation for BECCS (Table 3). It is important to note that these two pathways are not predictions nor recommendations of the future but simply illustrate how sustainability and resilience outcomes vary with different land use configurations (reflecting possible collective stakeholder actions over time).

4.3. Sustainability assessment

Sustainability in the AFOLU sector can be measured as an ability to deliver food, energy, and materials while remaining within planetary boundaries (Steffen et al., 2015).

A critical sustainability indicator is net GHG emissions, i.e. gross GHG emissions to the atmosphere minus CDR from the atmosphere (otherwise known as a "carbon sink"). Under the BAU pathway, net emissions are projected to increase to around 30 Mt CO_2e by 2050 (Figure 15), leaving the sector far adrift of national and international regulatory targets. This trajectory is driven by a 6% increase in cattle numbers and minimal progress in CDR and emission abatement technologies. In contrast, the BE pathway is designed to achieve split-gas climate neutrality by 2050.

Ambitious afforestation brings Land Use, Land Use Change & Forestry (LULUCF) net emissions close to zero by 2050 and provides new biomaterial supply into the economy into the second half of the century - contributing to avoided GHG emissions via concrete, steel and fossil energy substitutions (Figure 15). Net GHG emissions across AFOLU are reduced by 66% from 2020 levels by 2050. Critically, via ambitious expansion of technical CDR (BECCS and/or biochar), net AFOLU emissions reduce to within 1 Mt CO_2e of all-gas net zero from 2065 onwards (Figure 14). By 2050, tCDR and wood products contribute up to 6.3 Mt CO_2e/yr of negative emissions in the BE pathway. From a life cycle perspective, over 11 Mt CO_2e of downstream annual climate mitigation is achieved by 2050 through the substitution of concrete, steel and fossil fuels with biomass and wood products.

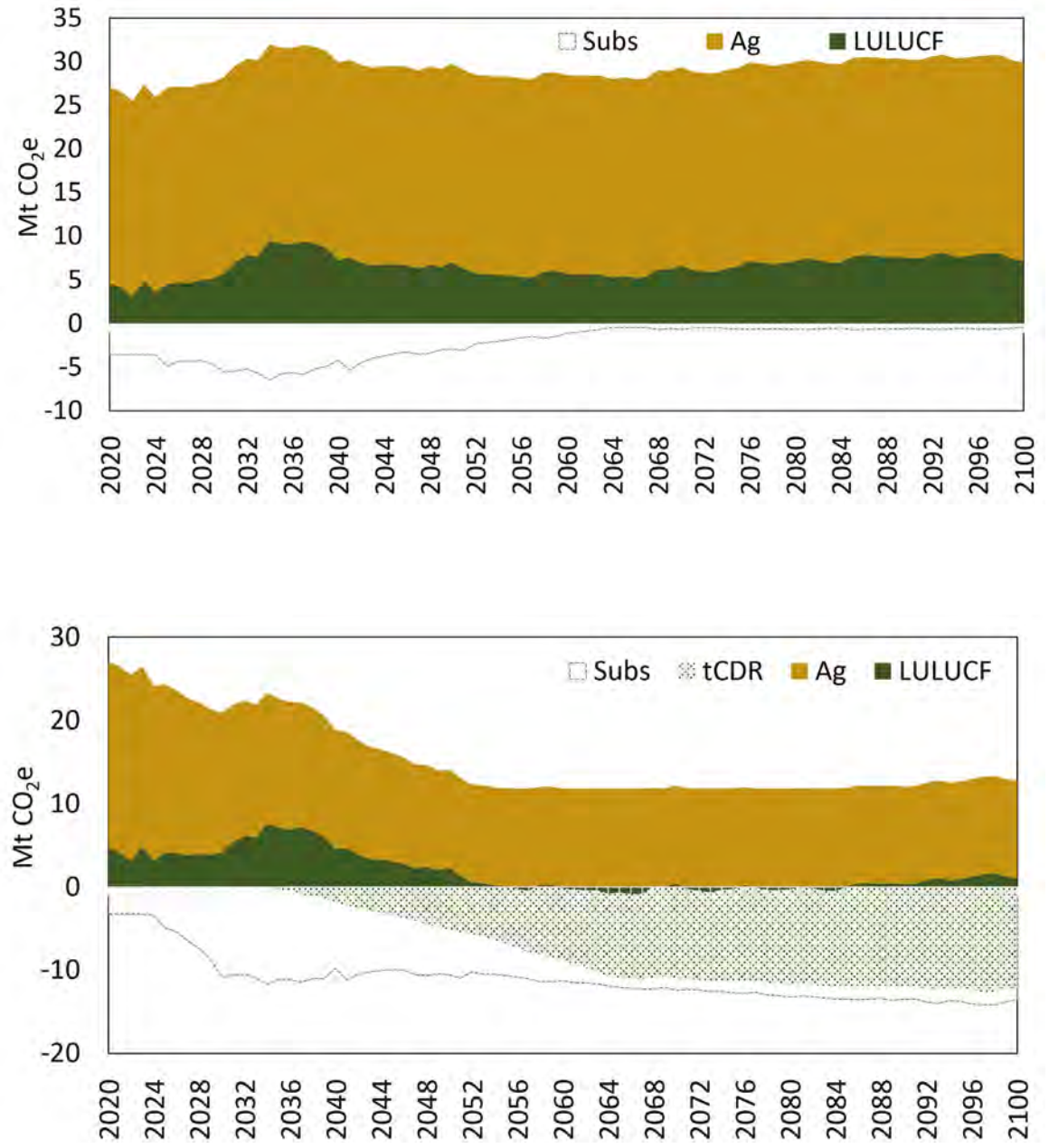


Figure 15.

Evolution of agricultural emissions (brown), Land Use Land Use Change & Forestry (LULUCF) net emissions (dark green) and technical carbon dioxide removal (tCDR) through to 2100 for Business as Usual (top) and the Bioeconomy pathway (below).

Sustainability also encompasses air and water quality. Under BAU, a trend of declining water quality is expected to persist due to increased nutrient loading (nitrogen and phosphorus) from intensive livestock farming. Conversely, the BE pathway achieves significant reductions in environmental externalities by 2050 relative to 2020 (Figure 16). Ammonia emissions to air and nutrient losses to water decline by 27-31% as a result of reduced pressures from livestock (Figure 16), although "hotspots" may remain in intensively farmed dairy regions. Meanwhile, potential HNV land use declines by 7% under BAU but increases by 41% for the BE pathway, via peatland rehabilitation, the establishment of new broadleaf forest, and conversion of 400,000 ha of grassland for cattle-rearing to low-input cultivation of willow as a feedstock for tCDR. Notably, the BE pathway achieves these reductions in environmental impact whilst ***increasing*** total protein output by 47% (more milk protein, crop protein and grass-protein from biorefineries), increasing bioenergy almost five-fold and increasing wood output by 160% by 2100 (Figure 16). Thus, it is clear that Ireland's landscape could contribute even more to food and energy security than it does today, whilst dramatically reducing environmental pressures, through ambitious deployment of bioeconomy value chains described in previous chapters.

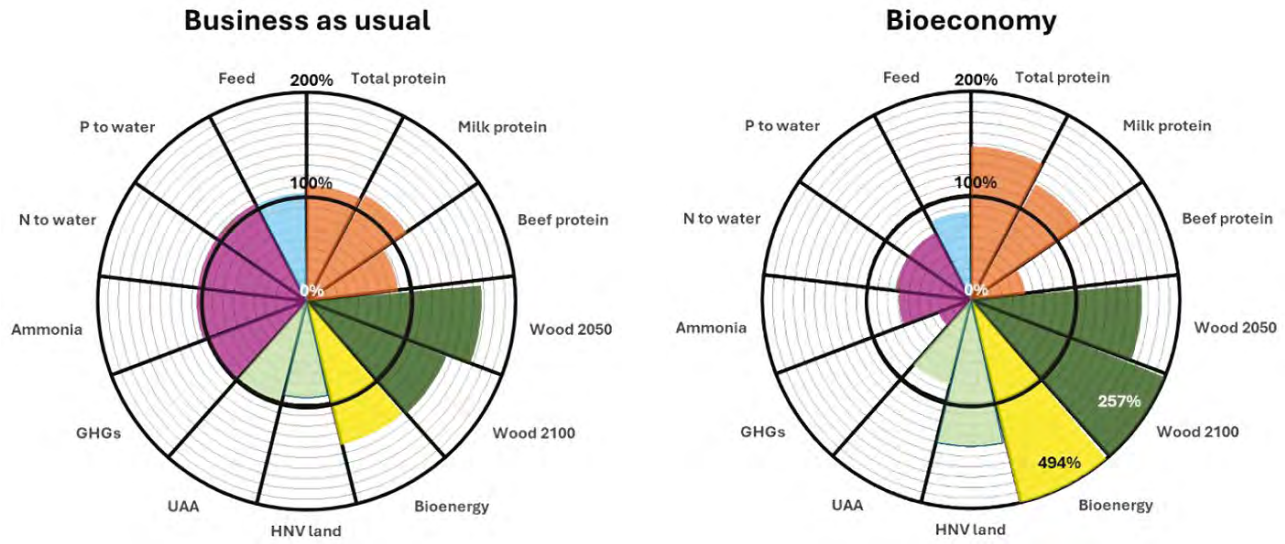


Figure 16.

