IEA Bioenergy
Technology Collaboration Programme

Task 42: Biorefining in a Circular Economy

Technical, Economic and Environmental (TEE) Assessment of multiple biorefinery pathways

Synthesis of four IEA Bioenergy Task 42 Case Studies

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Synthesis report of four Case Studies

IEA Bioenergy: Task 42

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Abstract

This report presents a structured framework for assessing biorefinery development under IEA Bioenergy Task 42, focusing on four case studies evaluated with an integrated Technical, Economic and Environmental (TEE) approach:

1. Fast pyrolysis biorefinery (FPBO, steam, electricity)
2. Biogas/biomethane plant coupled with industrial wastewater treatment (LBG, biofertilizer)
3. Lignocellulosic ethanol biorefinery (ethanol, lignin-CHP, vinasse)
4. Sustainable aviation fuel (SAF) biorefinery via a bio-isobutene pathway (SAF, ethanol, lignin, fertilizer, feed)

All concepts use residues and waste as feedstocks and are described using the IEA Bioenergy Task 42 classification (feedstock, platform, products, processes). Assessment is based on ISO 14040/44 life cycle principles, EU RED II/III GHG accounting and VDI 6310 classification and evaluation approaches.

Across the four cases, overall energy efficiencies are typically in the 80–85% range when all energy outputs and co-products are considered. GHG savings relative to fossil comparators range from roughly 45% (industrial symbiosis/wastewater case) to >90% (optimized lignocellulosic ethanol and SAF pathways). Economic results vary from break-even to clearly positive margins, strongly influenced by feedstock and product prices, co-product valorization and the presence of supporting policy instruments.

The report highlights cross-case insights on feedstock suitability, platform characteristics, co-product integration, technology readiness levels (TRLs), and the role of policy and industrial symbiosis. It concludes with implications for deployment, recommendations for policy and industry, and priorities for future research and data transparency.

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1 Introduction

Biorefineries are central elements of a circular, low-carbon bioeconomy. Instead of producing a single fuel or product, they are designed to convert biomass into a **portfolio of outputs**: transport fuels, electricity, process heat, chemicals, materials and fertilizers. This multi-product nature is both an opportunity (higher resource efficiency, multiple revenues) and a challenge (greater complexity, need for integrated assessment).

IEA Bioenergy Task 42 "Biorefining in a Circular Economy" has developed a systematic way to classify and evaluate such systems. Its work combines a **poly-hierarchical classification system** with a joint **TEE assessment framework** that allows very different biorefinery concepts to be compared on a consistent basis.

This report synthesizes the results of TEE assessments for four selected pathways that were analyzed in detail using standardized fact sheets:

- A **fast pyrolysis biorefinery** converting woody residues into fast pyrolysis bio-oil (FPBO), steam and electricity.
- A **biogas biorefinery** (EffiSludge-type concept) converting paper mill biosludge and additional organic residues into liquefied biomethane (LBG) and biofertilizer, integrated with an existing wastewater treatment plant (WWTP).
- A **lignocellulosic ethanol biorefinery** using cereal straw to produce advanced ethanol, with lignin-based CHP and vinasse as fertilizer.
- A **SAF biorefinery** based on a wood-to-sugars → bio-isobutene → SAF route with multiple co-products (lignin, C5 ethanol, fertilizer sludge, microbial biomass).

In the next section, we briefly describe the common methodological basis used across all case studies. We then summarize each biorefinery concept, before drawing cross-cutting conclusions and discussing policy and deployment implications. To make the synthesis accessible, key information is condensed into comparative tables and complemented with short explanatory text rather than long narrative descriptions.

2 Methods and Framework

2.1 ASSESSMENT FRAMEWORK

To make meaningful cross-case comparisons, all four case studies are evaluated using a common TEE framework:

- **Technical dimension**
  - Feedstock type, composition and origin (residue vs dedicated crop)
  - Conversion platform and process steps
  - Throughput (plant scale)
  - Main products and co-products
  - Overall energy efficiency (including co-products)
  - Technology readiness level (TRL)
- **Economic dimension**
  - Order-of-magnitude CAPEX and OPEX
  - Composition of operating costs (feedstock, utilities, enzymes/chemicals, labour, maintenance)
  - Main revenue streams and indicative annual turnover
  - Simple profitability indicators (approximate margin) and key sensitivities (e.g. feedstock price, product price)
- **Environmental dimension**
  - Cradle-to-gate GHG intensity of main fuel products (g CO_2eq/MJ)
  - Relative GHG savings vs fossil comparators (e.g. 94 g CO_2eq/MJ for gasoline or jet fuel in RED II/III)
  - Primary energy demand (especially fossil primary energy)
  - Role of co-products (e.g. fertilizer, feed, materials) and system integration (e.g. wastewater treatment, industrial symbiosis)

Using the same indicators and functional logic across all cases ensures that differences in results reflect differences in the **systems themselves**, not in how they are assessed.

2.2 STANDARDS AND GUIDELINES

The assessment approach is aligned with established standards and guidelines:

- **ISO 14040/44 (LCA framework and requirements)** provides the overarching structure for defining functional units, system boundaries and impact categories.
- **EU RED II/III** provides specific rules and fossil comparators for renewable fuels, including advanced biofuels and SAF. We follow these rules for GHG accounting and for energy-based allocation among energy co-products.

- **VDI 6310** offers a framework for classifying biorefineries and for structuring technical and economic evaluations. It helps to ensure that the fact sheets cover the necessary information and that results can be benchmarked against other biorefinery concepts described in the same way.
- For the SAF case, **CORSIA** is used as a reference for aviation-specific GHG accounting and sustainability requirements.

These standards and guidelines anchor the assessments in widely accepted methodologies and ensure compatibility with certification and regulatory frameworks.

2.3 IEA TASK 42 BIOREFINERY CLASSIFICATION

IEA Bioenergy Task 42 uses four axes to classify biorefineries:

- **Feedstock** – type and origin of biomass (e.g. softwood sawdust, cereal straw, biosludge, fish waste).
- **Platform** – intermediate carriers or process families (e.g. fast pyrolysis vapours, biogas, C5/C6 sugars, bio-isobutene).
- **Products** – final energy carriers, materials and co-products (fuels, heat, power, fertilizers, animal feed, lignin products).
- **Processes** – key conversion steps (pyrolysis, anaerobic digestion, enzymatic hydrolysis, fermentation, catalytic upgrading, CHP).

This classification is explicitly applied to each case, allowing us to map the four very different systems onto the same conceptual grid. It also facilitates modular thinking: for example, the sugar platform of the ethanol and SAF cases is similar at the front-end, even though their downstream product pathways diverge.

2.4 SYSTEM BOUNDARIES AND ALLOCATION

To focus on **production performance** and maintain comparability, all four case studies use a **cradle-to-gate system boundary**:

- Upstream: feedstock provision (collection, pre-treatment, transport)
- Core: all conversion and upgrading steps, internal energy generation, utilities
- Downstream: product at plant gate (e.g. FPBO, LBG, ethanol, SAF, co-products ready for use or sale)

End-use emissions of the fuels (biogenic CO_2 from combustion) are not included, except indirectly via comparison to a fossil reference. In most regulatory frameworks, this biogenic CO_2 is accounted as climate-neutral if the biomass is sourced sustainably.

Co-products are handled as follows:

- For **energy products** (fuels, electricity, steam, lignin used as fuel) we apply **energy-based allocation**, as prescribed by RED II/III.
- For **non-energy co-products** (fertilizer, animal feed, materials) we apply an **avoided-burden approach**, assigning credits for the displacement of functionally equivalent products (e.g., mineral fertilizers or conventional protein feed).

Where relevant, alternative allocation schemes (e.g. economic allocation) are explored in sensitivity analyses at the case study level, but the synthesis emphasises the RED-compatible approach to maintain alignment with regulatory practice.

3 Case Studies - Overview

Before looking at each pathway in more detail, Table 1 provides a concise overview of their main characteristics. This allows the reader to see immediately how the cases differ in feedstock, platform, main products, scale and TRL, and sets the stage for the more detailed summaries that follow.

Table 1: High-level overview of the four biorefinery case studies.

Case	Feedstock & Context	Platform	Main Products	TRL	Typical Scale (approx.)
1 - Fast pyrolysis biorefinery	Woody residues (e.g. chips); stand-alone plant, integrated steam export to nearby industry	Thermo-chemical - fast pyrolysis	FPBO (bio-oil), steam, electricity (CHP)	9 (com-mercial)	~25 MW_{th} input (~48,600 t/a biomass)
2 - Biogas (EffiSludge -type)	Paper mill biosludge + external organic residues (fish/agri), integrated with WWTP	Biochemical - anaerobic digestion (CSTR + UASB)	Biogas → biomethane (LBG), solid/liquid biofertilizer, nutrient recycling to WWTP	9 (com-mercial)	~125 GWh/a biomethane from ~20,000 m^3/d WW + ~100 t/d co-substrates
3 - Ligno-cellulosic ethanol biorefinery	Cereal straw, agricultural region	Biochemical - C5/C6 sugar platform (enzymes + fermentation), lignin CHP	Advanced ethanol, steam, electricity (CHP), vinasse (fertilizer/energy)	8-9 (early com-mercial)	~270,000 t/a straw → ~50,000 t/a ethanol (~63 Mio L/a)
4 - SAF via bio-isobutene	Softwood sawdust, regional sawmill cluster	Hybrid - sugars → bio-isobutene → oligomerisation/hydrogenation	SAF (iso-paraffins), ethanol (C5→EtOH/ETBE), lignin (energy/binder), fertilizer sludge, microbial biomass (feed)	6-7 (demo con-cept)	~415,000 t/a sawdust → ~30,200 t/a SAF + co-products

The following section briefly describes each case, focusing on process logic, mass/energy balances and the role of co-products.

4 Case study summaries

4.1 CASE 1 - FAST PYROLYSIS BIOREFINERY (FPBO, STEAM, POWER)

In the fast pyrolysis biorefinery, dried woody biomass is rapidly heated in the absence of oxygen. The main product is a **liquid bio-oil (FPBO)**; by-products are **char** and **non-condensable gases**. Char and gases are combusted on-site in a boiler/CHP unit, providing heat for the pyrolysis process and generating **steam and electricity**.

Key points:

- About **5 t/h dry biomass** enter the plant.
- The plant produces roughly **3.2 t/h FPBO** plus surplus steam and electricity.
- On an annual basis, this corresponds to **~720 TJ** biomass input and **>620 TJ** useful energy output (bio-oil, steam, power).
- Overall energy efficiency is **~85-86%** when all outputs are counted.

This configuration has been demonstrated at commercial scale and is relatively modular. FPBO can replace heavy fuel oil in industrial boilers or be co-processed in petroleum refineries. Export steam and power enhance overall value and can be tailored to local conditions (e.g. supplying an industrial neighbor or district heating).

From a TEE perspective, this case represents a **mature, efficient, thermochemical platform** with strong environmental performance and modest but positive economics, particularly when all co-products are fully valorized.

4.2 CASE 2 - BIOGAS BIOREFINERY INTEGRATED WITH PULP MILL (EFFISLUDGE-TYPE)

The EffiSludge-type concept adds an anaerobic digestion step to an existing **pulp and paper mill wastewater treatment system**. High-strength industrial biosludge and external organic wastes (e.g. fish farming residues, manure) are co-digested in a combination of CSTR and UASB reactors.

The process logic is as follows:

- **Biogas production**: The two digestion lines together produce ~**342 MWh/d** of biogas. This corresponds to roughly **125 GWh/a** of biomethane when upgraded and liquefied to LBG.
- **Digestate handling**: The digestate is separated into a solid fraction (used as **biofertilizer**) and a liquid fraction. The **liquid fraction**, rich in nitrogen and phosphorus, is recycled to the WWTP to cover a large share of nutrient demand.
- **WWTP integration**: Because most organic load is handled anaerobically, the remaining aerobic treatment requires far less aeration. The aeration power demand drops by about half (e.g. from ~39 to ~20 MWh/d).

This integrated concept delivers multiple benefits:

- The pulp mill achieves **lower operating costs** and **lower GHG emissions** due to reduced electricity consumption and chemical nutrient use.
- The biogas plant generates **renewable gas (LBG)** suitable for transport or industrial use.

- Nutrients are recycled, and waste streams become valuable products (fertilizer, energy).

The technology is fully commercial, with real-world reference plants. Economic analysis shows **solid profitability**, supported by energy sales, gate fees for waste and fertilizer revenues. Environmentally, the system roughly halves the fossil primary energy use and GHG emissions of the reference wastewater treatment solution, even before counting benefits from substituting fossil fuels with biomethane.

4.3 CASE 3 – LIGNOCELLULOSIC ETHANOL BIOREFINERY (STRAW-BASED, LIGNIN CHP, VINASSE)

The lignocellulosic ethanol plant represents a **straw-to-ethanol** concept that mirrors first-generation ethanol in some aspects but uses agricultural residues rather than food crops.

Process overview:

1. **Feedstock preparation**: Baled cereal straw is collected and pre-processed (chopped, possibly washed).
2. **Pretreatment and hydrolysis**: A thermochemical pretreatment (e.g. steam explosion or dilute acid) opens up the biomass structure, followed by enzymatic hydrolysis converting cellulose and hemicellulose into sugars.
3. **Fermentation and ethanol recovery**: The resulting C5/C6 sugar mixture is fermented to ethanol and distilled to fuel-grade quality.
4. **Lignin CHP**: The lignin-rich solid fraction is separated and combusted in a CHP unit, which supplies process steam and part of the electricity.
5. **Vinasse utilisation**: The stillage or vinasse is used as fertilizer (returning nutrients and organic matter to fields) or further valorised (e.g. via biogas or co-firing).

At a scale of ~**270,000 t/a straw**, the plant produces around **50,000 t/a ethanol** (≈ 63 million litres). Lignin-CHP provides most of the heat and some electricity; the remaining power demand is imported.

TEE characteristics:

- Technical: Overall energy efficiency including lignin-CHP is ~**80–85%**. Technology is at **TRL 8-9**, with multiple demonstration and early commercial plants worldwide.
- Economic: Base-case economics are close to **break-even**, strongly dependent on ethanol price, straw cost and co-product valorisation.
- Environmental: GHG savings of ~**85–92%** vs fossil gasoline are achievable, especially if the remaining electricity demand is met by renewable sources.

This pathway is attractive where straw is abundant and where policy frameworks support advanced biofuels (e.g. mandates, premium pricing, carbon credits).

4.4 CASE 4 - SAF BIOREFINERY (WOOD-TO-SUGARS → BIO-ISOBUTENE → SAF)

The SAF case represents an **emerging, multi-output biorefinery** targeting sustainable aviation fuel via a biochemical and catalytic route. It integrates a wood-to-sugars platform with bio-isobutene fermentation and petrochemical-style conversion to iso-paraffins.