Radar plots showing environmental impacts (left; smaller values better) and productive outputs (right; larger values better) for Business as usual and Bioeconomy pathways in 2050 – expressed as a ratio of 2020 impacts or outputs (inner circle).

4.4. Resilience

Resilience refers to the ability of a system to withstand shocks and adapt to volatile, unknowable future contexts. One way to reflect the range of possible futures is to use the five Shared Socioeconomic Pathways (SSPs) used for this purpose in integrated assessment models (O'Neill et al., 2017). Based on narrative descriptions of these futures, risks and opportunities can be identified for particular AFOLU pathways as determined by long-term investment decisions. A semi-quantitative risk screening across nine factors (including commodity price volatility, insolvency, and climate impacts) revealed that the BE pathway is less exposed to risk (and therefore more resilient) across the range of possible futures (Figure 17).

In a sustainable future (SSP1), BAU is highly exposed to the public and private costs of regulatory risk and high carbon pricing. The BE pathway thrives here due to high demand for alternative proteins, energy, and negative emissions.

In a regional rivalry future (SSP3), the export-oriented BAU cattle sector is particularly vulnerable to trade disruption. The BE pathway is more resilient because it prioritises diversified indigenous energy and food production.

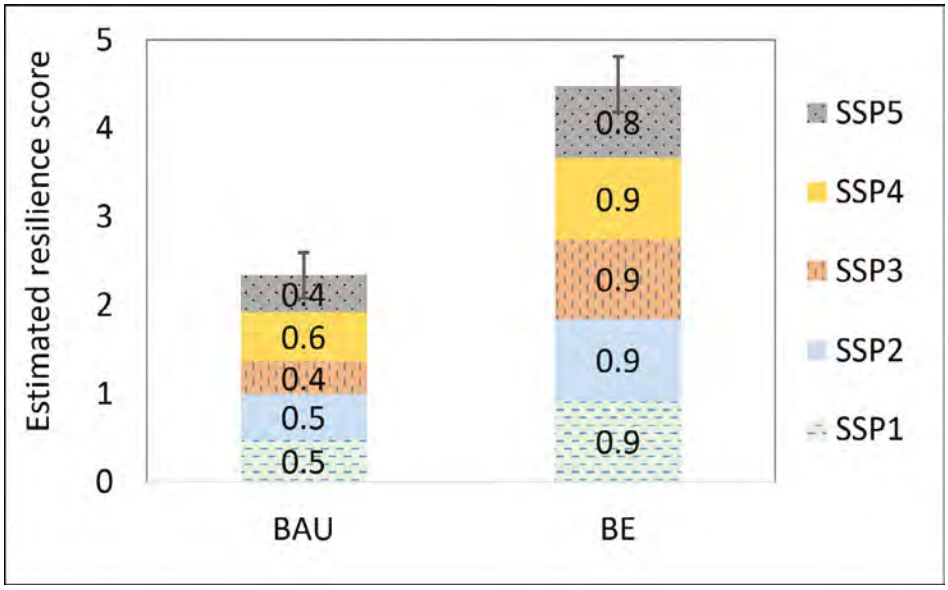


Figure 17.

Estimated resilience scores for business as usual (BAU) and the Bioeconomy (BE) pathway. A maximum resilience score of 1 is possible within each future context, and 5 in aggregate. Error bars represent 95% confidence intervals in aggregate scores.

In a fossil-fuelled development future (SSP5), BAU faces extreme risk from climate impacts that reduce the feasibility of grazing-based production. The BE pathway mitigates this through diversified revenue across multiple crops and systems.

This screening indicates high risks for farmers under BAU where they remain highly specialised in cattle, making them particularly vulnerable to price volatility in a few key export and import commodities. In addition, considerable annual investment by farmers (€1.5 bn annually) is concentrated in assets that may become stranded as regulations tighten and markets change (Kortleve et al., 2026). In the BE pathway, resilience is built through diversification. Farmers move into energy crop cultivation, protein cropping, and grass biorefining. While this requires higher initial investment (€2.3 - €2.9 bn annually), it provides multi-stream revenue less exposed to individual risks.

Tax-payers and government also face risks under BAU. The state faces massive fiscal exposure due to potential multi-billion-euro liabilities for failing to meet EU climate targets, and mal-investment in assets that become stranded (e.g. grants for cattle sheds). In contrast, whilst the BE pathway requires higher public subsidies for infrastructure (e.g. biorefineries and tCDR), it reduces the risk of compliance cost liability by providing a viable path to climate neutrality.

Finally, the whole of society faces systemic risk under BAU, including balance of trade exposure because 90% of beef and milk is exported, while all fertilisers and large quantities of feed are imported, alongside water pollution and low farm viability. BE enhances energy security, reduces dependence on imported foods, reduces environmental degradation (external costs) and supports rural community viability by maintaining distributed land use and creating new value chains.

4.5. Just transition

The transition from BAU to BE requires a fundamental shift in the activities of existing and new actors in the land sector. Under the BE pathway, suckler-beef farming, beef processing, and fertiliser/feed sales significantly contract as farming moves away from cattle specialisation. Meanwhile, the BE pathway sees rapid expansion in energy crop cultivation, grass biorefining, alternative protein processing, anaerobic digestion, and forestry. Realising the BE vision will thus involve possible losses to some stakeholders but gains to actors specialising in CO_2 capture and transport, peatland rehabilitation, and industrial bioeconomy supply chains.

While a transition towards a BE carries significant and visible short-term risks, such as private insolvency during the shift or failure to scale BECCS, these must be weighed against a multiplicity of severe risks facing stakeholders under BAU. The BE pathway could ultimately realise a more resilient, sustainable, and vibrant rural economy that delivers food, energy, and material security whilst substantially reducing environmental impact towards levels compatible with planetary boundaries. The BE pathway elaborated here comprises ambitious scaling of value chains identified as promising within InformBio, as needed to achieve climate neutrality by 2050. However, the range of value chains and degree of scaling may vary considerably; a plethora of bioeconomy development pathways is possible and requires further exploration.

4.6. Next steps

The comparison between indicative business as usual and bioeconomy futures underscores the necessity for transformative change across AFOLU to mitigate large environmental, economic and social risks facing all stakeholders in a volatile world. Business as usual represents a trajectory of increasing GHG emissions, declining biodiversity, and high vulnerability to geopolitical and regulatory shocks. The bioeconomy pathway, while requiring significantly higher investment and radical policy interventions (such as carbon pricing and strategic land planning), offers superior performance across a broad range of sustainability and resilience indicators. By diversifying land use towards alternative food, energy and biomaterial product, along with the production of ecosystems services, the bioeconomy not only achieves climate neutrality but also confers robust resilience within a volatile world. There is an urgent need to engage stakeholders, not least farmers, in a constructive and open debate that considers risk and opportunity over the short-, medium- and long-term. This could reframe perceptions around the very real short-term risks that constitute a major barrier to change. Crucially, parallel development of bio-based industries is a critical enabler of change, given that farmers need new (regional) markets in order to diversify. Informed by appropriate multi-dimensional evidence, bold, cross-sectoral policies targeting ambitious expansion of new bio-based value chains could simultaneously address multiple societal challenges.

5. HOW DO WE GET TO THESE FUTURES?

Chapter 3 and Chapter 4 demonstrate the strong potential of a circular bioeconomy to contribute to Ireland's target of net zero emissions along with other sustainability targets including air and water pollution and biodiversity management, while also significantly increasing total protein, wood and bioenergy outputs by 2100.

To achieve this ambition and support outscaling, investment and policy support (e.g., for development of new facilities) will be required along with buy-in from inudstry, farmers, communities and others. However, this will also create benefits including reduced risks of fines and compliance costs, increased resilience in areas like energy and protein, and improved market diversification and competitiveness for primary producers and industry.

In order to reach these futures and outscale these bioeconomy value chains, various supports will be required. To help identify some of the requirements needed to bring these value chains into implementation, InformBio hosted a workshop with expert stakeholders from different backgrounds including research and academia, policy makers, industry, and community groups at the University of Galway on 20th April 2026 (Figure 18).

The workshop divided stakeholders based on expertise into groups related to specific InformBio prioritised value chains including green biorefinery, anaerobic digestion, BECCS and biochar. The workshop used a PESTEL analysis approach, which is a well-established framework used to analyse and monitor the macro-environmental factors that have an impact on an industry. This examines the Political, Economic, Social, Technological, Environmental, and Legal factors in the external environment. The approach has previously been used to understand the barriers and supports required to support a broader Irish bioeconomy (O'Connor et al., 2023).

Figure 18.

Stakeholder workshop to provide recommendations on outscaling of bio-based value chains.

This participatory co-creative method is in line with InformBio's commitment to engage with stakeholders relevant to value chain development, in order to foster inclusive development and secure buy-in from different types of stakeholders.

Below the PESTEL findings for each value chain are presented along with some additional summary findings from the InformBio analyses. In addition, case studies of relevant established international value chain-specific policy mechanisms are presented to highlight the development of policy in this area.

5.1. Grass biorefinery value chain

The insights from stakeholders in relation to the Grass Biorefinery value chain PESTEL analysis are presented below:

Table 4.

Key characteristics of, and indicative policy interventions needed to realise the two AFOLU pathways evaluated in this chapter

Political	Economic	Social
• Policies used to prioritise bioenergy (e.g., RHO) - there also needs to be more support for new products from grass • Land use and grass choices across different regions • Funding mechanisms for research with public /private partnerships for product development • Support for cascading use of biomass in policy • Political influence on land use and grassland use in different regions	• Influence of feedstock costs are significant • Improved pricing mechanisms (e.g., levelised prices, feed in tariffs or floor prices • Developers require operational support than CAPEX only • Training grants • Offtake agreements with industry partners • Development of bottom-up business models • Research on suitable economic and business models	• Cooperative/community initiatives to develop biorefinery models • More transparency (i.e., positive and negative stories should be told when promoting bio-based solutions) • Public participation and awareness in the early stages • Promote participation of existing supply chain stakeholders: farmers, feed suppliers, equipment suppliers
Technological	**Environmental**	**Legal**
• Connection to other value chains (e.g., AD) • Increased trials to improve products and data • Further optimisation of technology including pilot and demo facilities • Industrial Symbiosis models • Tailoring scale to regional needs and biomass availability • Scale up/ Scale out/ Scale deep • Ensuring possibilities for residual nutrient transfer (e.g., back to farm)	• Nitrates Directive on digestate • Life Cycle Assessment to understand if a product is sustainable or not	• Novel food regulations if the protein is to be used for human nutrition or other products for food • Certifications for products especially the protein • Standards on waste categorisation • Derogation challenges to farmers using digestate

Insights from InformBio Project: Chapter 3 investigated a case study of a grass biorefinery with leaf protein concentrate (LPC) for animal feed as the main core product, reflecting current commercial developments. It is likely that this model would require policy support. The activities of InformBio indicate positive potential for GHG mitigation through additional grass-based protein production, and that grass protein (LPC) delivers a significantly lower CO_2 footprint compared with soybean meal. A low emission price bonus (e.g., green premium), or carbon credit support for such products would enhance the viability of a baseline green biorefinery scenario. The Carbon Border Adjustment Mechanism supports additional tax of high-carbon imports and may be another mechanism to increase the viability of the current model. While it currently does not consider soybean in its remit, it may do in future and would offer an opportunity to increase the competitiveness of the current LPC model. In addition to product pricing, partial support on the CAPEX side for early adopters would likely support upscaling and reduce some of the cost barriers. Finally, there is the new EU Protein Action Plan which plans to support the development of local resilient plant proteins. The Action Plan references grass protein concentrates and, in this context, it could be possible that LPC may benefit from some additional subsidies or supports linked to the action plan (European Commission, 2026).

Apart from support and subsidies required for this baseline model, grass biorefinery research is evolving quickly and demonstrating the potential of developing future higher value products to complement the current baseline production scenarios considered within this report. These include food-grade proteins, volatile fatty acids for use in flavours or chemical buildings blocks and fructo-oligosaccharides for development of nutraceutical products. Previous Irish projects, such as Biorefinery Glas, have indicated that the development of such products, even in relatively moderate volumes will greatly influence the economics of green biorefinery processes. However, some of these products will need approval under regulations such as the Novel Food Regulations (EU Regulation 2015/2283) which will take some time and costs for approval. Some of these products are already under development in European and nationally funded grass biorefinery projects.

Policy Case Study: In Denmark a Green Biorefinery Feasibility and Establishment support has been established by the Ministry of Food, Agriculture and Fisheries of Denmark (2023). The initiative commenced in 2021 with an allocation of €35 million to support the expansion of green biorefining in Denmark. The two independent supports include a feasibility support and a support for establishing a green biorefinery. The fully funded feasibility support enables the different players in a green biorefinery value chain (which must include at least one farmer) to investigate and assess the potential for establishing a green biorefinery resulting in a feasibility study. The support to establish a green biorefinery is a subsidy support aiming to expand green biorefineries in Denmark, so that Danish agriculture becomes more self-sufficient in protein feed, thus contributing to the green transformation. The established biorefinery should be able to refine grass, clover, alfalfa, etc. to protein concentrate for animal feed for monogastric animals. The protein concentrate has to have minimum 35% crude protein per dry matter content. The eligible expenses are 65% EU-funded. Eligible costs include building renovation, equipment purchasing for storage, processing or monitoring of green biorefinery processes and equipment for establishment of utility services. This support has resulted in multiple collaborations undertaking the feasibility study with a number advancing towards establishment of a commercial green biorefinery.

5.2. Biochar value chain

The insights from stakeholders in relation to the Biochar value chain PESTEL analysis are presented below:

Table 5

PESTEL findings with stakeholder insights for the biochar value chain

Political	Economic	Social
• Interdepartmental coordination required to support biochar sector (e.g., DAFM, DECC, others) – political champions needed • Public procurement required to support market • Government to promote benefits to society • Market interventions required	• High cost of biochar is a barrier • Innovation Valley of Death from research to commercialisation • Market creation from public procurement, as well as private partners • CAPEX grants to support implementation • Cost of planning application can be considerable	• Discuss positives and negatives associated with solutions • Local buy-in critical to success • Build incentives around local communities • Improve awareness of benefits
Technological	**Environmental**	**Legal**
• Scale-up support (e.g., pilot, demonstration) • Diversification of co-products	• Biochar can contribute to emission removals • Pyrolysis could replace other more harmful practices like incineration • Pyrolysis can reuse energy	• Standards/certification • Guidance for use required • Verification systems for carbon credits

Insights from InformBio Project: Based on findings of Chapter 3, biochar production and use can clearly deliver sustainability benefits that align with Ireland's climate neutral future. The challenge to biochar commercialisation lies in its challenging business case, which is highly dependent on carbon credits associated with emission removals. As a consequence, it is vital that steps are taken to develop and transpose carbon farming legislation, which could support its further market development, alongside robust verification processes to develop more regulated carbon markets rather than relying on voluntary markets. Given that the level of credits required can be higher than the current carbon market prices, a consideration could be made to subsidise carbon credits until the market is willing to pay a high enough price.

Apart from subsidies, research should also explore and scale viable pathways to develop different pyrolysis-related streams. For example, to consider production and use of bio-oil and/or syngas as co-products, or to investigate the production of extractives which could have high value functional applications.

Policy Case Study: Klimatklivet (Climate leap) is a Swedish government investment support programme financing local and regional measures that reduce greenhouse gas emissions (Spinverse, 2026). Managed by the Swedish Environmental Protection Agency (Naturvårdsverket) and the County Administrative Boards, Klimatklivet supports concrete investments that deliver measurable and immediate climate impact.