Process logic:

1. **Wood-to-sugars platform**: Softwood sawdust is pretreated and hydrolysed to produce a mixture of C6 and C5 sugars; lignin is separated as a solid stream.
2. **Bio-isobutene production**: C6 sugars are fermented by engineered microorganisms to gaseous bio-isobutene, which is purified.
3. **SAF conversion**: Bio-isobutene is oligomerised and hydrogenated to produce iso-paraffinic kerosene suitable for jet fuel blending (ASTM D7566 SIP-type route).
4. **C5 ethanol**: C5 sugars are fermented to ethanol, which can be sold as fuel or converted to ETBE using part of the isobutene.
5. **Lignin and other co-products**: Lignin (≈165 kt/a) can be burned in a CHP unit or used as a binder in asphalt; fermentation sludge is used as fertilizer; microbial biomass is processed as protein feed.

At a feedstock input of **~415,000 t/a sawdust**, the plant produces around **30,200 t/a SAF** plus ethanol, lignin, fertilizer sludge and microbial biomass.

TEE characteristics:

- Technical: Concept integrates proven unit operations into a new configuration, at **TRL 6-7**. Utilities configuration (natural gas vs lignin CHP; grid vs high-RES electricity) is a dominating design choice.
- Economic: Highly capital-intensive (CAPEX ~€600 M). Under optimistic yet plausible assumptions (SAF price ~€2,200/t plus co-product revenues), annual profit is **~€9-10 M**, implying slim margins and strong dependence on policy support and offtake contracts.
- Environmental: In a lignin-CHP + high-renewables-electricity scenario, GHG intensity can be as low as **~6.6 g CO_2eq/MJ**, i.e. about **93% reduction** vs fossil jet. Less favourable utility mixes still deliver substantial savings but illustrate the importance of renewable process energy.

This pathway is strategically important for deep decarbonisation of aviation, but it is also the most challenging in terms of TRL, CAPEX and policy dependency.

5 Cross-case comparison

The previous section outlined each case individually. To better understand how they relate to each other, we now compare key technical, economic and environmental indicators side by side. The tables below provide a compact summary, followed by short interpretation.

5.1 TECHNICAL COMPARISON

Table 2: Key technical indicators (indicative).

Indicator	FPBO Biorefinery	Biogas (EffiSludge)	Lignocellulosic Ethanol	SAF (Bio-IBN)
Feedstock type	Woody residues	Industrial biosludge + fish/agri residues	Cereal straw	Softwood sawdust
Main conversion	Fast pyrolysis + CHP	Anaerobic digestion (CSTR + UASB)	Pretreatment + enzymatic hydrolysis + fermentation + CHP	Sugars → bio-IBN → oligomerisation/hydrogenation + CHP
Main fuel product	FPBO	LBG (biomethane)	Advanced ethanol	SAF (iso-paraffins)
Key co-products	Steam, electricity	Solid digestate (fertilizer), nutrient-rich liquid, WWTP services	Steam, electricity, vinasse (fertilizer/energy)	Lignin (energy/binder), ethanol/ETBE, fertilizer sludge, feed
Overall energy efficiency (incl. co-products)	~85-86%	High; fossil CED ~50% lower vs ref. WWTP	~80-85% (incl. lignin-CHP)	High total utilisation; ~22% of energy in SAF, remainder in co-products/utilities
TRL	9	9	8-9	6-7

Interpretation:

All four pathways demonstrate high overall energy utilisation when co-products are included. Fast pyrolysis and biogas stand out for their combination of high efficiency and full commercial maturity. Lignocellulosic ethanol is close behind, while the SAF pathway is clearly less mature but strategically important for aviation. The SAF case illustrates the typical pattern of high total resource utilisation, but relatively low fraction of energy ending up in the main target product (SAF), with significant shares in co-products and internal utilities.

5.2 ECONOMIC COMPARISON

Table 3: Indicative economic indicators (order of magnitude).

Indicator	FPBO Biorefinery	Biogas (EffiSludge)	Lignocellulosic Ethanol	SAF (Bio-IBN)
CAPEX (order)	~€20 M	~€25 M	~€200-300+ M	~€600 M
OPEX (per year)	~€8-8.5 M	~€4.5-5 M	~€48 M	~€85 M
Main revenue sources	FPBO, steam, electricity	LBG, gate fees, digestate fertilizer	Ethanol, vinasse	SAF, lignin, ethanol, fertilizer, feed, power export
Indicator	FPBO Biorefinery	Biogas (EffiSludge)	Lignocelulosic Ethanol	SAF (Bio-IBN)
Indicative revenues (per year)	~€8.7-9.5 M	~€9-10 M	~€48.7 M	~€94-95 M
Indicative profit (per year)	Small positive (~€0.3 M)	Clearly positive (~€2-3+ M, EBIT ~16%)	Small positive (~€0.7 M)	Modest (~€9-10 M)
Economic sensitivity	FPBO price, biomass cost, value of steam/power	Biomethane price, gate fees, fertilizer value	Ethanol price, straw cost, co-product valorisation	SAF price, feedstock cost, policy/credit levels, utility configuration

(Values are illustrative to show relative magnitude/sensitivity, not exact project benchmarks.)

Interpretation:

In economic terms, the biogas concept is the most robust under current assumptions, benefitting from several favourable features: waste-based feedstock (often with gate fees), low CAPEX compared to output value and tangible cost savings for the host mill. Fast pyrolysis and lignocellulosic ethanol operate near break-even in conservative scenarios, but both could become more attractive under higher product prices, better co-product valorisation or stronger policy incentives. The SAF case, finally, illustrates that while high revenues are possible, the combination of high CAPEX and high OPEX means profitability is modest and highly sensitive to SAF price and policy support.

5.3 ENVIRONMENTAL COMPARISON

Table 4: Environmental performance overview (qualitative).

Aspect	FPBO Biorefinery	Biogas (EffiSludge)	Lignocellulosic Ethanol	SAF (Bio-IBN)
System boundary	Cradle-to-gate (bio-oil, steam, power)	Cradle-to-gate vs stand-alone WWTP	Cradle-to-gate (ethanol, co-products)	Cradle-to-gate (SAF and co-products)
GHG intensity (relative)	Very low; ~90-96% savings vs fossil fuel	~45% reduction vs reference WWTP system; much larger if counted vs fossil gas	~85-92% savings vs gasoline (depending on grid mix)	~93% savings (best-case, lignin-CHP + RES); ~40-80+% in other scenarios
Key drivers	Internal use of char/gas, high efficiency, residue feedstock	Avoided WWTP aeration energy, fossil energy displacement by LBG, nutrient credits	Lignin-CHP, straw as residue, renewable electricity share	Lignin use (energy vs materials), grid carbon intensity, hydrogen source, co-product credits
Other benefits	Renewable heat & power, potential integration with refineries	Industrial symbiosis, nutrient recycling, reduced sludge, improved WWTP performance	Residue utilisation, fertilizer substitution, reduced open-field straw burning	Avoids ILUC from lipid feedstocks, multiple co-products (fertilizer, feed, materials), strategic aviation decarbonisation

Interpretation:

All four pathways deliver substantial GHG reductions. Fast pyrolysis and lignocellulosic ethanol achieve >80-90% savings vs fossil fuels under realistic conditions. The biogas case shows somewhat moderate relative savings when compared to a specific WWTP baseline, but the absolute GHG and energy benefits are significant once avoided fossil gas use and nutrient recycling are considered. The SAF case, in its best configuration, is capable of >90% GHG reduction relative to fossil jet, underscoring its potential role in long-term aviation decarbonisation.

5.4 STRATEGIC ROLES AND COMPLEMENTARITIES

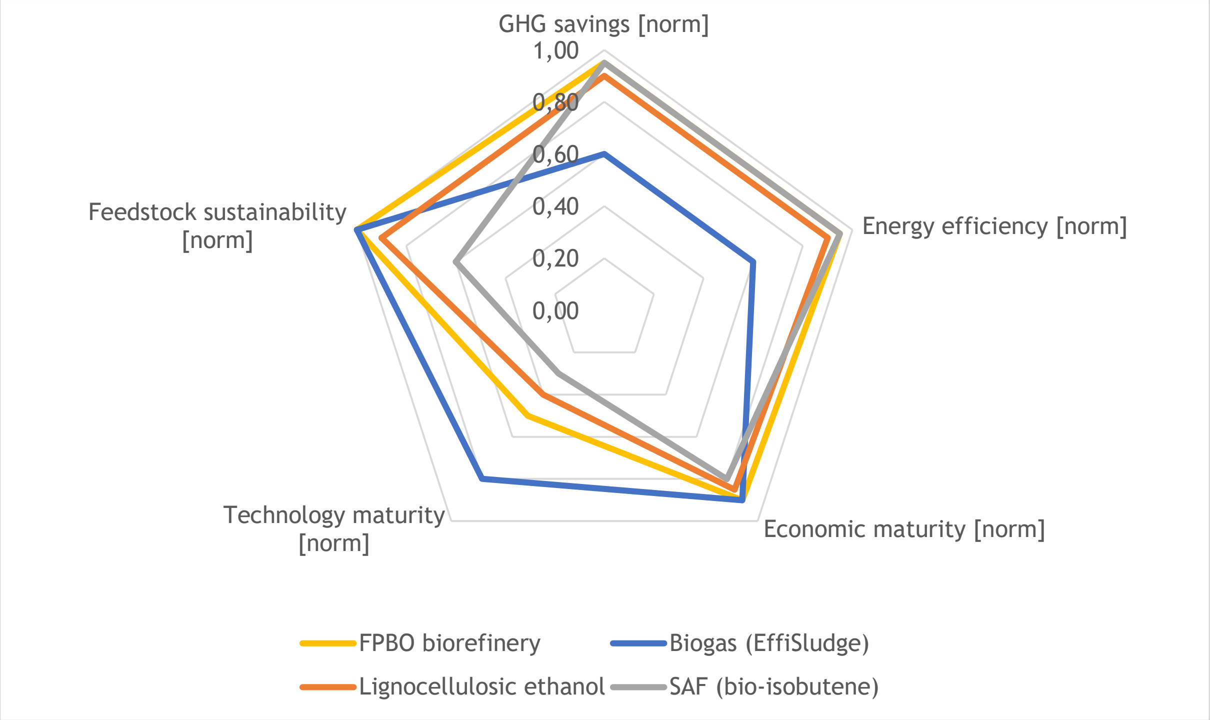
Table 5: Strategic role of each pathway.

Case	Strategic niche	Main strengths	Main challenges
FPBO	Renewable heating, refinery co-processing, marine/industrial fuel markets	High efficiency, commercial maturity, polygeneration, flexible feedstock	Product upgrading needs for some uses, tight base-case economics, market development for FPBO
Biogas (EffiSludge)	Industrial symbiosis, waste/wastewater treatment, renewable gas	Proven technology, strong GHG and energy benefits for host industry, multiple revenue streams	Site-specific integration, dependence on long-term waste contracts and regulatory framework
Lignocellulosic Ethanol	Advanced road transport fuel, chemical feedstock, possible ATJ feed	High GHG savings, use of residues, integration of energy and nutrient loops, existing ethanol infrastructure	Enzyme/chemical costs, feedstock logistics, high CAPEX, strong dependence on policy and product price
SAF (Bio-IBN)	Deep decarbonisation of aviation, multi-product bioeconomy hub	Very high potential GHG savings, residue feedstock, flexible product slate (SAF/ION/ETBE), innovation platform	High CAPEX and OPEX, lower TRL, strong reliance on SAF mandates, carbon pricing and long-term offtake

Taken together, the four pathways illustrate how a portfolio of biorefinery routes can serve different parts of the energy system: local waste-to-gas solutions (biogas), industrial heat and refining integration (pyrolysis), advanced road fuels and chemicals (ethanol) and aviation fuels (SAF). They are complementary rather than competing, and deployment strategies should reflect this.

The radar chart visualises the relative performance profiles of the four pathways across these criteria. Each polygon represents one pathway, illustrating strengths and weaknesses in comparison to the others.

Figure 1: TEE radar chart of the four biorefinery case studies



The underlying dataset presents a normalised (0–1) multi-criteria assessment of four biorefinery case studies: FPBO biorefinery, Biogas (EffiSludge), Lignocellulosic ethanol, and SAF (bio-isobutene). Five evaluation axes are included: **GHG savings**, **energy efficiency**, **economic maturity**, **technology maturity**, and **feedstock sustainability**. All metrics are based on expert judgement and scaled between 0 (lowest performance) and 1 (best performer within this set). Overall, the radar chart highlights the trade-offs among pathways: some perform strongly in environmental metrics but face economic or technological barriers, while others show advanced maturity but rely on less sustainable feedstocks. The visualization thus supports a nuanced comparison of biofuel pathways, helping to identify where further development or policy support may be most impactful.

6 Policy implications and recommendations

Moving from individual case performance to wider deployment raises several policy-relevant points:

1. **Support advanced and waste-based biorefineries through stable, long-term frameworks**
    - Advanced biofuel and SAF targets (e.g. in RED III and RefuelEU Aviation) must be stable over time to justify the large CAPEX of ethanol and SAF plants.
    - Carbon pricing and crediting schemes should recognise the high GHG savings of residue-based biorefineries.
2. **Promote industrial symbiosis and integration**
    - EffiSludge-type concepts show that integrating AD with existing industrial sites can deliver substantial GHG and cost reductions.
    - Policies could support feasibility studies and pilot projects where biorefineries are co-located with mills, refineries or other major industrial facilities.
3. **Enable sustainable feedstock mobilisation**
    - Straw and sawdust logistics require clear guidelines and planning to avoid over-harvesting and to maintain soil and forest health.
    - Support for farmer and forest-owner cooperatives can facilitate stable feedstock supply.
4. **Recognise co-products in sustainability and incentive schemes**
    - Fertilizers, animal feed and lignin-based materials provide real environmental and economic value and should be appropriately credited.
    - Clear regulatory frameworks for digestate, vinasse and lignin applications reduce uncertainty and open markets for these co-products.
5. **Improve data transparency and methodology harmonisation**
    - Encouraging operators to share performance data (possibly anonymised) will improve future TEE assessments and de-risk investments.
    - Further harmonisation between RED, ISO, VDI 6310 and CORSIA can reduce confusion and ensure consistent accounting across pathways and regions.

7 Conclusions

The TEE assessments carried out under IEA Bioenergy Task 42 and synthesised in this report demonstrate that **biorefineries based on residues and wastes can be technically mature, environmentally robust and economically viable**, provided that they are well integrated and operate within supportive policy frameworks.

Key messages include:

- **High GHG savings are achievable across all pathways**, often exceeding 80–90% relative to fossil references, when appropriate energy integration and co-product utilisation are in place.
- **Different platforms serve different niches** in the energy system; no single pathway will dominate. A balanced portfolio of thermochemical, biochemical and hybrid routes is needed.
- **Co-products are not optional extras**, but core contributors to both environmental and economic performance. Biorefinery design must therefore consider the entire product slate from the outset.
- **Industrial symbiosis and integration with existing infrastructure** (mills, refineries, grids) unlock synergies and reduce costs and emissions, as clearly shown in the biogas and pyrolysis cases.
- **Policy stability and adequate economic incentives** are crucial for capital-intensive, lower-TRL pathways, especially lignocellulosic ethanol and SAF. Without them, many projects will remain on paper.