The programme plays a key role in Sweden's climate policy by accelerating the transition to fossil-free transport, renewable energy solutions and low-carbon infrastructure. The programme has included biochar production within its scope.

Sweden have also initiated a new carbon credit standard developed through the project "Kolsänksrätter med biokol" (translates to biochar-based carbon removal credits) which is opening opportunities for Swedish farmers to improve soil quality and obtain a new income stream.

The first carbon credits under this standard were verified and issued during 2025, marking a major milestone for climate-smart agriculture. The system has been designed for local farmers who can apply biochar to their fields in a verified and traceable way and can earn income by generating carbon credits (Stratus, 2025).

Switzerland have also introduced a wider CDR favourable policy mechanism, which offers up to 50% CAPEX for projects >5000 tonne CO_2/year and which includes biochar among its supported mechanisms.

5.3. BECCS value chain

The insights from stakeholders in relation to the BECCS value chain PESTEL analysis are presented below:

Table 6

PESTEL findings with stakeholder insights for the BECCS value chain

Political	Economic	Social
• Carbon dioxide removal policy needed • Changing priorities of political parties • Education of decisionmakers • Still too early - uncertainty of carbon markets (in EU) • Who gets credited, who gets taxed: Where it is made or where it is consumed or stored • Communication with research bodies	• Capital costs - set up costs very high • Where does this revenue come from? • Economics of feedstocks • Economics of each technology/ process very different. Different implications depending on what product is desired • Need for transparency of the accounting of mass and carbon flows	• Winners and losers unclear • Understanding of the public opinion critical • Need regional as well as national benefits • Job creation • Proper communication with public required to highlight benefits • Transparency required on risks
Technological	**Environmental**	**Legal**
• Need proof of concept • Need full value chain infrastructure - chicken and egg? • It is unclear how efficient it is • Needs skilled labour force • Connectivity to other established sectors/ plants • Life span and reliability of of the equipment	• Other aspects of the environment affected or improved depending on feedstock type • Sustainability of feedstock supply: avoid indirect effects • Ensure aspects other than water, soil, etc need to be considered • Biodiversity considerations (homogenous feedstock or crops are not diverse)	• Need a common reporting format & standard • Legislation required • Monitoring and audits required

Insights from InformBio Project: Results from InformBio's foresight study indicate that BECCS could be a key value chain to contribute to Ireland's climate neutrality targets. In particular, it could be an effective mechanism to achieve emission removals leading to negative emissions which could offset other hard-to-abate sectors. As this is a relatively new development area, strong public engagement will be required to secure public buy-in for BECCS investments. As the model is highly dependent on securing carbon credits, strong CAPEX and OPEX support would be required due to the still uncertain carbon market. Strong verification procedures would also be recommended to demonstrate carbon savings compared with conventional forestry. Strong inclusion of cascading value chains will be essential to maximise both environmental and economic benefits.

Policy Case Study: The Swedish Energy Agency has developed a support system for BECCS in the shape of reversed auctioning (Swedish Energy Agency, 2025). Reversed auctioning means that, for example, a pulp and paper industry or a combined heat and power plant can submit a bid on how much carbon dioxide they can capture and store, and at what cost. The winning bid is best solution at the lowest cost. The first call was held in autumn 2024, in which Stockholm Exergi was awarded just over SEK 20 billion (approximately €2 billion) to store approximately 11 million tonnes of carbon dioxide (National Centre for CCS, 2025). The second such call opened in late 2025 with a budget of SEK 10 billion. The program provides funding across the whole value chain of BECCS projects, including capture, transport, and geological storage, while also financing capital and operational expenses.

5.4. Anaerobic digestion value chain

The insights from stakeholders in relation to the Anaerobic Digestion value chain PESTEL analysis are presented below:

Table 7

PESTEL findings with stakeholder insights for the anaerobic digestion value chain

Political	Economic	Social
• Targeted incentives to support sector • National Implementation of regulations e.g. update of fertiliser regulations: Mandatory blend of biofertilisers • Development of a clear and realistic roadmap to develop AD in Ireland/ Government commitment • Treating AD as an integrated part of a wider bioeconomy strategy beyond biogas	• Tax incentives • Scaling up – Economies of scale reduce CAPEX cost per product	• Tackling misinformation and false information • Dedicated advisory for farmers
Technological	**Environmental**	**Legal**
• Scaling of stable VFA production and extraction • Make capacity to support planning • Shared learnings between planners, technology suppliers and businesses	• Nutrient recovery will reduce water pollution • Further research and monitoring of potential environmental impacts (impact of digestate on soils, emissions, noise and odour) • Prioritise higher value (non-AD) use of non-contaminated waste streams from bakery, brewing etc	• Flexible interpretation of digestate pasteurisation requirements • Regulation enforcement on brown waste contamination • Biofertilisers quality regulations

Insights from InformBio Project: Chapter 3 investigated a variety of AD scenarios focused on food waste and also large-scale and small-scale agri-AD. It is clear that AD is a mature technology which can help to deliver a range of sustainability impacts for the farming sector and wider economy. A challenge still remains on improving the economic viability of such technologies to support wider adoption so that these benefits can be realised. A number of additional suggestions could be made to improve the integration of AD systems in Ireland. Some additional operational support e.g., incentive for electricity or methane would create market certainty.

Currently there is already a capital grant available under the government's National Biomethane Strategy which is de-risking capital expenditure. For smaller-scale AD systems, a greater distinction could be made compared to large systems on the benefits of nutrient management, since treated digestate could be returned to the farms. Therefore, consideration of AD and nutrient biorefineries integration into farming systems to ensure nitrates compliance could be a driving factor. In this case, rewarding farmers and industry for effective manure and nutrient management in small-scale AD systems (in addition to renewable heat incentive) could be an effective mechanism.

Selection of feedstocks for AD systems influences profitability greatly and requires strong consideration. Incentives for AD facilities should be strongly linked to mitigation delivery and other environmental benefits and should allow enterprises to deal with market volatility.

Apart from such supports, further steps should be taken to explore and develop different AD-based biorefinery pathways which are robust enough to reduce the long-term need for subsidies. For example, companies are already considering possibilities to capture and use CO_2 produce in AD for use in industries such as the beverage industry. Others are considering higher value products such as the development of volatile fatty acids which can serve as platform chemicals and ingredients. The wider integration of AD systems within biorefinery systems as well as the wider food sector should be considered as a mechanism to balance between sustainability and profitability.

Policy Case Study: As a country with similar population and size as Ireland, Denmark represents a good policy case study for comparison. In 2023 the share of biomethane in the Danish gas system reached almost 40% and by 2030 Danish gas consumption is expected to be 100% (Danish Energy Agency). The production of biogas in Denmark increased rapidly since the 2012 when a new subsidy scheme entered into force. The subsidy scheme which included a fixed subsidy level across eligible biogas producers, was targeted at increasing the production of biogas for electricity production, processing, heat production and upgrading to biomethane, where the latter is to be injected into the gas system, where it displaces natural gas. The subsidy scheme implemented in 2012 was closed for new applications in 2018, but as subsidies were granted for a 20-year period the major share of biogas produced in Denmark today is still subsided. Currently there are no subsidy schemes available for new production capacity, but a series of tenders for the production of biogas and other green gases is planned.

5.5. Other contributing factors

As noted in Chapter 4 several policy and strategy steps could be taken to improve the environment for wider deployment of bio-based value chains. Within the BAU scenario, existing subsidy supports of circa €2bn per annum continue to be directed towards existing farming systems – which includes circa €0.6 bn for agri-environmental measures. While there is ongoing promotion of abatement measures through agri-advisory support in the BAU scenario, no additional regulation or strong policies such as agricultural emission pricing to drive abatement and diversification were introduced. Meanwhile, afforestation grants are financially attractive in BAU case, but uptake remains low owing to various "lock ins" to current farming and farmer preference to keep options open for future land use.

In the supportive bioeconomy (BE) scenario, aimed at increasing implementation and adoption, carbon tax or cap and trade is introduced to constrain sectoral emissions and leverage diversification (including higher uptake of afforestation grants). Hypothecation is prioritised for technological productivity and abatement measures ("sustainable intensification"). Additionally, supports for protein and energy crops and a herd retirement (exit) scheme are introduced.

These steps, combined with low gross margins for beef cattle farms, could drive suckler-beef destocking whilst preserving efficient dairy systems alongside expansion of protein and energy/carbon farming. Land sparing by design could be prioritised, encouraging uptake of afforestation grants and diversification on spared land.

CAPEX or bioenergy mandates could drive AD and wood energy deployment, and such strategies could be extended to incentivise AD-integrated protein biorefineries and tCDR. This would need to be accompanied by an ambitious industrial bioeconomy development strategy to drive demand and supply chains.

In addition to above, it will also be important to consider future-proofing incentives to support farmers and others in supporting a just transition. As previously mentioned in Chapter 4, the transition towards a bioeconomy can carry short-term risks, however these are likely to be less risky than the costs of the BAU scenario, and will bring significant opportunities to increase sustainability, resilience and boost income diversification. But to deal with this transition and negate any short-term risks, a repurposing of existing incentives towards more future-proofed activities would be very beneficial.

5.6. Monitoring and measuring bioeconomy developments – Bioeconomy Monitoring Framework

Apart from leveraging public and private investments towards the development of new bio-based value chains and supporting the development of such initiatives with strong policy measures, it is also vital that work is undertaken to set targets to monitor and measure these initiatives and the evolving bioeconomy as a whole. This objective was set out as an action at an EU level in the 2018 EU Bioeconomy Strategy, following a 2017 assessment of the initial EU 2012 Bioeconomy Strategy which called for "better monitoring and assessment frameworks are needed to assess progress" and suggested that "new actions are needed to develop relevant indicators and scientific evidence for policy making, and to implement a more holistic monitoring and assessment framework" (European Commission, 2018b). In 2020, the EU published its approach to developing an EU Bioeconomy Monitoring Framework which developed specific bioeconomy indicators linked to the five objectives of the EU Bioeconomy Strategy (Giuntoli et al., 2020), namely;

- Ensuring Food and Nutrition Security
- Managing Natural Resources Sustainably
- Strengthening European Competitiveness and Creating Jobs
- Mitigating and Adapting to Climate Change
- Reducing Dependence on Non-Renewable, Unsustainable Resources

Additionally, each indicator was mapped to the addressed sustainability pillar: economic, social or environmental and, where possible, defined according to the relevant biomass source it refers to: agriculture, forestry, fisheries, aquaculture. The monitoring was subsequently made public through a series of interactive dashboards designed to improve public access and engagement across member states (Kilsedar et al., 2021).

Various approaches have since been undertaken at member state level to implement a bioeconomy monitoring system, including product-based approaches (Austria and France), and territorial approaches (e.g., Germany and Finland) and hybrid approaches (e.g., Netherlands). Each system also has their own country-specific KPIs for measuring this progress.

In Ireland, the development of a bioeconomy monitoring system and the need to measure bioeconomy developments has been referred to both in the Bioeconomy Action Plan and the Climate Action Plan (list of actions) (DCEE, 2021; DECC & DAFM, 2023). Specifically, the actions with the Bioeconomy Action Plan include:

- 1.4.1 Leverage the knowledge outputs of the InformBio project to provide the research basis for monitoring bioeconomy development
- 1.4.2 Measure and report on the Irish bioeconomy using economic indicators: output, value added, investments, employment and exports based on annual national accounts
- 1.4.3 Develop indicators to measure the sustainable development of the bioeconomy encompassing environmental, social, and economic indicators

The InformBio project set out to develop a prototype national bioeconomy monitoring framework and dashboard following from earlier EU and member state developments. As part of this process, the project undertook a review of existing systems across Europe to inform the requirements for developing a robust and effective monitoring system for Ireland's bioeconomy, ensuring alignment with EU standards while addressing national priorities. The approach to developing the prototype monitoring system aligns closely with that described by Camia, 2026 with a similar inclusion of *conceptualisation* , *implementation* and *assessment/ communication* stages, an approach which was outlined previously by Bogdanski et al. (2021). The final monitoring framework has been designed with input from various internal, departmental and external stakeholders to finalise its scope, relevant indicators, data units and to identify data availability. The overall scope of the system is primarily aligned with the seven pillars of Ireland's Bioeconomy Strategy 2023-2025 which include:

- Governance and Awareness
- Research, Development and Innovation
- Nature, Climate Energy and Circular Economy
- Agriculture, Food, Forestry and the Marine
- Communities, Regions and Cities
- Industry and Enterprise
- Knowledge and Skills

The design approach included a stakeholder workshop hosted on 20th April 2026 (Figure 19), which brought together stakeholders to review, provide feedback on, and prioritise a proposed set of potential bioeconomy indicators. For each of the seven pillars of Ireland's Bioeconomy Action Plan 2023–2025, an initial set of six indicators was presented and evaluated against criteria such as relevance, robustness, data availability, and policy alignment. As part of the discussion, feedback from participants helped to refine a list of indicators that best capture the performance and progress of each pillar.

The final selection of indicators reflects a balance between the environmental, economic, and social dimensions of the bioeconomy.

Particular emphasis was placed on indicators that are measurable using existing data sources (e.g. Central Statistics Office, (CSO); Sustainable Energy Authority of Ireland, (SEAI); and the Environmental Protection Agency, (EPA), while others were identified as desirable and should be targeted for future development to further support the monitoring effort. Some of these indicators relate to the influence of bioeconomy development on knowledge and skills, such as the number of education policies aligned with bioeconomy objectives and the share of training and reskilling within the bioeconomy workforce. In the case of industry and enterprises, consideration is also given to indicators such as the number of new businesses and enterprises established with policy support.

Figure 19.

Bioeconomy Monitoring Framework workshop

Building on this effort, an interactive dashboard was developed to facilitate dissemination of the selected indicators and to support ongoing monitoring through a user-friendly and interactive platform. Using ArcGIS Hub technology (ESRI, Redlands, CA, USA) as the underlying development framework, the dashboard has been designed to include visualisations of indicators, and their potential trends, thereby enabling stakeholders to track progress across the pillars in a coherent and accessible manner. It also incorporates a spatial analysis component, allowing for the visualisation and comparison of bioeconomy performance across different regions of Ireland.

Table 8.

List of refined indicators for the bioeconomy readiness of Ireland for each of the Bioeconomy Pillars of the Bioeconomy Strategy 2023-2025

Political	Economic	Social
Governance and Awareness	Government support to agricultural research and development.	Euro per inhabitant
	Agriculture orientation index for government expenditure	% of government expenditure
	Value of Imports and exports of bioproducts	Euro thousand
Research, Development and Innovation	Research and development expenditure as a proportion of GDP.	Euro Millions
	Actual and estimated business expenditure on research and development	Euro thousand
Nature, Climate, Energy and Circular Economy	Greenhouse gas emissions per sector	tCO_2eq/yr
	Net Material Accumulation	Million Tonnes
	Proportion of municipal solid waste collected and managed in controlled facilities by cities	Avg. kilos per capita
	Renewable energy share by mode	% of gross final consumption
	Renewable energy share in transport, of electricity and of heat	%
Agriculture, Food, Forestry and the Marine	Crop Provision- crop residues (Used), fodder crops and grazed biomass	Thousand tonnes
	Forestry-roundwood removals	Thousand cubic metres
	Ireland's Ocean Economy	Turnover, gross value added, GNI%
Communities, Regions and Cities	Biodiversity Expenditure	Euro Millions
	Number of bioeconomy enterprises developed with policy support	Number
Industry and Enterprise	Turnover / output of bioeconomy sectors	Euro Millions
	Contribution of bioeconomy sectors to GDP	%
	Persons employed per bioeconomy sectors	Number
Knowledge and Skills	National education policies in accordance with the bioeconomy	Number
	Number of research outputs in the field of bioeconomy	Number
	Share of workers with training and re-qualification of the workforce in the bioeconomy sectors	%

The platform has been designed to integrate data from multiple sources and to allow for regular updates as new data becomes available. This ensures that the dashboard remains relevant and responsive to changes in the bioeconomy landscape. By combining temporal and spatial insights, the tool enhances indicator interpretation and supports evidence-based decision making.

In addition to visualising indicator status, the platform is designed to also facilitate hosting of relevant documents and additional materials, including research outcomes, project reports, and links to relevant resources for further understanding of the Irish bioeconomy. More information on the bioeconomy monitoring framework and related outputs is available **here**.