Looking ahead, further deployment of biorefineries will depend on:

- Continued **technology innovation** (better enzymes, microbes, catalysts; improved process integration).
- Development of **robust feedstock supply chains** for residues and wastes.
- **Transparent data sharing and standardised assessment** to build investor and public confidence.
- Smart **policy design** that rewards high GHG savings, recognises co-products and facilitates industrial partnerships.

If these conditions are met, biorefineries such as those described in this report can play a central role in delivering a circular, low-carbon energy and materials system.

8 List of Tables

Abbreviations

ATJ – alcohol-to-jet (SAF pathway based on alcohols such as ethanol or isobutanol); BC – base case; CAPEX – capital expenditure; CBAM – Carbon Border Adjustment Mechanism; CHP – combined heat and power; CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation; ETBE – ethyl tert-butyl ether; FID – final investment decision; GHG – greenhouse gas(es); GWP – global warming potential; IBN – isobutene (bio-isobutene); IEA – International Energy Agency; IRR – internal rate of return; ISO – International Organization for Standardization; LCA – life cycle assessment; LCI – life cycle inventory; LHV – lower heating value; LI-CHP – lignin-fired combined heat and power; MSP – minimum selling price; NG – natural gas; OPEX – operating expenditure; PED – primary energy demand; RED II / RED III – Renewable Energy Directive II / III; RES – renewable electricity supply / renewable energy sources; SAF – sustainable aviation fuel; SARPs – Standards and Recommended Practices (ICAO); SIP – synthetic iso-paraffins (ASTM D7566 Annex 3); TEA – techno-economic assessment; TEE – Technical-Economic-Environmental assessment; TRL – technology readiness level.

Appendix

Appendix A: Fact Sheet Case 1 – Fast Pyrolysis Biorefinery
(FPBO, Steam, Power)

Appendix B: Fact Sheet Case 2 – Biogas Biorefinery Integrated With Pulp Mill
(Effisludge-Type)

Appendix C: Fact Sheet Case 3 – Lignocellulosic Ethanol Biorefinery
(Straw-Based, Lignin CHP, Vinasse)

Appendix D: Fact Sheet Case 4 – SAF Biorefinery
(Wood-To-Sugars → Bio-Isobutene → SAF)

References for Appendices A, B, C and D

Appendix A

3-PLATFORM (BIO-OIL, STEAM, ELECTRICITY PYROLYSIS PLANT USING LIGNOCELLULOSIC BIOMASS & WOODY RESIDUES FOR THE PRODUCTION OF FAST PYROLYSIS BIO-OIL, PROCESS STEAM AND ELECTRICITY

This case study presents a comprehensive Technical, Economic, and Environmental (TEE) assessment of a fast pyrolysis biorefinery that converts lignocellulosic biomass—primarily woody residues—into fast pyrolysis bio-oil (FPBO), process steam, and electricity. Fast pyrolysis represents a key thermochemical pathway for sustainable bioenergy production and is increasingly seen as integral to achieving circular economy objectives and reducing greenhouse gas (GHG) emissions.

The assessment is based on a commercial-scale biorefinery located in Europe, however, *it should be noted that the data is based on literature created by the technology provider*[1] *and does not necessarily reflect actual operating conditions*. The plant in the case study operates at a 25 MWth capacity and processes up to 5 tonnes of feedstock per hour. The plant outputs approximately 24,000 tonnes of FPBO annually, along with 222 TJ of steam and 8 TJ of electricity. Its polygeneration configuration allows for a high energy efficiency of 85 %, with co-products (char and pyrolysis gas) internally recycled for energy use. In this case study, charcoal (biochar) is combusted on-site together with pyrolysis gases to provide process heat; it is not exported as a product.

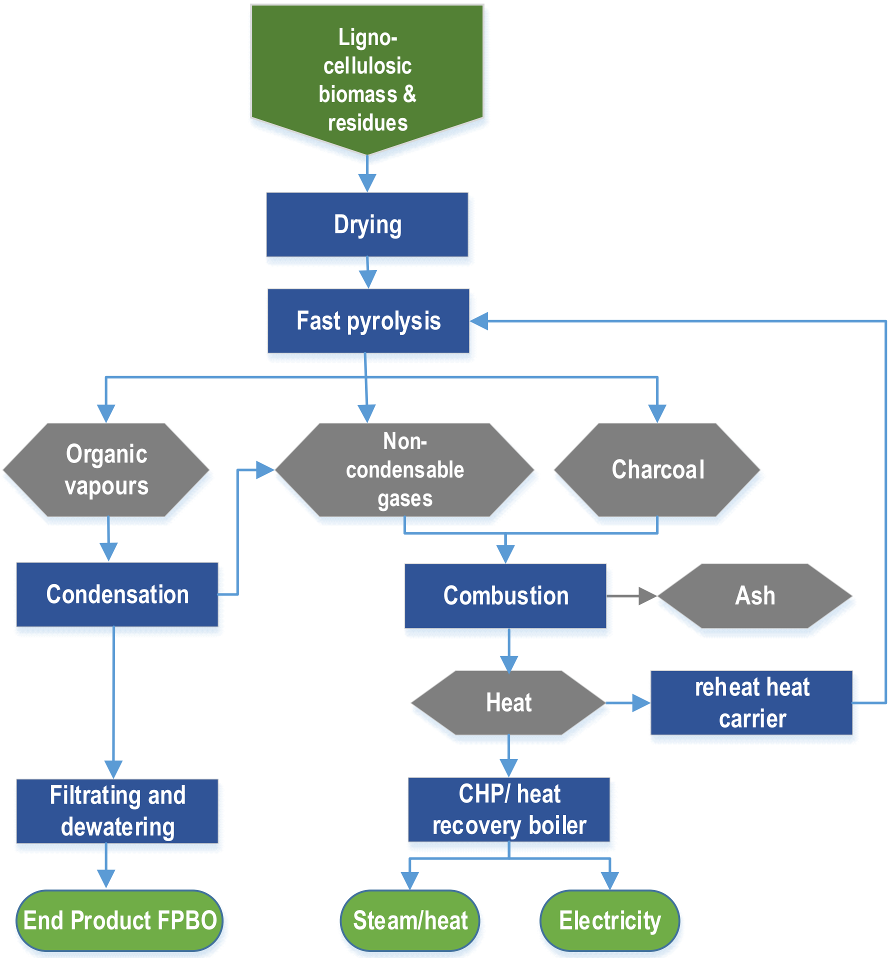


Figure 2: Basic flow chart of the fast pyrolysis plant case study.

Economic analysis indicates annual revenues of € 8.68 million/year against costs of € 8.41 million/year, showing modest profitability under conservative assumptions. Moreover, less conservative scenarios (considering additional ~ 12 % revenues for steam & electricity in external used) illustrate that the comprehensive utilization of all energy and material product and by-product streams significantly enhances the economic efficiency of biorefinery pathways. Importantly, life cycle analysis (LCA) under EU RED and NTA8080 certification frameworks reveals a max. 96 % GHG emissions reduction compared to fossil-derived energy systems. The biorefinery thus meets stringent sustainability criteria and demonstrates clear environmental superiority.

Demand for drop-in biofuels and renewable process heat is expanding, particularly in food, chemical, and maritime sectors. Integration of bio-oil into existing refinery infrastructure—via co-processing—is gaining traction as a low-CAPEX pathway for decarbonization.

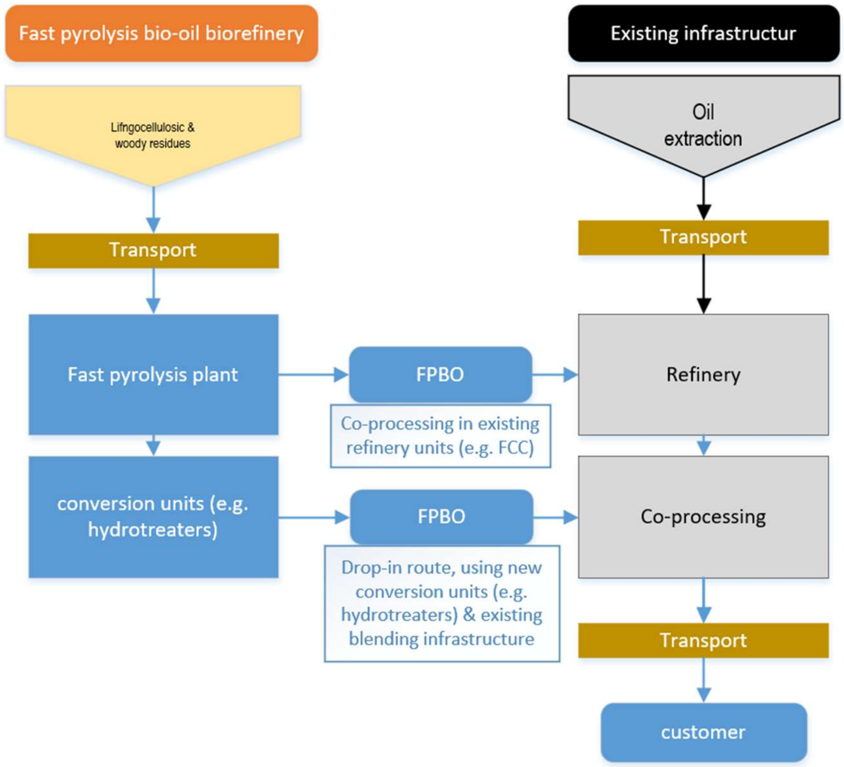
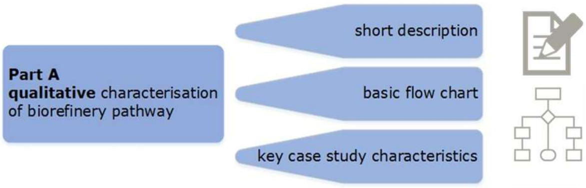


Figure 3: Fast Pyrolysis Bio-Oil as refinery feedstock-advanced biofuels: drop-in and co-processing.

This study highlights fast pyrolysis as a technically viable and environmentally effective approach to bioenergy valorization. While financial margins remain narrow, especially without policy support, the concept shows significant promise, particularly when integrated into local industrial symbiosis networks.

1. Introduction



Global energy systems are undergoing a rapid transformation in response to the dual pressures of climate change and fossil fuel depletion. As urbanization and industrialization accelerate, the demand for low-carbon, renewable alternatives has intensified. Among these, **biorefineries**—industrial systems that convert biomass into fuels, power, heat, and value-added products—offer a promising pathway toward a more circular and resilient bioeconomy.

Fast pyrolysis, a thermochemical conversion process that rapidly heats biomass in the absence of oxygen to produce a high-energy liquid known as fast pyrolysis bio-oil (FPBO), is increasingly recognized for its efficiency, feedstock flexibility, and decarbonization potential. Biomass is fed to a fast-pyrolysis reactor where it contacts a hot circulating heat carrier (sand), forming vapours/aerosols and a small fraction of char. The vapours are routed to a condenser that yields two streams: the main product, fast-pyrolysis bio-oil (FPBO), and uncondensed gases. Char from the reactor and the uncondensed gases are mixed and combusted to supply process heat and reheat the circulating sand for the next cycle. Surplus heat is recovered in a boiler/CHP unit to produce export steam and electricity. Ash is removed from the combustion section as a residual.

Unlike traditional biorefineries focused on single-product outputs, fast pyrolysis systems support **polygeneration**—simultaneously delivering FPBO, steam, and electricity—thereby enhancing both economic and environmental performance. Across Europe, several demonstration and commercial-scale facilities are validating fast pyrolysis's market readiness, e.g.[2]:

- **Empyro (Netherlands):** A 25 MW_{th} facility producing 24,000 tonnes of FPBO annually for an industrial boiler operated by a dairy facility for steam supply.
- **Côte-Nord (Canada):** A 45 MW_{th} facility producing 45,000 tonnes of FPBO annually, which is being sold for heating applications.
- **Pyrocell (Sweden):** A 25 MWth demonstration project for production and co-feeding of FPBO to a fluid catalytic cracker in the Preem refinery for the production of transportation fuels.[3]

However, many biorefinery technologies remain at early development stages, with Technology Readiness Levels (TRL) ranging from 5 to 8. For fast pyrolysis systems, the critical gap lies not in basic science, but in demonstrating their **scalable, economically viable, and environmentally sustainable integration** into industrial value chains.

This case study addresses that gap. It presents a Technical, Economic, and Environmental (TEE) assessment of a commercial-scale fast pyrolysis biorefinery in Europe, using lignocellulosic biomass—primarily woody residues—as its feedstock. The analysis is structured using a transparent fact-sheet methodology aligned with IEA Bioenergy Task 42 guidelines and VDI 6310 standards for biorefinery classification.

This work contributes to:

- Improving transparency and comparability across emerging biorefinery concepts;
- Identifying process-level efficiencies and bottlenecks in pyrolysis technology;
- Informing policymakers and investors about the real-world performance of low-TRL bioenergy systems.

Given the increasing emphasis on industrial decarbonization, particularly in sectors where electrification is difficult, the deployment of regionally integrated fast pyrolysis plants presents a viable solution for replacing fossil-based heat and fuels—especially where local biomass residues are underutilized.

2. Method of assessment for fast pyrolysis biorefinery case study

2.1. CURRENT STATUS AND DEVELOPMENT TRENDS OF BIOREFINERIES

Modern biorefineries aim to convert diverse biomass sources—including forestry residues, agricultural byproducts, and aquatic biomass—into a variety of energy carriers and bio-based products. Concepts under development include **fast pyrolysis**, **hydrothermal liquefaction**, and **gasification**, each with differing levels of technology readiness and market applicability. To contextualize the performance of the fast pyrolysis biorefinery, the following table presents a comparative snapshot against two other prominent technologies, whereas a fair comparison is admittedly difficult especially on the product based-level.