5.7. Future Scope and Strategic Recommendations

The BBVCs considered for deeper analysis in Chapters 3 and 4 of this foresight report demonstrate the strong potential of the bioeconomy to contribute to Ireland's climate and sustainability targets. However, these findings represent only the beginning of a longer-term strategic transition. Some of the analysed value chains align with recent infrastructure investments made by the Irish government to support the development of BBVCs, including a green biorefinery (DAFM, 2023), anaerobic digestion (Maluf Braga & Crosson, 2026) and biochar facilities (UL, 2026). Investments have also been made in other relevant areas such as marine biorefining (Teagasc, 2025), multi-trophic aquaculture (TUS, 2024) and upcycling of food waste.

As technologies mature, data availability improves, stakeholder priorities evolve and areas such as carbon and natural capital accounting develop, the opportunity landscape for BBVCs is expected to expand far beyond the current prioritised selection. Sustainable biomass is increasingly recognised as a strategic renewable carbon resource that can support climate neutrality, strengthen energy security, and enhance industrial competitiveness. Consequently, future bioeconomy development will require adaptive strategies that respond to changing technological, environmental, and market conditions.

5.7.1 UNLOCKING THE POTENTIAL OF THE BLUE BIOECONOMY

While this study focus on a selection of prioritised land-based BBVCs, there is a growing interest in the blue bioeconomy, particularly in the valorisation of marine biomass such as macroalgae and aquaculture side streams. Recent research highlights the potential of seaweed-derived biochemicals, biofuels, and food and feed additives to contribute to national climate targets and marine services (Collins et al., 2022; Wenhai et al., 2019).

Although marine blue BBVCs received lower scores during the initial stakeholder prioritisation process, largely due to the selected criteria weightings, they remain strategically important. Future sustainability assessments are therefore required to better understand their long-term contribution to Ireland's bioeconomy.

5.7.2 INFRASTRUCTURE INTEGRATION

A recurring theme across the technical and environmental assessments in Chapter 3 was the strong influence of strategic siting on both commercial viability and environmental performance. Therefore, economy developments should therefore consider implementation as integrated regional bioeconomy clusters rather than as isolated facilities. Co-location of complementary technologies can generate significant operational and environmental benefits. For example, integrating biochar production units with AD plants could enable the utilisation of excess heat that would otherwise be wasted, thereby reducing operational costs and environmental burdens.

Similarly, locating processing facilities close to feedstock sources can minimise transportation requirements and strengthen local circular bioeconomies. The siting of pyrolysis facilities near sawmills provides one example of how feedstock proximity can improve efficiency and reduce emissions. For food waste AD systems, facility location must align with regional feedstock availability in order to address spatial disparities in waste generation and ensure secure and cost-effective supply chains. Such integrated approaches can maximise resource efficiency while promoting regional economic development.

5.7.3 POLICY REQUIREMENTS AND FINANCIAL ENABLERS

The transition from technically robust processes to commercially viable industries require a comprehensive policy framework and targeted financial mechanisms capable of bridging the gap between environmental value and market returns. Stable and increasing carbon prices will be particularly important for the economic viability of carbon sequestration pathways. Certification mechanisms, including the EU Carbon Removal Certification Framework and the European Biochar Certificate, will play an important role in creating revenue streams associated with long-term carbon storage.

Direct financial support measures, including capital grants, feed-in tariffs for biomethane, tax incentives, and other targeted investment supports, will be essential for reducing the risks associated with high capital expenditure projects such as biorefineries and carbon capture infrastructure. Accelerating industrial scale-up will also require stronger connections between research and innovation, policy development, and industrial deployment. The development of further demonstration and pilot scale facilities as well as advisory supports and clusters to support commercial adoption, along with the development of public procurement programmes to support market uptake of sustainable new bio-based products will also be critical. Financial instruments such as loan guarantees, blended finance mechanisms, and risk-sharing arrangements can further support the commercialisation of emerging technologies.

In addition, the development of carbon capture and storage infrastructure will require significant regulatory and policy reform. Although Ireland has transposed the EU CCS Directive, current legislation prohibits the geological storage of CO_2 within Irish territory and offshore areas, creating a substantial barrier to the deployment of CCS and BECCS technologies.

Revising the existing regulatory framework, establishing clear permitting pathways, and assessing the suitability of domestic or shared regional CO_2 transport and storage infrastructure will therefore be necessary if negative emissions technologies are to contribute to national climate targets. The development of cross-border CO_2 transport networks and access to storage infrastructure in neighbouring jurisdictions may also provide interim solutions while domestic policy frameworks evolve.

5.7.4 AN ADAPTIVE AND INCLUSIVE STRATEGY

The future success of the Irish bioeconomy will depend on the development of an adaptive and inclusive approach. This requires improved data collection, robust monitoring, reporting and verification systems, continuous stakeholder engagement, and dedicated innovation funding to refine value chain assessments as technologies mature. Harmonised sustainability governance, transparent carbon accounting and in future natural capital accounting, and robust certification systems will remain critical for building market confidence and supporting the long-term deployment of bio-based value chains.

By integrating BBVC systems, capturing cross-sectoral synergies, and supporting both technological innovation and market development, Ireland can ensure that its bioeconomy strategy remains inclusive, resilient, and aligned with national climate objectives and European Union sustainability goals. Through coordinated action across policy, industry, and research communities, sustainable biomass can serve as a strategic renewable carbon resource that supports climate neutrality, strengthens energy security, and enhances the competitiveness of Ireland's expanding bioeconomy. It is also important that the bioeconomy community continue to engage positively with new stakeholders who will be essential to growing the bioeconomy thereby ensuring that the full impacts of this report can be realised. For example, adoption of new technology or diversification of existing business models in regions will require the commitment of farmers and local communities, while market penetration of new bio-based products will require the engagement of businesses and consumers. Ireland's annual Bioeconomy Ireland Week held each October has been very successful in growing the bioeconomy over recent years, but this will need to be further upscaled, supported by governments, universities, companies and others to facilitate commercial implementation and outscaling.

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Credits to the InformBio team to the development of this project and report.

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References

Allied Offsets. (2026). *Voluntary Carbon Markets Emerging Trends for 2026. 2025 Review Emerging Trends for 2026.* https://alliedoffsets.com/wp-content/uploads/2025/12/2025-VCM-Overview-Report.pdf

Andrade, T. A., & Ambye-Jensen, M. (2022). Process Integration and Techno-Economic Assessment of a Green Biorefinery Demonstration Scale Platform for Leaf Protein Production. In L. Montastruc & S. Negny (Eds.), *Computer Aided Chemical Engineering* (Vol. 51, pp. 877-882). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-323-95879-0.50147-8

Bishop, G., Duffy, C., Berndes, G., Brandão, M., Cowie, A., Healey, J. R., Hennig, C., Koponen, K., Gaffey, J., & Styles, D. (2026). Cascading wood use into bioenergy with carbon capture and storage ensures continuous and enduring temperature reduction. *Communications Earth & Environment*, 7(1), 233. https://doi.org/10.1038/s43247-026-03333-1

Bishop, G., Girón-Domínguez, C., Gaffey, J., Henchion, M., Fealy, R., Zimmermann, J., Kargupta, W., & Styles, D. (2025). A life cycle thinking-based environmental risk framework for screening sustainable feedstocks in early-stage bioeconomy projects. *Resources, Environment and Sustainability*, 20, 100201. https://doi.org/10.1016/j.resenv.2025.100201

Bogdanski, A., Giuntoli, J., Mubareka, S., Gomez San Juan, M., Robert, N., & Tani, A. (2021). *Guidance note on monitoring the sustainability of bioeconomy at a country or macro-regional level*. (Vol. 90). FAO and EC-JRC. https://openknowledge.fao.org/handle/20.500.14283/cb7437en

Camia, A. (2026). Bioeconomy Monitoring. In I. Lewandowski, L. Mayorga-Duarte, P. Scheurich, R. Vargas-Carpintero, V. Schlecht, & J. Weik (Eds.), *Bioeconomy: Advancing the Transition to a Sustainable, Biobased Economy* (pp. 795-803). Springer Nature Switzerland. https://doi.org/10.1007/978-3-032-09098-0_43

Coalition for Negative Emissions. (2021). *The case for Negative Emissions, A call for immediate action*. https://coalitionfornegativeemissions.org/wp-content/uploads/2021/06/The-Case-for-Negative-Emissions Coalition-for-Negative-Emissions-report-FINAL-2021-06-30.pdf

Collins, N., Kumar Mediboyina, M., Cerca, M., Vance, C., & Murphy, F. (2022). Economic and environmental sustainability analysis of seaweed farming: Monetizing carbon offsets of a brown algae cultivation system in Ireland. *Bioresource Technology, 346, 126637*. https://doi.org/https://doi.org/10.1016/j.biortech.2021.126637

DAFM. (2023). *Ministers McConalogue and Heydon announce €3 million for integrated anaerobic digestion and green biorefining demonstration initiative* https://www.gov.ie/en/department-of-agriculture-food-and-the-marine/press-releases/ministers-mcconalogue-and-heydon-announce-3-million-for-integrated-anaerobic-digestion-and-green-biorefining-demonstration-initiative/

Danish Energy Agency. *Biogas in Denmark*. Retrieved 08/07/2026 from https://ens.dk/en/energy-sources/biogas-denmark#:~:text=In%202023%20the%20share%20of,expected%20to%20be%20100%20pct

DCEE. (2021). Climate Action Plan 2021. *Annex of Actions*. https://assets.gov.ie/static/documents/climate-action-plan-2021-annex-of-actions-7e41c131-9201-413b-93cc-2122018ee036.pdf

DCEE, & DAFM. (2024). *National Biomethane Strategy*. https://www.gov.ie/en/department-of-climate-energy-and-the-environment/publications/national-biomethane-strategy/

DECC, & DAFM. (2023). *Ireland's Bioeconomy Action Plan 2023-2025*. **https://www.gov.ie/en/publication/a1bb6-bioeconomy-policy/#:~:text=Ireland's%20Bioeconomy%20Action%20Plan%202023%2D2025,-Ireland's%20first%20national&text=The%20plan%20has%20a%20high,by%20biobased%20industries%20in%20Ireland.**

Department of An Taoiseach. (2018). *National Bioeconomy Policy Statement of Ireland*. Dublin, Ireland Retrieved from **https://www.gov.ie/en/publication/c1e596-national-policy-statement-on-the-bioeconomy/**

DGB Group. (2025). *Shell and Microsoft lead the carbon credit market in 2024.* **https://www.green.earth/news/shell-and-microsoft-lead-the-carbon-credit-market-in-2024**

Digital Europa Thesaurus. (2024). *Feedstock*. Retrieved 19/12/2024 from **https://knowledge4policy.ec.europa.eu/glossary-item/feedstock_en**

dos Passos, N. H. M., & Ambye-Jensen, M. (2024). Fractionation of proteins from alfalfa juice at demonstration scale: Effects of temperature and centrifugation strategies on removal of green protein and recovery of the soluble white protein fraction. *Separation and Purification Technology*, 330, 125461. **https://doi.org/https://doi.org/10.1016/j.seppur.2023.125461**

Duffy, C., Henn, D., Saber, T., & Styles, D. (2026). OptiGob: A decision support tool for Agriculture, Forestry and Other Land Use transitions. *Journal of Open Source Software*, 11(119), 9271. **https://doi.org/10.21105/joss.09271**

Emenike, O., Michailos, S., Hughes, K. J., Ingham, D., & Pourkashanian, M. (2021). Techno-economic and environmental assessment of BECCS in fuel generation for FT-fuel, bioSNG and OMEx. *Sustainable Energy & Fuels*, 5(13), 3382-3402. **https://doi.org/10.1039/d1se00123j**

European Commission. (2018a). *Report from the commission to the council and the European Parliament on the development of plant proteins in the European Union*. **https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_18_6495/IP_18_6495_EN.pdf**

European Commission. (2018b). *A sustainable bioeconomy for Europe : strengthening the connection between economy, society and the environment : updated bioeconomy strategy*. **https://doi.org/10.2777/792130**

European Commission. (2024). Carbon Removals and Carbon Farming (CRCF). *Regulation* (EU) 2024/3012. **https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming/carbon-removals-and-carbon-farming-crcf-regulation_en**

European Commission. (2025). A Strategic *Framework for a Competitive and Sustainable EU Bioeconomy*. Brussels, Belgium

European Commission. (2026). Action Plan for resilience, strategic autonomy and sustainability of the EU protein system. *COM(2026) 355 final*. **https://webgate.ec.europa.eu/circabc-ewpp/d/d/workspace/SpacesStore/ef70a412-028e-49c0-b966-7344a46952f1/download**

Feed & Additive Magazine. (2025). *Global Animal Feed Market.* **https://www.feedandadditive.com/global-animal-feed-market/**

Fortune Business Insights. (2025a). *Biochar Market Size, Share & Analysis | Growth Report [2034]*. **https://www.fortunebusinessinsights.com/industry-reports/biochar-market-100750**

Fortune Business Insights. (2025b). *Biogas Market Size, Share & Growth. Industry Analysis Report [2034]*. **https://www.fortunebusinessinsights.com/industry-reports/biogas-market-100910**

Fortune Business Insights. (2025c). *Syngas Market Size, Share, Growth | Outlook Report, 2034*. **https://www.fortunebusinessinsights.com/syngas-market-109820**

Gaffey, J., Matinez, A. A., Andrade, T. A., Ambye-Jensen, M., Bishop, G., Collins, M. N., & Styles, D. (2024). Assessing the environmental footprint of alternative green biorefinery protein extraction techniques from grasses and legumes. *Sci Total Environ*, 949, 175035. https://doi.org/10.1016/j.scitotenv.2024.175035

Girón-Domínguez, C., Alaydi, H., Sameti, M., Kargupta, W., Bishop, G., Styles, D., Zimmermann, J., Díaz Huerta, J., Fealy, R., McMahon, H., & Gaffey, J. (2026). Quantifying and Mapping Biomass Resources in Ireland: A Holistic Assessment of Primary and Secondary Feedstocks. *Energies, 19*(4), 1068. https://www.mdpi.com/1996-1073/19/4/1068

Giuntoli, J., Robert, N., Ronzon, T., Sanchez Lopez, J., Follador, M., Girardi, I., Barredo Cano, J., Borzacchiello, M., Sala, S., M`barek, R., La Notte, A., Becker, W., & Mubareka, S. (2020). *Building a monitoring system for the EU bioeconomy* (Vol. EUR 30064 EN). https://doi.org/10.2760/717782

Grand View Research. (2024). *Biofuels Market Size, Share & Growth Analysis Report, 2030*. https://www.grandviewresearch.com/industry-analysis/biofuels-market

Grand View Research. (2025). *Bioenergy With CCS Market Size, Share & Trends Analysis Report By Technology (Oxy-combustion, Pre-combustion, Post-combustion), By Application, By Region, And Segment Forecasts, 2024 - 2030*. https://www.grandviewresearch.com/industry-analysis/bioenergy-ccs-market-report#

Heimann, T., Wähling, L.-S., Honkomp, T., Delzeit, R., Pirrone, A., Schier, F., & Weimar, H. (2025). Expert projections on the development and application of bioenergy with carbon capture and storage technologies. *Environmental Research Letters, 20*(2). https://doi.org/10.1088/1748-9326/ada16f

Imarc. (2025). *Soy Protein Market Size, Share, Report Analysis 2025-33*. https://www.imarcgroup.com/soy-protein-market

International Biochar Initiative. (2024). *Global biochar market report 2023*. https://biochar-international.org/wp-content/uploads/2024/06/Global-Biochar-Market-Report-2023-%E2%80%93-Public.pdf

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment. Report of the Intergovernmental Panel on Climate Change.*

Johnstone, I., Fuss, S., Walsh, N., & Höglund, R. (2026). Carbon markets for carbon dioxide removal. *Climate Policy, 26*(1), 151-158. https://doi.org/10.1080/14693062.2025.2478288

Kilsedar, C., Wertz, S., Robert, N., & Mubareka, S. (2021). Implementation of the EU bioeconomy monitoring system dashboards. *Knowledge Centre for Bioeconomy: Brussels, Belgium*.