Table 6: Comparative basic indications of emerging thermochemical biorefinery technologies, based on data from [4,5,6,7,8,9]

Metric	Fast Pyrolysis	Hydrothermal Liquefaction (HTL)	Gasification-to-Fuels
TRL	6-9	5-7	5-6
Feedstock Type	Woody residues	Wet biomass, sewage sludge	Woody/agro biomass
Main Liquid Product	FPBO (bio-oil)	Biocrude	Syngas-derived fuels
Product Energy Yield	~60-70 %	~65-75 %	~45-55 %
Polygeneration Capability	Yes	Limited	Yes
Energy Efficiency	~85 % (total)	~60-70 %	~55-65 %
GHG Reduction (vs fossil)	~96 %	~85-90 %	~80-90 %
Drying Requirement	Required (~5% moisture)	None (wet feed accepted)	Moderate
CAPEX (€/MWth)	~750-1,200 k	~1,200-1,500 k	~2,000 k+
Product Upgrade Requirement	Yes (stabilization/co-processing/ hydrotreating)	Yes (hydrotreating)	Yes (Fischer-Tropsch)

Insights: Fast pyrolysis exhibits the highest energy efficiency due to its internal heat recovery and polygeneration capabilities. Hydrothermal liquefaction (HTL) effectively processes wet feedstocks without the need for prior drying, offering significant flexibility in waste management scenarios. Gasification facilitates the production of high-quality transport fuels; however, it necessitates expensive syngas cleanup and synthesis processes. These comparisons indicate that, although fast pyrolysis may not directly produce fully drop-in fuels, it excels in energy integration, system simplicity, and modular scalability. It is particularly well-suited for regional deployment where waste biomass and industrial steam demand are co-located. Emerging European facilities, such as Pyrocell and Resolute, exemplify the practical evolution of these concepts. Nonetheless, commercial deployment is hindered by challenges related to biomass transport costs, capital expenditure (CAPEX) intensity, and integration complexity.

2.2. KEY CHALLENGES IN ASSESSMENT

Assessment of biorefinery systems is complicated by:

- Limited availability of high-quality data, especially for low-TRL systems
- Methodological inconsistencies in Life Cycle Assessment (LCA)
- Allocation and system boundary decisions that affect comparability

This study addresses these issues using standardized guidelines:

- ISO 14040 series for LCA methodology[10]
- EU Renewable Energy Directive (RED III) for GHG accounting[11]
- VDI 6310 for classification and economic parameters[12]

2.3. CLASSIFICATION SYSTEM USED

To ensure comparability, this study uses the IEA Bioenergy Task 42 classification, which organizes biorefineries along four axes:

1. **Feedstock** (e.g., lignocellulosic residues)
2. **Platforms** (e.g., organic vapors, syngas)
3. **Products** (e.g., FPBO, electricity, steam/heat)
4. **Processes** (e.g., fast pyrolysis, combustion)

This modular system allows biorefinery pathways to be expanded or adapted over time as new processes and outputs are introduced.

2.4. THE TEE ASSESSMENT FRAMEWORK

The Technical, Economic, and Environmental (TEE) framework used here builds on prior work by Lindorfer et al. (2019)[13]. It applies:

- **Technical metrics**: yield efficiency, polygeneration performance, …
- **Economic indicators**: CAPEX, OPEX, revenue balance, …
- **Environmental indicators**: GHG emissions, energy demand, …

The assessment uses generic and site-specific data from open-access databases, techno-economic reports, and LCA studies, all consolidated into a transparent MS Excel-based model for reproducibility and easy to handle.

3. Case Study Analysis – Part A: Biorefinery Plant

3.1. OVERVIEW AND SYSTEM BOUNDARY

This case study focuses on the **fast pyrolysis biorefinery**, whereas a commercial-scale facility is located in Europe. The plant converts lignocellulosic woody residues into fast pyrolysis bio-oil (FPBO), steam, and electricity. The assessment follows a **cradle-to-gate** system boundary, covering raw material acquisition through to the point of product delivery.

Table 7: Key technical characteristics of the fast pyrolysis biorefinery case study.

Key Parameter	Characteristic
Raw Material	Woody biomass (e.g., wood chips)
Process	Fast pyrolysis (450–600 °C)
Main Products	FPBO, process steam, electricity
Capacity	25 MWth
FPBO Output	24,000 tonnes/year
Energy Efficiency (total)	~85 %
TRL Level	9
Geographic Location	Europe

3.2. PROCESS DESCRIPTION

The process route aligns with the fast pyrolysis biorefinery process as delineated by van de Beld and Muggen.[14] This case study examines a fast pyrolysis biorefinery utilizing lignocellulosic woody residues, such as agricultural residues, to produce fast pyrolysis bio-oil (FPBO) as an alternative to fossil fuels. The primary input and output streams, along with the plant's capacity, are depicted in Figure 2. The process accommodates most lignocellulosic (non-edible) feedstocks, including wood chips, sugarcane bagasse, straw, and sunflower hulls. Fast Pyrolysis Technology entails the rapid heating of biomass in the absence of air, followed by the swift condensation of the resulting organic vapors to yield FPBO. Under these conditions, non-condensable gases and char are also generated. FPBO is the principal product; non-condensable pyrolysis gases and char are combusted to supply the heat necessary for the pyrolysis process. Excess heat is available and can be utilized, for instance, to co-generate additional steam and electricity for external supply.

The fast pyrolysis plant can be regarded as a polygeneration unit, as it concurrently produces three distinct products. Steam and electricity are utilized internally to power the process. Surplus process steam is provided to a nearby chemical company site, while surplus electricity is supplied to the grid. FPBO is transported to an external customer, thereby displacing natural gas.[15]

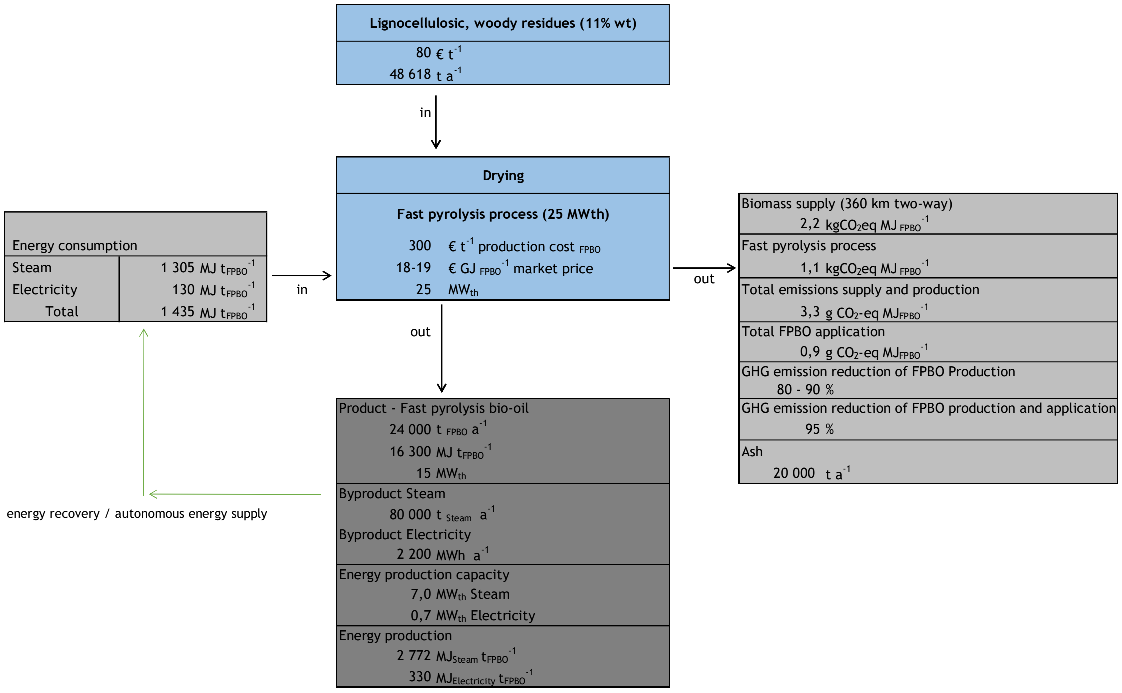


Figure 4: Overview of TEE assessment: Process pathway for fast pyrolysis bio-oil synthesis from lignocellulosic biomass. Based on own calculations with data from literature referenced at table 1 and additional sources[16,17,18]

The process begins with **drying and conditioning** of biomass feedstock to reduce moisture to ~5 wt%. The feed is then fed into a **rotating cone reactor**, where biomass is rapidly mixed with heated sand, triggering fast pyrolysis under oxygen-free conditions.

The core process steps include:

- **Fast Pyrolysis**: Rapid heating (<2 seconds) at 450–600 °C
- **Separation**: Char and non-condensable gases removed via cyclones
- **Condensation**: Organic vapors condensed into FPBO using spray cooling
- **Combustion**: Char and gases burned in a fluidized bed to generate process heat
- **Energy Recovery**: Steam turbine generates electricity; excess steam and electricity sold externally

System Design Benefits:

- Co-generation of electricity and steam
- Internal energy self-sufficiency
- Sale of surplus steam to adjacent industrial client

3.3. MASS AND ENERGY BALANCE

At full capacity:

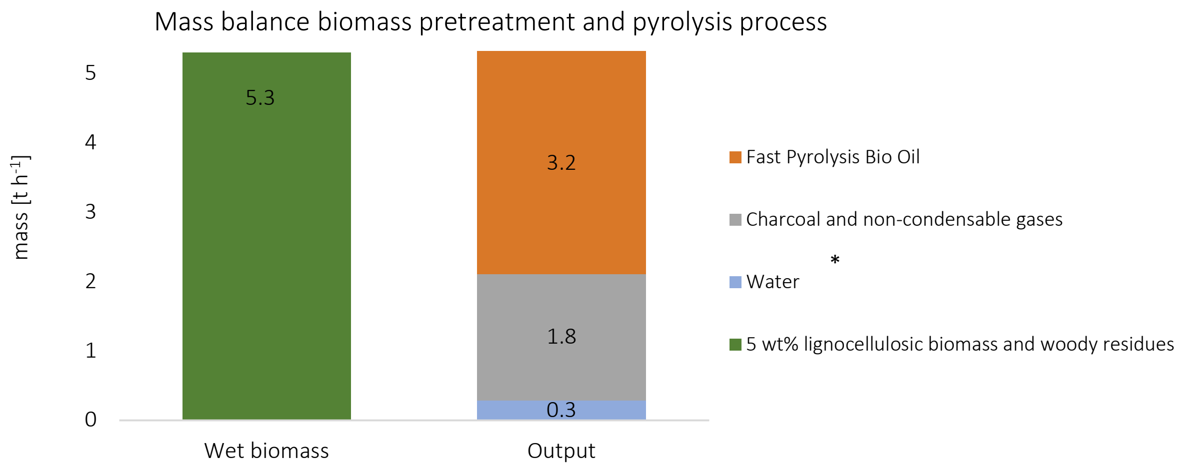
- **Feedstock input**: 5 t/h (wet) → 3.2 t/h of FPBO (~50–75% yield)

- **Output energy**: 391 TJ FPBO, 222 TJ steam, 8 TJ electricity per year
- **Ash/wastewater**: Minor by-products (~20 t/year ash, ~0.3 t/h water)

Table 8 summarizes the key characteristics of the considered case study.

Table 8: Key characteristics case study.

3-platform (bio-oil, steam, electricity) pyrolysis plant using lignocellulosic biomass & woody residues for the production of fast pyrolysis bio-oil, process steam and electricity							
State of technology		Industrial (TRL 9)					
Country		Europe					
Main data source		Literature (sources referenced in table 1 & [19,20,21]					
Products				**Auxiliaries**			
	FPBO	391	TJ a^{-1}		Energy	34.4	TJ a^{-1}
		24	kt a^{-1}				
	Electricity	8	TJ a^{-1}				
	Steam	222	TJ a^{-1}				
Costs				**Feedstock**			
	Investment Dep.	1.9	Mio. €		Wood Chips	48.6	kt a^{-1}
	Feedstock	3.6	Mio. €				
	Operating	3.9	Mio. €	**Conversion rates (Efficiencies)**			
	Labour	0.8	Mio. €		Feedstock to FPBO	50-75	wt%
					Overall Energy efficiency through circularity	85	%



*water is released as part of the FPBO and after combustion of char/uncondensed gases in the flue gas as water vapor. There is no separate water output.

Figure 5: Simplified balance of mass of input and output stream.

PART B: VALUE CHAIN ASSESSMENT

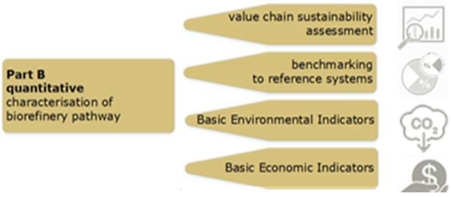


Figure 6 illustrates the annual revenue and cost structure of the fast pyrolysis biorefinery case study. The revenues are primarily derived from the sale of FPBO, complemented by approximately 12 % from electricity and steam exports. On the cost side, the largest share is attributed to biomass feedstock procurement, followed by personnel expenses and finance costs—including depreciation and equity-related charges. Other fixed and variable costs contribute minimally. The figure highlights a narrow but positive operating margin, underscoring the importance of co-product valorization and capital efficiency for economic viability.

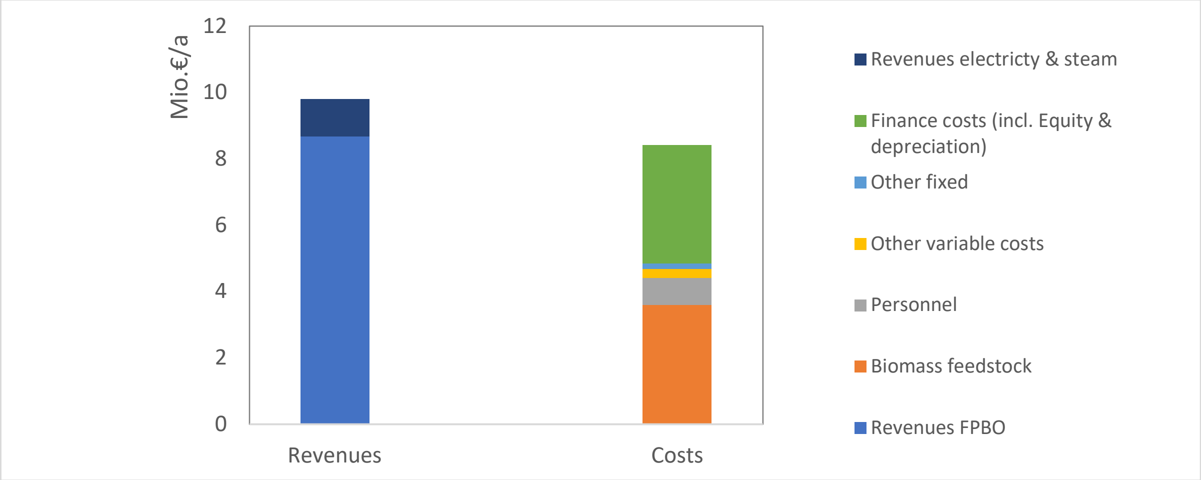


Figure 6: Costs and revenues case study of fast pyrolysis bio-oil production biorefinery plant.

Chum et al. (2011)[22] and Giwa et al. (2022)[23] have demonstrated that the cost structure of feedstock supply chains, which varies considerably across different geographical regions due to the cost of raw material supply, significantly impacts the techno-economic performance of lignocellulosic biorefineries. The biorefinery's self-sustaining energy supply, derived from co-products, presents both environmental and economic benefits. Factors such as economies of scale, technological innovation, and increased competition have collectively led to a reduction in the economic and energy costs of supply chains by more than 50% (see figure 8).

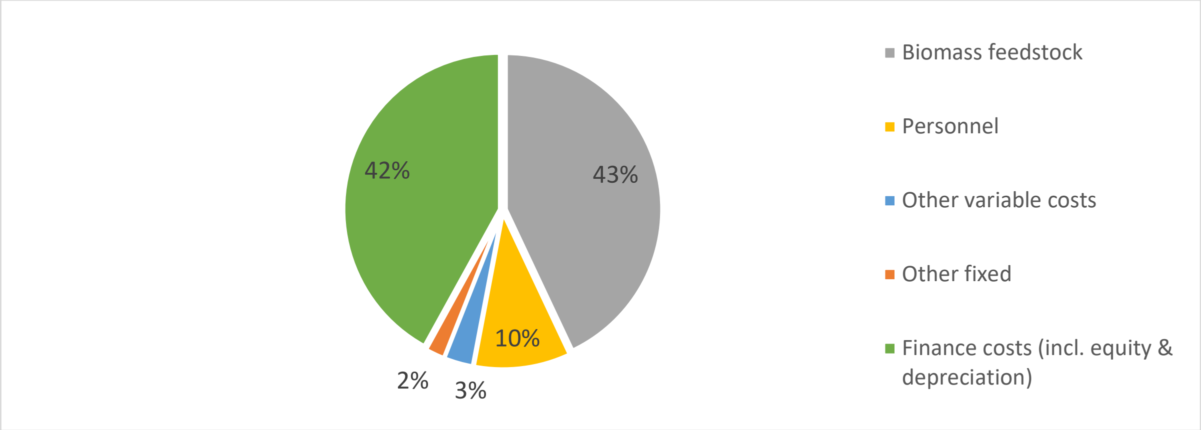


Figure 7: Share breakdown of costs of the fast pyrolysis bio-oil case study. (see Table 3)

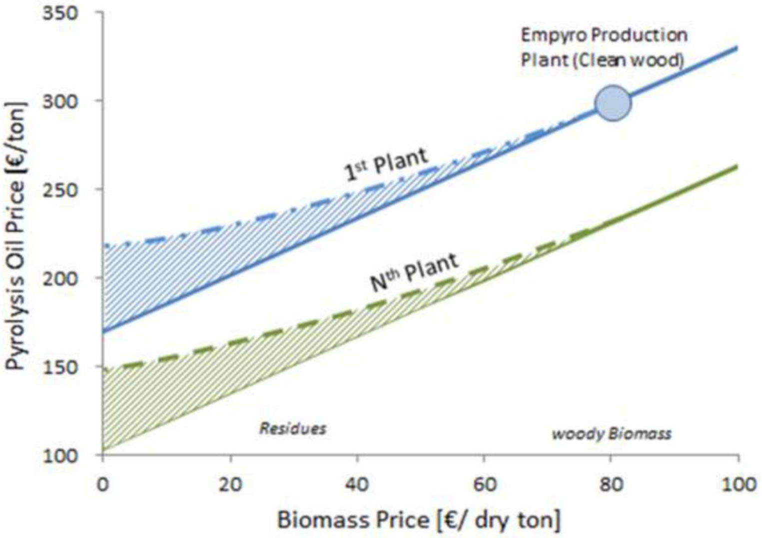


Figure 8: Correlation curves between FPBO price and biomass price.[24]

To enhance the economic viability of fast pyrolysis, a viable strategy involves marketing biochar for high-value applications. This approach includes its use as activated carbon[25], a soil amendment[26], an adsorbent[27], and in the production of carbon nanomaterials.[28,29,30] However, this would reduce the amount of excess heat that can be supplied locally to almost zero.

Table 9: Simplified economic sensitivity analysis of fast pyrolysis biorefinery profitability.

Parameter	Base Case	Low Scenario	High Scenario
Biomass Feedstock Cost (€/t)	80	60	100
FPBO Market Price (€/GJ)	19	23	15
Annual Profit	+270,000	+970,000	-450,000

Findings:

- A 25% increase in biomass cost and/or reduction in product pricings can turns the plant unprofitable in a very simplified sensitivity approach.
- A moderate increase in FPBO price significantly improves the margin.
- Combining low-cost feedstock with modest price increases yields the highest returns.

Implications: Economic resilience depends on feedstock availability, stable FPBO markets, and policy instruments like green heat subsidies or carbon credits.

The following diagram shows a basic flow chart of the fast pyrolysis process and fossil benchmark (Figure 9). In addition to the end product, there is the main customer for the fast pyrolysis plant. A fast pyrolysis plant will only be built if the offtake of oil can be guaranteed and a dedicated oil boiler will only be built if the required fuel can be guaranteed. Having both in place simultaneously has been a critical part of developing the value chain.[31]

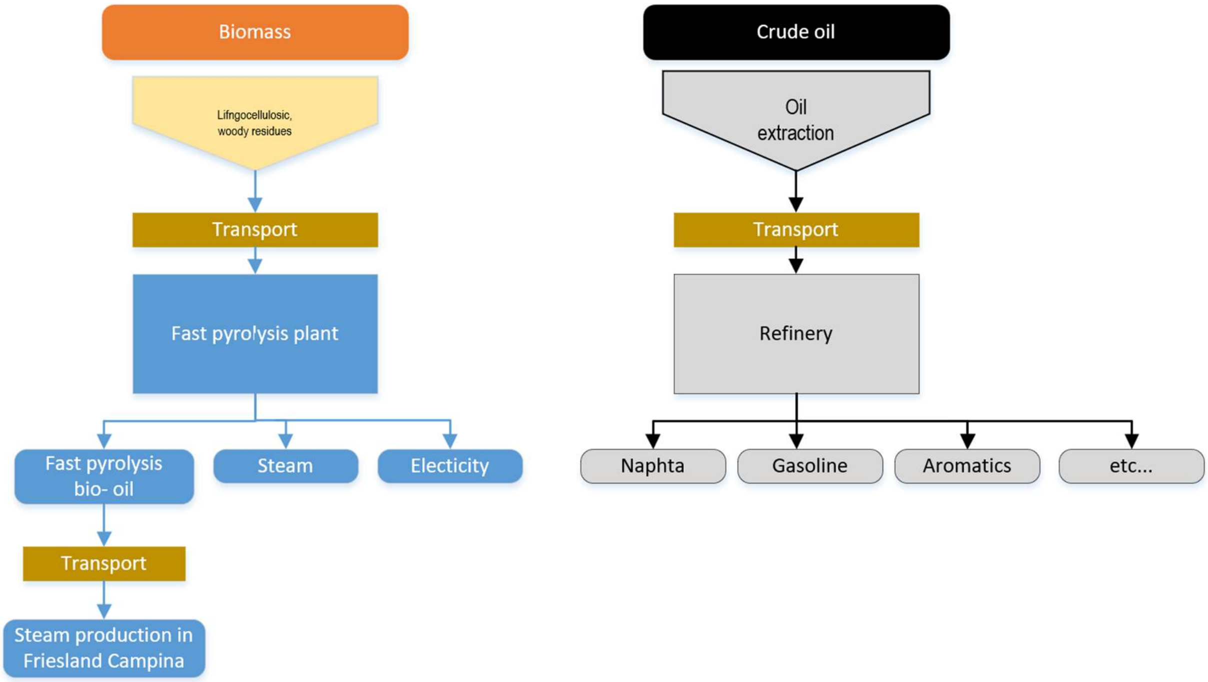


Figure 9: Flow chart to visualize the fast pyrolysis plant in comparison to the oil extraction refinery reference system.

The results of the environmental assessment based on GHG emissions and annual cumulated energy demand are shown in Figure 10. A comparison of the fast pyrolysis biorefinery with the production of fossil fuels is presented. Concerning (Muggen, 2021) the fast pyrolysis process saves 80-90 % of GHG.[32] In the following scheme, a scenario is calculated, showing an 85 % reduction in the biorefinery compared to the fossil refinery.

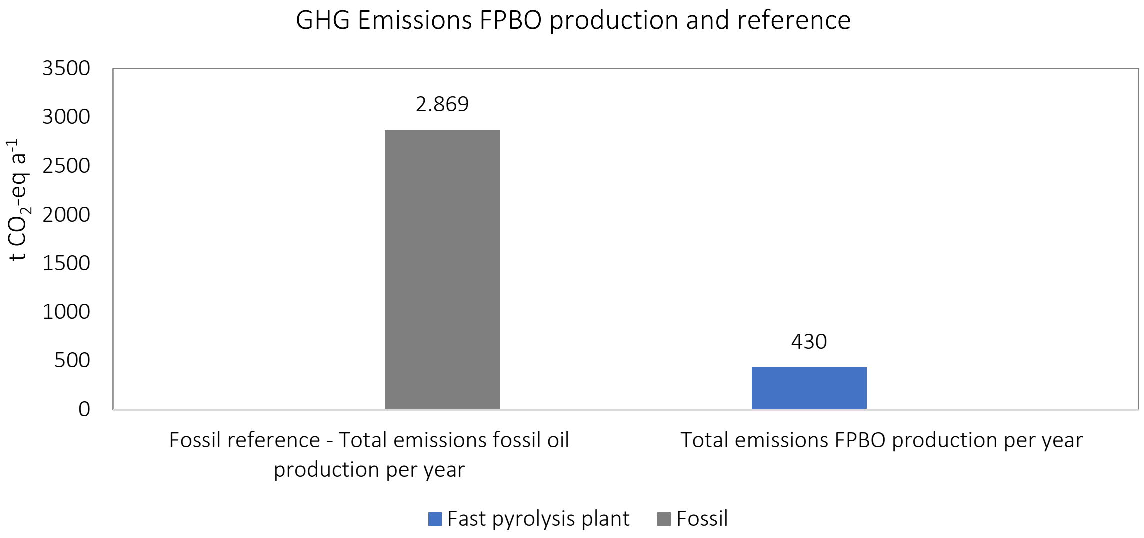


Figure 10: Comparison of Annual GHG Emissions - Fast Pyrolysis Plant vs. Fossil Reference.

Table 10: Overview of GHG emissions reduction in the fast pyrolysis case and application.

Greenhouse gas emissions		
Biomass supply (360 km two-way)	2.2	kg CO_2-eq GJ_{FPBO}^{-1}
Fast pyrolysis process	1.1	kg CO_2-eq GJ_{FPBO}^{-1}
Total emission fast pyrolysis	3.3	kg CO_2-eq GJ_{FPBO}^{-1}
Allocated to FPBO (energy basis)	70	%
Total emission FPBO production	**2.3**	**kg CO_2-eq GJ_{FPBO}^{-1}**
Transport FPBO to Borculo (60 km two-way)	0.4	kg CO_2-eq GJ_{FPBO}^{-1}
FPBO combustion	0.5	kg CO_2-eq GJ_{FPBO}^{-1}
Total FPBO application	**0.9**	**kg CO_2-eq GJ_{FPBO}^{-1}**
Total emissions FPBO production & application	**3.1**	**kg CO_2-eq GJ_{FPBO}^{-1}**
Emission per MJ of Heat (95 % efficiency)	3.3	kg CO_2-eq GJ_{FPBO}^{-1}
Fossil reference case	77	kg CO_2-eq GJ_{FPBO}^{-1}
GHG emission reduction FPBO production & application	**96**	**%**

Table 11: Overview of the TEE assessment results case study.

Greenhouse gas emissions		
Biorefinery	~430	t CO_2-eq a^{-1}
Fossil reference refinery	~2867	t CO_2-eq a^{-1}
Savings	80-96	%
Cumulated energy demand		
Biorefinery	230	TJ
Reference System	587	TJ
Difference	455	TJ
Costs		
Annual costs	8.41	Mio. € a^{-1}
Specific costs	0.420	€ l_{FPBO}^{-1}
Investment costs	19	Mio. €
Revenues		
Revenues FPBO	8.681	Mio. € a^{-1}
Specific Revenues	~0.434	€ l_{FPBO}^{-1}

5. Conclusions & strategic outlook

This case study demonstrates that fast pyrolysis biorefineries are **technically feasible, environmentally superior, and economically near breakeven**, especially when backed by supportive policies and industrial integration.

Key Conclusions

- **Technical Performance**: With an overall efficiency of ~85%, fast pyrolysis biorefineries can continuously operate using internal energy generated from char and pyrolysis gases. Their polygeneration setup allows simultaneous production of FPBO, steam, and electricity, with opportunities to supply external heat through industrial symbiosis. In this case study, charcoal (biochar) is combusted on-site together with pyrolysis gases to provide process heat; it is not exported as a product.
- **Environmental Impact**: The system achieves up to **96% GHG reduction** compared to fossil fuels, surpassing EU RED II thresholds. While total energy demand may not be lower than fossil alternatives, it is entirely met using renewable inputs from residual biomass.
- **Economic Viability**: Estimated at a modest annual profit (~€270,000), the project proves financially viable with long-term contracts and renewable subsidies. Competitiveness is expected to improve with lower feedstock costs, scale-up efficiencies, and market maturation.

Strategic Outlook

- **Policy Integration**: Carbon pricing, renewable fuel mandates, and symbiosis incentives are essential to accelerate deployment, particularly in hard-to-electrify sectors like food, chemicals, and heavy industry.
- **Technology Scale-Up**: Wider adoption depends on modular, replicable systems suited for regions with abundant biomass, industrial heat demand, and supportive policy frameworks. The specific system in this case study has been replicated already twice (in Sweden and Finland) and consequently is referred to TRL 9.
- **Innovation Pathways**: Co-processing FPBO in existing refineries offers a low-CAPEX route to advanced biofuels. Additional revenue streams could emerge from biochar applications in soil improvement and carbon materials.
- **Comparative Edge**: Compared to alternatives like HTL and gasification, fast pyrolysis stands out for its integration simplicity, energy efficiency, and scalability—positioning it as a strong solution for near-term decarbonization.
- **Final Remark:** Fast pyrolysis biorefineries exemplify the circular bioeconomy in practice, enabling local, low-emission fuel and heat production. Their role in industrial decarbonization and energy diversification is poised to expand significantly as policy, market, and technology landscapes converge.

MORE DETAILED INFORMATION ON THE DATA BASIS AND THE METHOD APPLIED ARE AVAILABLE IN THE ACCOMPANYING REPORTS AT HTTPS://TASK42.IEABIOENERGY.COM/DOCUMENT-CATEGORY/REPORTS-PAPERS/

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Appendix: Data basis and calculations used in the TEE fact sheet

This appendix summarises the key assumptions, calculations, and primary sources underpinning the case study.

- Nominal capacity and operating hours: 25 MW_{th} × 8,000 h a^{-1} = 720 TJ a^{-1} thermal input.

- FPBO output: 24 kt a^{-1} with lower heating value (LHV) ~16.3 GJ t^{-1} ⇒ ~391 TJ a^{-1} (consistent with Empyro operating data).