Kortleve, A. J., Mogollón, J. M., Harwatt, H., Bruckner, M., Liu, B., & Behrens, P. (2026). Stranded assets in European agriculture during food system transformations. *Nature Food, 7*(1), 38-44. https://doi.org/10.1038/s43016-025-01283-z

Kuparinen, K., Lipiäinen, S., Vakkilainen, E., & Laukkanen, T. (2023). Effect of biomass-based carbon capture on the sustainability and economics of pulp and paper production in the Nordic mills. *Environment, Development and Sustainability, 25*(1), 648-668. https://doi.org/10.1007/s10668-021-02074-9

Lange, L., 2022. Business models, including higher value products for the new circular, resource-efficient biobased industry. *Frontiers in Sustainability, 3, p.789435.*

Maluf Braga, A. F., & Crosson, P. (2026). *Teagasc Grange Anaerobic Digestion Programme* https://teagasc.ie/insights/teagasc-grange-anaerobic-digestion-programme/

Markets and Markets. (2023). *Biomethane Market report 2025-2030*. **https://www.marketsandmarkets.com/Market-Reports/biomethane-market-190903532.html?gad_source=1&gad_campaignid=401403796&gbraid=0AAAADxY7SzCicZBCMfNexoYpnEknWtBT&gclid=Cj0KCQiAq7HIBhDoARIsAOATDxD6KuAKg0a0xo2b-Lz4H-o9l3ZD8jRruRYuWR-_5I22z58G-hcNOSoaAlSBEALw_wcB**

MarkNtel Advisors. (2024). *Organic Fertilisers Market to Accelerate at a CAGR of Around 11.88% During 2025-30*. **https://www.marknteladvisors.com/press-release/organic-fertilisers-market-size**

Martínez-Arce, A., Kargupta, W., Domínguez, C. G., Odey, E. A., McMahon, H., Huerta, J. D., Zimmermann, J., Bishop, G., Gaffey, J., & Styles, D. (2025). An integrated technoeconomic and environmental assessment of biomethane production via anaerobic digestion of food waste in Ireland: Updated insights under market volatility. *Sustainable Energy Technologies and Assessments, 82*, 104563. **https://doi.org/https://doi.org/10.1016/j.seta.2025.104563**

Menon, A., Ravindran, R., Koopmans, S., Sanders, J. P. M., Rai, D. K., Gaffey, J., Augustyniak, A., & McMahon, H. (2024). Purification, characterisation, and determination of prebiotic potential of fructooligosaccharide from perennial rye grass. *International Journal of Biological Macromolecules, 279*, 135031. **https://doi.org/https://doi.org/10.1016/j.ijbiomac.2024.135031**

Ministry of Food Agriculture and Fisheries of Denmark. (2023). *Green biorefining from political ambition to implementation of new subsidies in Denmark*. **https://lbst.dk/Media/638527439483192746/Green_Biorefining_-_LBSTs_oplaeg_paa_Go_Grass_event_24_maj_Supplerende_slides.pdf**

MSCI Carbon Markets. (2023). BECCS – *Promising Technology for Net Zero or an Expensive Bet?*. **https://www.msci.com/research-and-insights/blog-post/BECCS-promising-technology-for-net-zero-or-an-expensive-bet**

National Centre for CCS. (2025). Sweden launches billion dollar fund for BECCS projects. *Carbon Capture Journal*(111). **https://www.carboncapturejournal.com/news/sweden-launches-billion-dollar-fund-for-BECCS-projects/7088.aspx?Category=all**

O'Connor, K., Gaffey, J., Gavin, E., Stout, J., & Holden, N. M. (2023). *Evidence Synthesis Report 2: Circular Bioeconomy Outlook Study 2030–2050 in Support of Climate Action, Sustainable Food and Biobased Systems*. **https://www.epa.ie/publications/research/evidence-synthesis-reports/evidence-synthesis-report-2-circular-bioeconomy-outlook-study-20302050-in-support-of-climate-action-sustainable-food-and-biobased-systems.php**

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change,* 42, 169-180. **https://doi.org/https://doi.org/10.1016/j.gloenvcha.2015.01.004**

Pitcairn, J., Warmington, J., Gandy, S., Deswarte, F., & Bell, J. (2017). Biorefining potential for Scotland. Zero Waste *Scotland*. **https://doi.org/https://www.zerowastescotland.org.uk/resources/report-biorefining-potential-scotland**

Prager, S. D., & Wiebe, K. (2021). Strategic foresight for agriculture: Past ghosts, present challenges, and future opportunities. *Global Food Security, 28*, 100489. **https://doi.org/https://doi.org/10.1016/j.gfs.2020.100489**

Research and Markets. (2025). *Carbon Dioxide Removal (CDR) Forecast 2025-2045: Technologies, Trends and Investment Insights*. **https://www.globenewswire.com/news-release/2025/02/19/3028948/28124/en/Carbon-Dioxide-Removal-CDR-Forecast-2025-2045-Technologies-Trends-and-Investment-Insights-Projections-Suggest-Market-Expansion-to-50-Billion-by-2030-and-Exceeding-250-Billion-by-20.html**

Rickels, W., Proelß, A., Geden, O., Burhenne, J., & Fridahl, M. (2021). Integrating Carbon Dioxide Removal Into European Emissions Trading [Policy and Practice Reviews]. *Frontiers in Climate, Volume 3 - 2021*. **https://doi.org/10.3389/fclim.2021.690023**

Ronzon, T., & Sanjuán, A. I. (2020). Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. *Journal of Cleaner Production, 254*, 119832. **https://doi.org/ https://doi.org/10.1016/j.jclepro.2019.119832**

Rural BioReFarmeries. (2024). *Rural BioReFarmeries: Small-scale circular green biorefineries for increasing farmer sustainability and competitiveness and building resilient rural areas.* Retrieved 08/07/2026 from **https://ruralbiorefarmeries.eu/**

Sanders, J., Koopmans, S., & Gaffey, J. (2020). *Biorefinery Leads to Increased Fertiliser Efficiency and Land Use Efficiency and to Better Incomes for Agriculture.*

Spinverse. (2026). *Klimatklivet ('Climate leap')*. **https://www.spinverse.com/funding-programme/klimatklivet#:~:text=Klimatklivet%20('Climate%20leap'),that%20reduce%20greenhouse%20gas%20emissions**

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223), 1259855. **https://doi.org/10.1126/science.1259855**

Stegmann, P., Londo, M., & Junginger, M. (2020). The Circular Bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation & Recycling: X, 6*, 100029. **https://doi.org/10.1016/j.rcrx.2019.100029**

Stern, N. (2016). Economics: Current climate models are grossly misleading. *Nature, 530*(7591), 407-409. **https://doi.org/10.1038/530407a**

Stratus. (2025). First Swedish Carbon Credit Standard with Biochar Rewards Farmers and Improves Soil Health. **https://stratusproject.eu/first-swedish-carbon-credit-standard-with-biochar-rewards-farmers-and-improves-soil-health/**

Styles, D., Henn, D., Duffy, C., Black, K., & Martinez-Arce, A. (2025). *Structured foresight reframes risk around transitions towards sustainable and resilient farming in a volatile world*. PREPRINT (Version 1) available at Research Square [**https://doi.org/10.21203/rs.3.rs-8254015/v1**]

Swedish Energy Agency. (2025). *State aid for BECCS*. **https://www.energimyndigheten.se/en/climate/carbon-capture-and-storage/state-aid-for-BECCS/**

Teagasc. (2025). *Teagasc Welcomes New Shared Island Investment to Drive Innovation in the Blue Bioeconomy* **https://teagasc.ie/news--events/news/teagasc-welcomes-new-shared-island-investment-to-drive-innovation-in-the-blue-bioeconomy/**

TUS. (2024). *Circular-IMTA Demo Project* **https://tus.ie/rdi/research/centres-groups/empower-eco/circular_imta_demo-project/**

UL. (2026). *University of Limerick to lead €5 million project to turn climate innovation into real-world solutions*

Wenhai, L., Cusack, C., Baker, M., Tao, W., Mingbao, C., Paige, K., Xiaofan, Z., Levin, L., Escobar, E., Amon, D., Yue, Y., Reitz, A., Neves, A. A. S., O'Rourke, E., Mannarini, G., Pearlman, J., Tinker, J., Horsburgh, K. J., Lehodey, P.,…Yufeng, Y. (2019). Successful Blue Economy Examples With an Emphasis on International Perspectives [Review]. *Frontiers in Marine Science, Volume 6 - 2019*. **https://doi.org/10.3389/fmars.2019.00261**

Zetterberg, L., Johnsson, F., & Möllersten, K. (2021). Incentivizing BECCS—A Swedish Case Study [Policy and Practice Reviews]. *Frontiers in Climate, Volume 3 - 2021*. **https://doi.org/10.3389/fclim.2021.685227**

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