- Steam and electricity export: 222 TJ a^{-1} (steam) and 8 TJ a^{-1} (electricity) ⇒ total useful energy out ~621 TJ a^{-1} ⇒ overall energy efficiency ≈ 86%.

- Feedstock requirement: 48.6 kt a^{-1} implies average feedstock LHV ≈ 16.4 GJ t^{-1}, compatible with dried woody residues.

- GHG performance: cradle-to-gate emissions allocated to FPBO ≈ 2.3 kg CO_2-eq GJ^{-1}; production + application ≈ 3.1 kg CO_2-eq GJ^{-1}, yielding 90–96% reduction vs. fossil reference depending on allocation and reference case assumptions.

- Economic basis (illustrative): CAPEX ≈ €19–20 million for 25 MWth (≈ €750–1,300 per kWth depending on boundary); feedstock ~€80 per dry tonne; indicative FPBO value €18–23 per GJ; sensitivity strongly driven by feedstock price and FPBO offtake price.

- Co-processing route: FPBO co-fed to FCC at Preem (Lysekil) demonstrated at commercial scale; offers a low-CAPEX decarbonisation pathway for transport fuels.

Appendix B

2-PLATFORM (BIOMETHANE, BIOFERTILIZER) BIOGAS PLANT USING PAPER-MILL WASTEWATER BIOSLUDGE & REGIONAL FISH/AGRI RESIDUES FOR THE PRODUCTION OF BIOMETHANE (LBG) AND BIOFERTILIZER

This case study describes a **two-platform industrial symbiosis** in which a pulp and paper mill's wastewater biosludge is co-digested with nearby fish/agricultural residues to produce **biomethane** and a marketable **biofertilizer**, while cutting the mill's aeration power needs in an efficient and symbiotic wastewater treatment plant (WWTP) configuration. The assessment is based on a commercial-scale biorefinery located in Europe, however, *it should be noted that the data is based on literature and public available data and does not necessarily reflect actual operating conditions.* The patented EffiSludge setup places anaerobic digestion upstream of parts of the biological treatment, so the aerators run at roughly half their former electricity demand (≈ 39 → ~20 MWh d^{-1}), and the recycled digestate liquor supplies all external nitrogen (~750 kg N/day) and about half the phosphorus (~120 kg P/day) otherwise dosed to the WWTP.

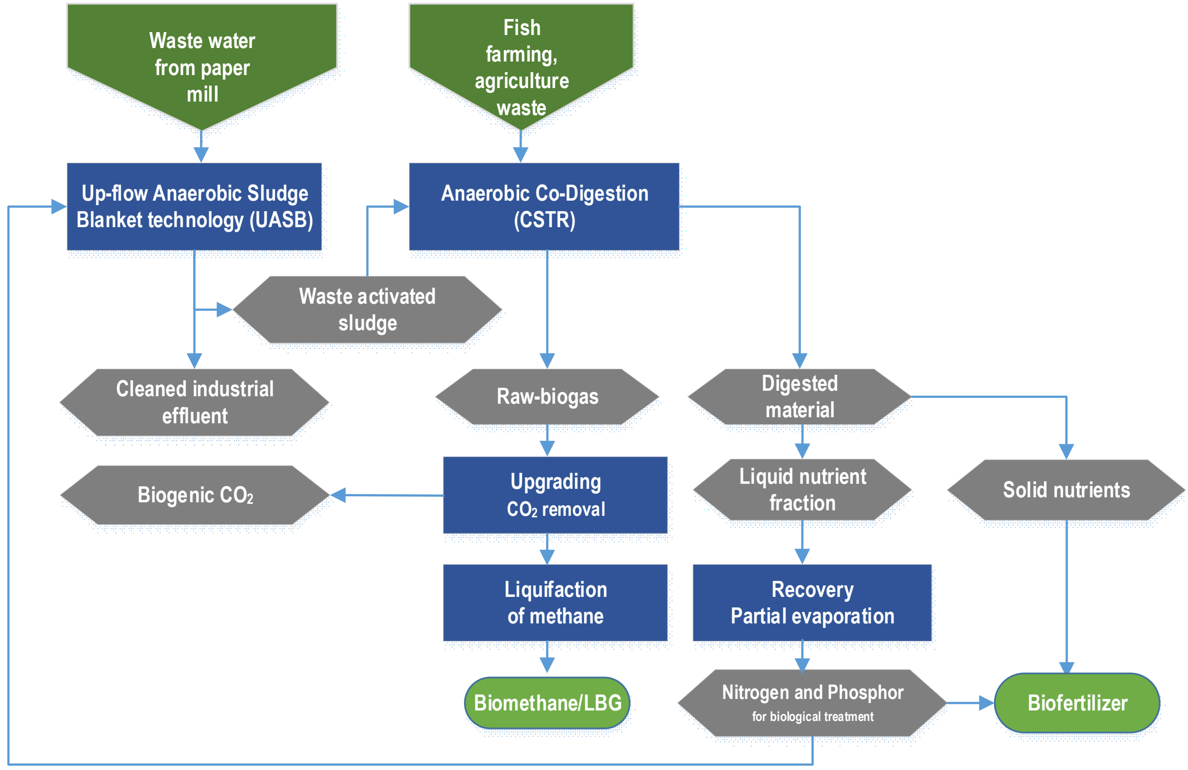


Figure 11: Basic flow chart of the biogas plant using paper mill wastewater, biosludge & regional fish/agri residues for the production of biomethane (LBG) and biofertilizer.

At full load the plant processes roughly **20,000 t/day** of mill wastewater and **~112 t/day** of fish/agri waste. Biogas originates mainly from CSTR digestion of solids (up to **~288 MWh d^{-1}**) and, to a lesser extent, from **UASB** treatment of the wastewater (**~55 MWh d^{-1}**). After **upgrading** and **liquefaction (~-160 °C)**, output totals about **342 MWh d^{-1}** of biomethane, i.e., **~125 GWh/year**—on the order of 12.5 million liters of diesel equivalent. A **solid digestate (~55 t/day)** forms the basis of a commercial biofertilizer; the liquid fraction is split between internal nutrient recycling and concentration for fertilizer products.[33]

Economically, literature-based TEE results indicate that the EffiSludge setup pairs a moderate **CapEx €25.4 M** with disciplined **OpEx ~€4.66 M/yr**, leveraging the host mill's wastewater synergies (lower aeration and internal nutrient recycling) to keep operating costs in check. On today's assumptions, biomethane/LBG priced around **€70/MWh**[34] provides the core income stream, while modest gate fees for incoming residues and steady biofertilizer sales add resilience without complicating operations. The result is a balanced business case that depends more on reliable offtake and stable integration with the mill than on aggressive pricing assumptions. With these conditions met, total revenues reach **~€9.6 M/yr**, supporting an **EBIT margin ~16%** after capital charges—comfortably above a 10% target and robust enough to weather typical fluctuations in energy and fertilizer markets. Strategic risks remain centered on product price volatility and contract durability, but the industrial-symbiosis design helps buffer both by reducing utility exposure and monetizing co-products.

Environmentally, the integrated system outperforms a conventional stand-alone WWTP reference. Reported **GHG emissions** decline from ~**4,200** to **~1,900 t CO_2-eq/year** (~**2,300 t/year avoided; ~45%** cut), driven by captured biogenic methane, displaced fossil fuels, lower aeration electricity, and nutrient circularity. **Cumulated energy demand** likewise halves, from ~**52,560** to ~**26,280 GJ/year**. These results were compiled with a **cradle-to-gate** scope and a **RED-aligned** simplified GHG approach using published data for mass/energy balances and prices.

Overall, this **TRL-9** biomethane-biofertilizer pathway illustrates how colocated digestion and wastewater treatment can create robust renewable gas output, monetize residues, and **close nutrient loops**—a replicable model for mills and regions with comparable waste streams seeking cost-effective decarbonization.

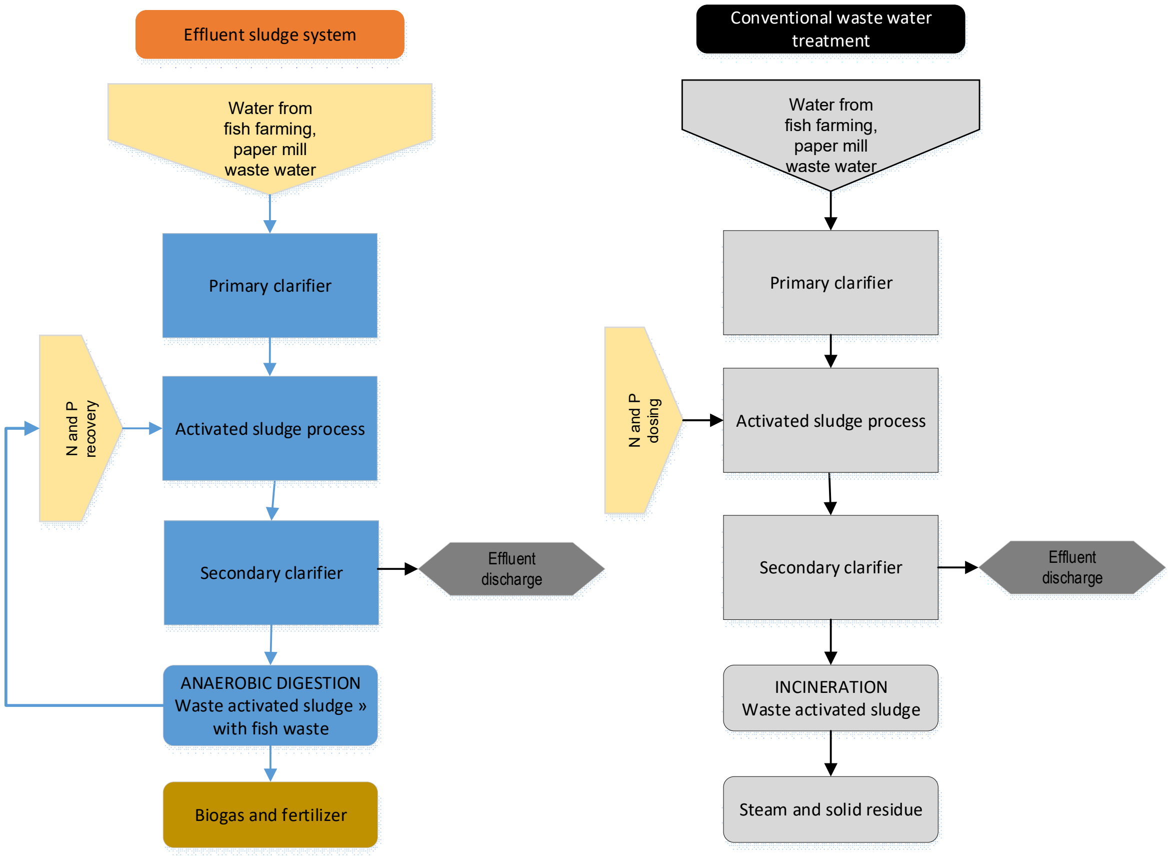
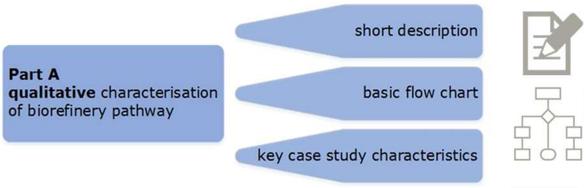


Figure 12: Simplified comparison of Effluent Sludge System and Conventional Wastewater Treatment Processes.

This study highlights the **effluent sludge system** as a practical, low-impact upgrade to conventional wastewater treatment. By recovering nitrogen and phosphorus and co-digesting waste activated sludge with fish waste, it turns liabilities into **biogas and marketable fertilizer**, cuts **chemical dosing**, lowers **nutrient discharges**, and avoids **incineration and solid residues**. Although margins can be tight without policy support, integrating the system with nearby aquaculture and paper mills strengthens the economics and advances a **local circular economy** with improved energy self-sufficiency.

1. Introduction



Global energy systems are being reshaped by the need to cut greenhouse-gas emissions while reducing reliance on depleting fossil resources. As urbanization and industrial output grow, the demand for low-carbon, circular solutions intensifies. **Biogas-based biorefineries**—industrial systems that convert organic residues and wastewater into renewable gas, power/heat, and nutrient products—offer a practical, near-market pathway for a more resilient bioeconomy.[35] In the **EffiSludge** concept, biosludge from a pulp & paper mill's wastewater treatment is co-digested with nearby fish/agricultural wastes to produce **biomethane** while **halving aeration electricity** and **replacing external nutrient dosing** (≈100% of N and ~50% of P) through digestate recirculation.[36]

Technically, the reference industrial symbiosis treats **~20,000 t/day** of mill wastewater plus **~112 t/day** of fish/agri residues. Biogas arises mainly from CSTR digestion of solids (≈**288 MWh d^{-1}**) with a smaller share from **UASB** treatment of the wastewater (≈**55 MWh d^{-1}**).[37] After upgrading and cryogenic liquefaction (~-160 °C), output totals **~342 MWh d^{-1}** —about **125 GWh/year** of biomethane—alongside a **solid digestate (~55 t/day)** marketed as biofertilizer and a liquid fraction recycled to the WWTP.

Unlike single-product facilities, this two-platform configuration (biogas + biofertilizer) delivers both **energy** and **material circularity**. A recent TEE (Technical, Economic, Environmental) assessment—aligned with IEA Bioenergy Task 42 fact-sheet methodology and VDI 6310—confirms **industrial-scale readiness (TRL 9)** with **CapEx ≈ €25.4 M** and **OpEx ≈ €4.66 M/yr**. On a representative **2025** basis, annual revenues total **~€9.56 M/yr** (≈**€8.75 M** from biomethane at **€70/MWh** (LHV basis), plus **~€0.41 M** gate-fee income and **~€0.40 M** fertilizer sales). Environmentally, cradle-to-gate results indicate a reduction from **~4,200 to ~1,900 t CO_2-eq/yr** (≈**2,300 t/yr** avoided; **~45%** cut), with **cumulated energy demand halved** relative to a conventional stand-alone WWTP.

This case study therefore shifts the focus from thermochemical fast-pyrolysis routes to a **mature anaerobic-digestion-centric solution** that integrates seamlessly with existing industrial infrastructure. By monetizing local residues, displacing fossil fuels in transport and heat, and closing nutrient loops, biogas-based biorefineries provide an immediately deployable option for industrial decarbonization where electrification alone is less practicable.

2. Method of assessment for biogas biorefinery case study

2.1. CURRENT STATUS AND DEVELOPMENT TRENDS OF BIOREFINERIES IN THE BIOGAS FIELD

Biogas biorefineries have evolved from single-purpose CHP plants into **multi-product platforms** that upgrade raw biogas to **biomethane/bio-LNG** and valorize **digestate** as a nutrient product. The sector is increasingly **residue-driven** (municipal/industrial sludges, food and agri by-products) and **site-integrated**, using industrial symbiosis with hosts such as mills and food processors to cut utility demand and chemical dosing. State-of-the-art features include **high-efficiency upgrading** (membranes, amines, PSA), **liquefaction** for transport markets, tighter **methane-slip control**, and options to use **biogenic CO_2** (e-fuels, greenhouses). EU policies (RED targets, Guarantees of Origin) and demand from **transport and hard-to-electrify sectors** underpin growth, while **gate fees** and **nutrient recycling** strengthen project economics. Emerging trends—**modular designs**, **digital O&M**, and **hybridization** with power-to-gas or carbon capture—are positioning biogas biorefineries as flexible nodes in a circular, low-carbon system.

A representative case is the **EffiSludge** configuration, where a paper-mill WWTP is coupled with AD: mill biosludge is **co-digested** with nearby fish/agri residues to produce biomethane (upgraded and liquefied as LBG) and a marketable biofertilizer. Placing AD ahead of parts of the aerobic step and **recycling liquid digestate** halves **aeration electricity** (≈ **39 → ~20 MWh·d^{-1}**) and replaces **~100% of external N (~750 kg N·d^{-1})** and **~50% of P (~120 kg P·d^{-1})**. At full load, about **20,000 t·d^{-1}** of wastewater and **~112 t·d^{-1}** of residues are treated, yielding **~342 MWh·d^{-1} (~125 GWh·yr^{-1})** of biomethane; the **~55 t·d^{-1}** solid digestate is sold as fertilizer, while the liquid fraction **closes the nutrient loop on-site**.

A TEE assessment (IEA Bioenergy Task 42 format; VDI 6310 classification) indicates industrial-scale readiness (TRL 9) with CapEx ≈ €25.4 M and OpEx ≈ €4.66 M·yr^{-1}. Straight-line depreciation is €2.54 M·yr^{-1} (or ~€3.3-3.5 M·yr^{-1} when including ~5% interest). On a representative 2025 basis, annual revenues are ~€9.56 M·yr^{-1} (≈€8.75 M biomethane at **€70/MWh** (LHV basis) plus ~€0.41 M gate fees and ~€0.40 M fertilizer). Compared with a standalone WWTP, the integrated system avoids ~2,300 t CO_2-eq·yr^{-1} (≈ 4,200 → ~1,900 t CO_2-eq·yr^{-1}) and halves cumulated energy demand (~52,560 → 26,280 GJ·yr^{-1}), illustrating how AD-centric, residue-based biorefineries decarbonize industry while closing nutrient loops.

*Table 12: **Comparative basic indications of biogas-based biorefinery configurations** (indicative; performance is site-specific and depends on feedstock mix, scale, and integration) based on literature sources* [38,39,40,41]

Metric	Industrial symbiosis (EffiSludge-type)	Stand-alone AD + upgrading (biomethane to grid/LBG)	WWTP sludge AD + CHP (legacy reference)
TRL	**9** (industrial scale)	High (commercial; varies by site)	High (mature in utilities)
Primary feedstocks	Mill biosludge + fish/agri wastes; **~20,000 t d^{-1} wastewater + ~112 t d^{-1} residues**	Manure/food waste/industrial organics (wet)	Sewage sludge from municipal/industrial WWTPs
Core processes	**UASB** + CSTR (solids) (wastewater) → upgrading → **liquefaction ~-160 °C**	CSTR/plug-flow → upgrading (to grid or LBG)	**dewatering and incineration of sewage sludge** or Mesophilic/thermophilic AD → **CHP on-site**

Main energy product	**Biomethane/LBG ~342 MWh d^{-1} (~125 GWh yr^{-1})**	Biomethane to gas grid or LBG for transport (scale-dependent)	Electricity/heat for plant loads (export limited)
Material co-products	**Biofertilizer (~55 t d^{-1})**; liquid digestate recycled as N/P source	Solid/liquid digestate (agri use)	Dewatered biosolids; limited nutrient valorization → **incineration**
Utility impacts	**~50 % lower aeration power; 100 % N and ~50 % P** dosing replaced	No WWTP synergy; utilities sized for AD/upgrading	Baseline WWTP energy demand; no AD-driven aeration relief
GHG performance (cradle-to-gate)	**~2,300 t CO_2-eq yr^{-1} avoided** vs reference; **~45 % cut**	Typically strong when diverting wastes; case-specific under RED	Lower relative benefit; depends on CHP efficiency & grid mix
Cumulated energy demand	**~26,280 GJ yr^{-1}** vs **~52,560 GJ yr^{-1}** reference (≈ 50 % lower)	Case-specific; no WWTP energy co-benefit	Baseline for comparison (reference)
Indicative economics	**CapEx ≈ €25.4 M; OpEx ≈ €4.66 M·yr^{-1}; Revenues ≈ €9.56 M·yr^{-1} (≈€8.75 M biomethane @ €70/MWh** (LHV basis) + **~€0.41 M gate fees + ~€0.40 M fertilizer)**	Commercial; costs depend on feedstock, tariffs, and gate fees	Utility-driven; value mainly from on-site energy offset
Best-fit context	**Co-located mills/industry** with steady wet residues & nutrient needs	Regions with **dispersed organic wastes** and gas/transport demand	WWTPs prioritizing **sludge stabilization** and energy self-use

These indications show why **industrial symbiosis AD** performs strongly where an anchor industry (e.g., pulp & paper) can offer **stable wet feedstocks**, **nutrient sinks**, and **utility synergies**—turning waste liabilities into **renewable gas and fertilizer** while cutting plant energy and emissions.

2.2. KEY CHALLENGES IN ASSESSMENT

Assessment challenges (biogas context). Evaluating biogas-based biorefineries is complicated by:

- Sparse, site-specific data (plants are heterogeneous; operators are cautious with sensitive OPEX/CAPEX and process data).
- Method differences in LCA/GHG accounting, especially when wastewater treatment is coupled to AD and when energy/credits are co-produced.
- Allocation & system boundaries (e.g., how to credit avoided WWTP aeration, nutrient substitution, and diverted wastes), which strongly affect comparability.

This study addresses these issues using standardized guidelines:

- ISO 14040 series for LCA methodology[42]
- **EU Renewable Energy Directive (RED) methodology** for simplified, cradle-to-gate GHG accounting of biomethane (instead of a full ISO 14040/44 LCA), ensuring consistent comparison with fossil benchmarks.[43]
- **IEA Bioenergy Task 42 fact-sheet approach** to structure inputs/outputs and document primary data sources transparently.

- **VDI 6310** concepts used for classification and for selecting techno-economic/environmental indicators relevant to biorefinery assessments.[44]

Note: International schemes like the U.S. RFS and Brazil's RenovaBio are acknowledged for context but not applied here.

2.3. CLASSIFICATION SYSTEM USED

To ensure comparability, this study uses the IEA Bioenergy Task 42 classification, which organizes biorefineries along four axes:

5. **Feedstock:** paper-mill biosludge and industrial/aquaculture residues; ~20,000 t d^{-1} wastewater plus ~112 t d^{-1} fish/agri wastes.
6. **Platforms: biogas/biomethane (energy) and digestate (material/nutrient platform).**
7. **Products: biomethane/LBG** (~342 MWh d^{-1} ≈ 125 GWh y^{-1}), **electricity/heat** (optional), and **biofertilizer (~55 t d^{-1})**; liquid fractions recycled as N/P source to the WWTP, cleaned industrial effluent discharged.
8. **Processes: UASB (wastewater) + CSTR co-digestion (solids), gas upgrading, and liquefaction (~-160 °C) for LBG;** internal nutrient recirculation reduces external N by ~100% and P by ~50%.

This modular scheme supports transparent comparison across biogas configurations and future pathway extensions (e.g., adding CO_2 utilization or different digestate valorization).

2.4. THE TEE ASSESSMENT FRAMEWORK

The Technical, Economic, and Environmental (TEE) framework used here builds on prior work by Lindorfer et al. (2019).[45] It applies:

- **Technical metrics**: feedstock throughputs, specific biogas/biomethane yields, upgrading/liquefaction performance, WWTP synergies (aeration cut ~50%, nutrient substitution).

- **Economic indicators:** CAPEX ≈ €25.4 M; straight-line depreciation ≈ €2.54 M/yr (or ~€3.3-3.5 M/yr incl. ~5% interest). OPEX ≈ €4.66 M/yr. Revenues ≈ €9.56 M/yr (≈ €8.75 M biomethane at **€70/MWh** (LHV basis) + ~€0.41 M gate fees at €10/t + ~€0.40 M fertilizer at €20/t)[46]. Together these yield an EBIT margin ~16% (with interest), with additional resilience from WWTP synergies (reduced aeration, nutrient recirculation).

- **Environmental indicators**: RED-aligned cradle-to-gate GHG and cumulated energy demand (CED); the integrated system shows about 2,300 t CO_2-eq y^{-1} avoided (~45% vs. conventional WWTP) and CED halved (~52,560 → 26,280 GJ y^{-1}).

All calculations rely on **published, site-specific and generic data** consolidated in a **transparent spreadsheet** model to enable replication and case-by-case adaptation (recognizing that biogas plants are highly site-dependent and not directly transferable without re-calculation).

3. CASE STUDY ANALYSIS – PART A: BIOREFINERY PLANT

3.1. OVERVIEW AND SYSTEM BOUNDARY

This case study examines an industrial-symbiosis, biogas-based biorefinery in Europe that couples a pulp & paper mill's wastewater treatment plant (WWTP) with anaerobic digestion (AD) of on-site biosludge and nearby fish/agricultural residues. The integrated concept—known as EffiSludge—produces biomethane (upgraded and liquefied as LBG) and a biofertilizer from digestate, while reducing aeration electricity by ~50% and substituting WWTP nutrient dosing via liquid-digestate recirculation (≈100% of N and ~50% of P). The assessment follows a cradle-to-gate boundary from raw material acquisition and internal energy/nutrient loops through to product at plant gate (biomethane/LBG and fertilizer), excluding downstream distribution and use.

Table 13: Key technical characteristics of the biogas-based biorefinery (EffiSludge-type) based on[47,48,49]

Key Parameter	Characteristic
Raw Materials	~**20,000 t d^{-1}** mill wastewater; ~**112 t d^{-1}** fish/agri residues (regional suppliers).
Core Processes	**CSTR** co-digestion (solids) + **UASB** (wastewater) → **upgrading** → **liquefaction (~-160 °C)** to LBG; internal **digestate nutrient recirculation**.
Main Energy Product	**Biomethane/LBG ~342 MWh d^{-1} (~125 GWh a^{-1}).**
Material Co-product	**Solid digestate ~55 t d^{-1}** (biofertilizer); liquid fraction recycled to WWTP as N/P source, cleaned industrial effluent discharged.
Utility Synergies	**Aeration power ~39 → ~20 MWh d^{-1}** (≈50% cut); external dosing replaced by **~750 kg N d^{-1}** and **~120 kg P d^{-1}** recovered internally.
TRL Level	**9 (industrial scale)**; best-practice reference includes Skogn LBG.
Geographic Location	Europe.
Balancing Scope	**Cradle-to-gate** for technical, economic, and environmental indicators.

3.2. PROCESS DESCRIPTION

Feedstock handling and digestion are split between two complementary lines. High-solids residues (fish waste, manure, wood-based biosludge from the mill) are fed to CSTRs, delivering the dominant share of methane—up to ~288 MWh d^{-1}. In parallel, the mill's wastewater is treated in a UASB reactor, contributing an additional ~55 MWh d^{-1}. The combined raw biogas stream is upgraded (CO_2 removal and polishing) to pipeline-quality biomethane and then liquefied (~-160 °C) to produce LBG, reducing volume to ~1/600 for storage and transport.

The digestate is mechanically separated. The solid fraction (~55 t d^{-1}) is marketed as biofertilizer, while the liquid fraction is partly evaporated to concentrate nutrients and partly recycled to the WWTP to replace external N and P dosing. This industrial symbiosis reduces the aeration load (shorter sludge age, lower blower power) and cuts aeration electricity roughly in half (from ~39 to ~20 MWh d^{-1}), which is reflected in the plant's internal energy balance. Overall, the facility exports biomethane (~125 GWh a^{-1}) and fertilizer while leveraging on-site energy and nutrient loops to minimize operating footprint.

Polygeneration & integration. Although the prime energy product is biomethane/LBG, the configuration inherently supports **polygeneration** (renewable gas + fertilizer; optional electricity/heat from biogas if not fully liquefied) and demonstrates **system-level benefits** versus a stand-alone WWTP—namely **lower cumulated energy demand** and **reduced GHG emissions** within a **cradle-to-gate** scope.

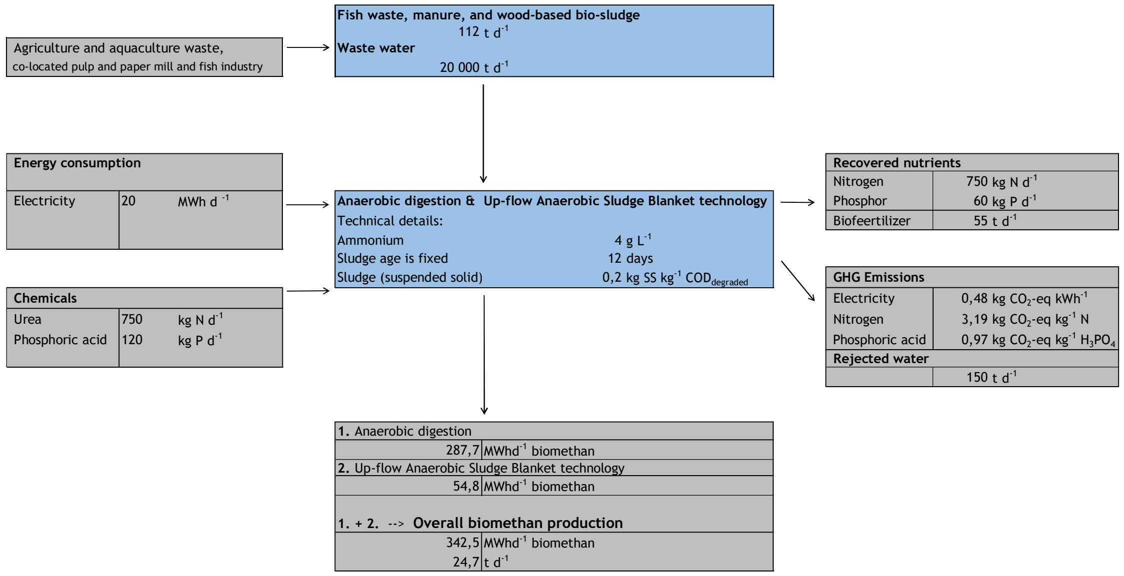


Figure 13: Overview of TEE assessment — Process pathway for biomethane (LBG) and biofertilizer from mill biosludge and fish/agri residues (EffiSludge industrial symbiosis: UASB + CSTR → upgrading → liquefaction; digestate solids to fertilizer, liquid to WWTP nutrient recirculation). Based on own calculations with data from literature referenced in table 1.

Process route:

Unlike thermochemical routes, the biogas-based plant processes **wet residues without drying.** Mill wastewater, biosludge and fish/agri wastes are received, screened/macerated, and pumped to digesters. Two complementary AD lines operate in parallel:

- **CSTR co-digestion (solids):** fish waste, manure, and paper-mill biosludge deliver the **dominant methane share (~288 MWh d^{-1}).**
- **UASB (wastewater):** treats the mill's process water and adds **~55 MWh d^{-1}** of biogas equivalent.

Raw biogas from both lines is **upgraded** (CO_2 removal and polishing) to biomethane, then **liquefied (~-160 °C)** to LBG for compact storage/transport (≈1/600 volume).

The **digestate** is separated: a **solid fraction (~55 t d^{-1})** sold as biofertilizer, and a **liquid fraction** partly evaporated (concentrate) and partly **recycled to the WWTP** to replace external nutrient dosing.

System design benefits:

- **No feedstock drying;** robust on wet, variable residues.
- **Utility synergy at the mill:** inserting AD upstream shortens sludge age and **halves aeration electricity (~39 → ~20 MWh d^{-1}).**
- **Nutrient circularity:** recycled liquor **replaces ≈100% external N (~750 kg N d^{-1}) and ~50% external P (~120 kg P d^{-1})** for the WWTP.
- **Flexible energy product:** pipeline-quality biomethane or **LBG** for transport; CHP is optional if liquefaction is curtailed.

3.3. MASS AND ENERGY BALANCE

full-load, cradle-to-gate:

- **Feedstock inputs:** **~20,000 t d^{-1}** paper-mill wastewater; **~112 t d^{-1}** fish/agri residues.
- **Biogas formation: CSTR ~288 MWh d^{-1} + UASB ~55 MWh d^{-1}.**
- **Biomethane/LBG output: ~342 MWh d^{-1} ~ 125 GWh a^{-1}** (≈12.5 million L diesel equivalent).
- **Digestate products: solid ~55 t d^{-1}** (biofertilizer); **liquid** recycled/evaporated (N/P source).
- **WWTP utilities (synergy):** aeration power **~39 → ~20 MWh d^{-1}** (≈50% cut); external nutrient dosing avoided **(N ~750 kg d^{-1}; P ~120 kg d^{-1} at ~50% substitution).**
- **Auxiliary energy import:** ~20 MWh d^{-1} (grid) shown as secondary input in the energy balance.

Table 8 summarizes the key characteristics of the considered case study.

Table 14: Key characteristics case study.

2-platform (biogas + biofertilizer) industrial symbiosis	
State of technology	**Industrial (TRL 9)**; best-practice reference includes Skogn LBG.
Country	Europe
Main data source	Literature (sources referenced in table 1)
Products (energy)	**Biomethane/LBG ~342 MWh d^{-1} (~125 GWh a^{-1}).**
Products (material)	**Biofertilizer (solid digestate) ~55 t d^{-1}; liquid for N/P recycling.**
Auxiliaries	**Electricity ~20 MWh d^{-1}** (external import in balance).
Feedstocks	**~20,000 t d^{-1} wastewater;** **~112 t d^{-1} fish/agri residues.**
Economic (indicative)	**CapEx ≈ €25.4 M; straight-line depreciation ≈ €2.54 M a^{-1}** (or ~€3.3-3.5 M a^{-1} incl. ~5% interest). OpEx ≈ €4.66 M a^{-1}; Revenues ≈ €9.56 M a^{-1} (≈ €8.75 M biomethane @ €70/MWh + ~€0.41 M gate fees @ €10/t + ~€0.40 M fertilizer @ €20/t).

Note: **Detailed mass/energy flows and balances are site-specific; figures here reflect the literature-based case used for the TEE assessment.**

Mass Balance in t / a			
Input		**Output**	
Wastewater	7 300 000	Cleaned industrial effluent	7 257 273
Fish waste	41 000	Biofertilizer	20 000
Nutrient phosphoric acid	44	Rejected water (evaporated)	54 749
Nutrient nitrogen acid	274	Nutrient phosphoric acid	22
		Nutrient nitrogen acid	274
		Biomethane	9 000

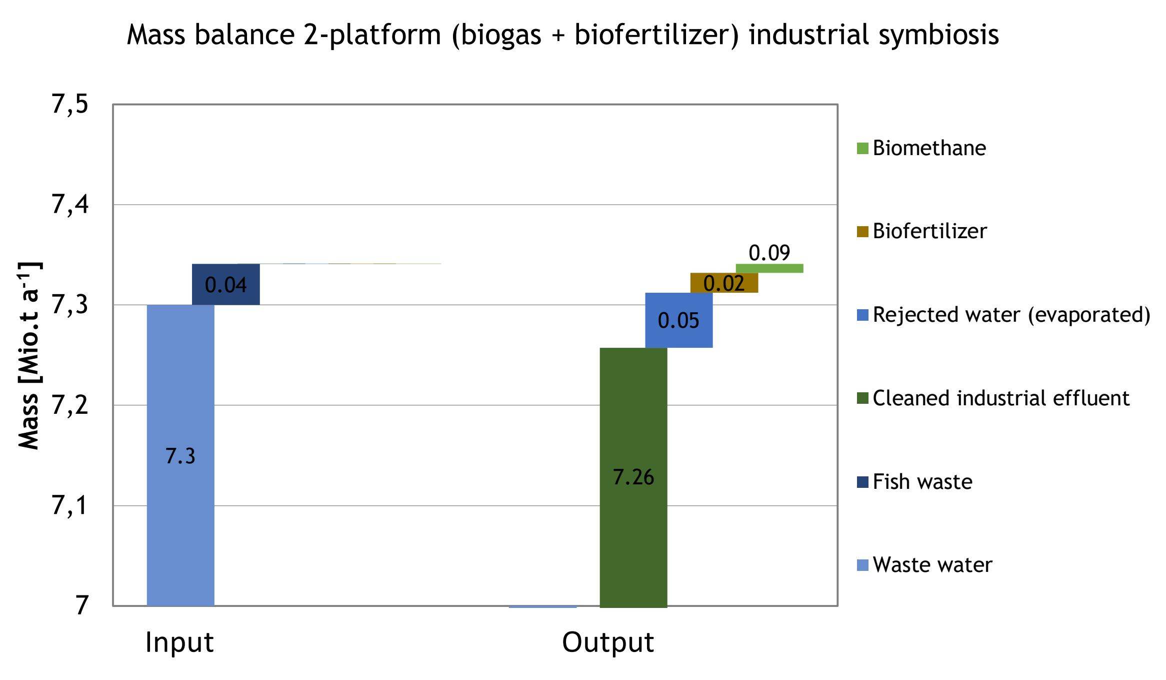


Figure 14: Simplified balance of mass of input and output stream.

PART B: VALUE CHAIN ASSESSMENT

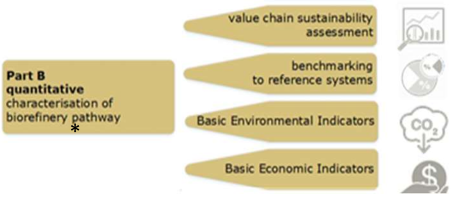


Figure 5 shows the annual revenue and cost structure for the biogas-based biorefinery. Revenues remain dominated by biomethane/LBG sales. On a **representative 2025 basis** of **€70/MWh** (LHV basis), total biomethane income is **~€8.75 million yr^{-1}** (for ~125 GWh yr^{-1}). Additional value arises from **gate fees** for incoming residues (~**€0.41 million yr^{-1}** at **€10/t** for ~41 kt yr^{-1}) and **biofertilizer** sales (~**€0.40 million yr^{-1}** at **€20/t** for ~20 kt yr^{-1}). **Total revenues ≈ €9.56 million yr^{-1}.**
On the cost side, **variable costs** (energy, O&M, labor) outweigh fixed OPEX; we retain **OpEx ≈ €4.66 million yr^{-1}. Fixed costs** reflect the capital charge on **€25.4 million CapEx**, i.e., **€2.54 million yr^{-1}** straight-line depreciation or **~€3.3-3.5 million yr^{-1}** including 5 % interest. This yields **total annual costs ≈ €8.06 million yr^{-1}** (with interest) and an **EBIT ~€1.50 million yr^{-1}**, i.e., a **~15.7 % margin**, above the 10 % target. Without interest, EBIT would be **~€2.36 million yr^{-1}** (~24.7 % margin). The profile underscores the importance of **energy-integration synergies** (reduced WWTP aeration) and **co-product valorization** (fertilizer, gate fees) for robust economics.

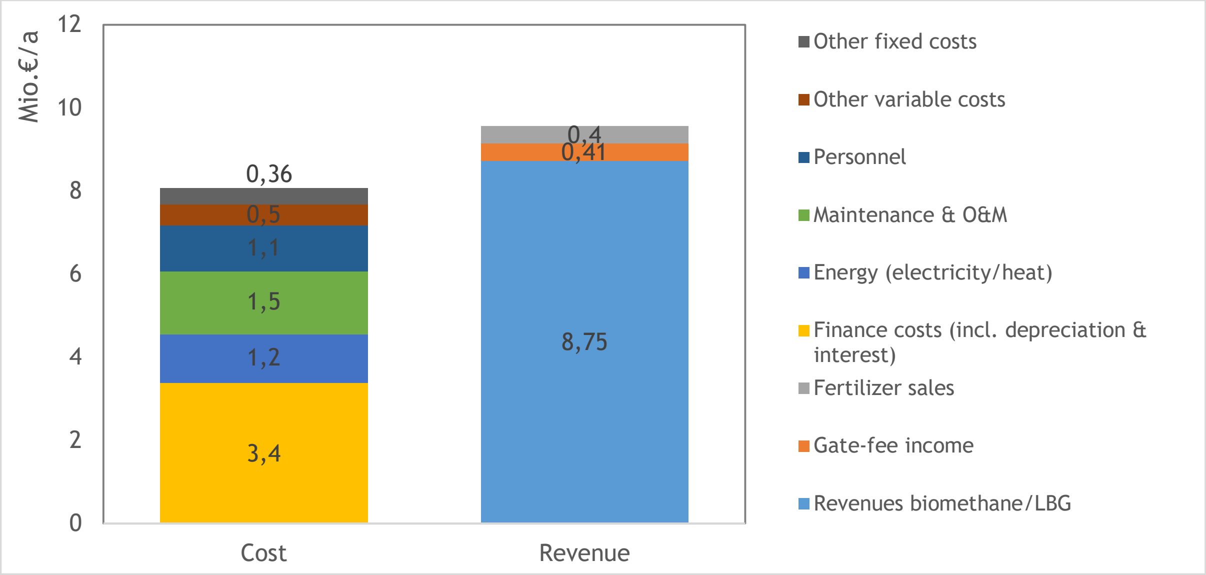
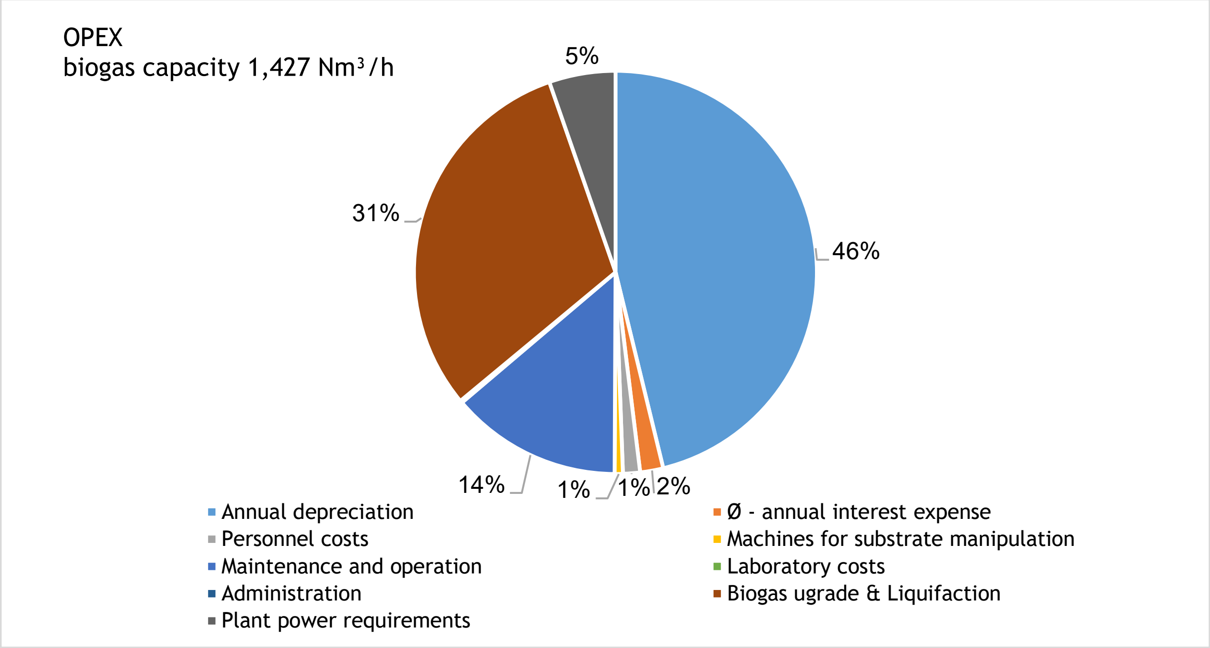


Figure 15: Costs and revenues for the biogas-based biorefinery (EffiSludge industrial symbiosis: biomethane/LBG and biofertilizer).

In biogas-based biorefineries, **local residue logistics, gate fees, and WWTP synergies**—rather than classic biomass purchase costs—tend to dominate the techno-economics. In the EffiSludge case, processing residual wastes keeps feedstock procurement subordinate; **variable costs** are led by **auxiliary energy and maintenance/operations**, while **fixed costs** reflect capital charges on **~€25.4 M investment** and **OpEx ~€4.66 M yr^{-1}**. **Revenues are chiefly from biomethane/LBG (~€8.75 M yr^{-1} at €70/MWh** (LHV basis)), with **gate fees (~€0.41 M yr^{-1})** and **biofertilizer (~€0.40 M yr^{-1})** providing additional contribution (**total ~€9.56 M yr^{-1}**). Critically, system integration trims operating burdens: inserting AD upstream **halves aeration power** (≈ 39 → ~20 MWh d^{-1}) and **substitutes nutrients** via digestate recirculation (**~100 % of external N and ~50 % of P**), while the integrated system's **cumulated energy demand** is **~50 % lower** than a conventional stand-alone WWTP. Together, **product sales + avoided utilities + gate fees** provide the main economic and environmental leverage; scale-up and process optimization then compound these gains (see Figure 8).



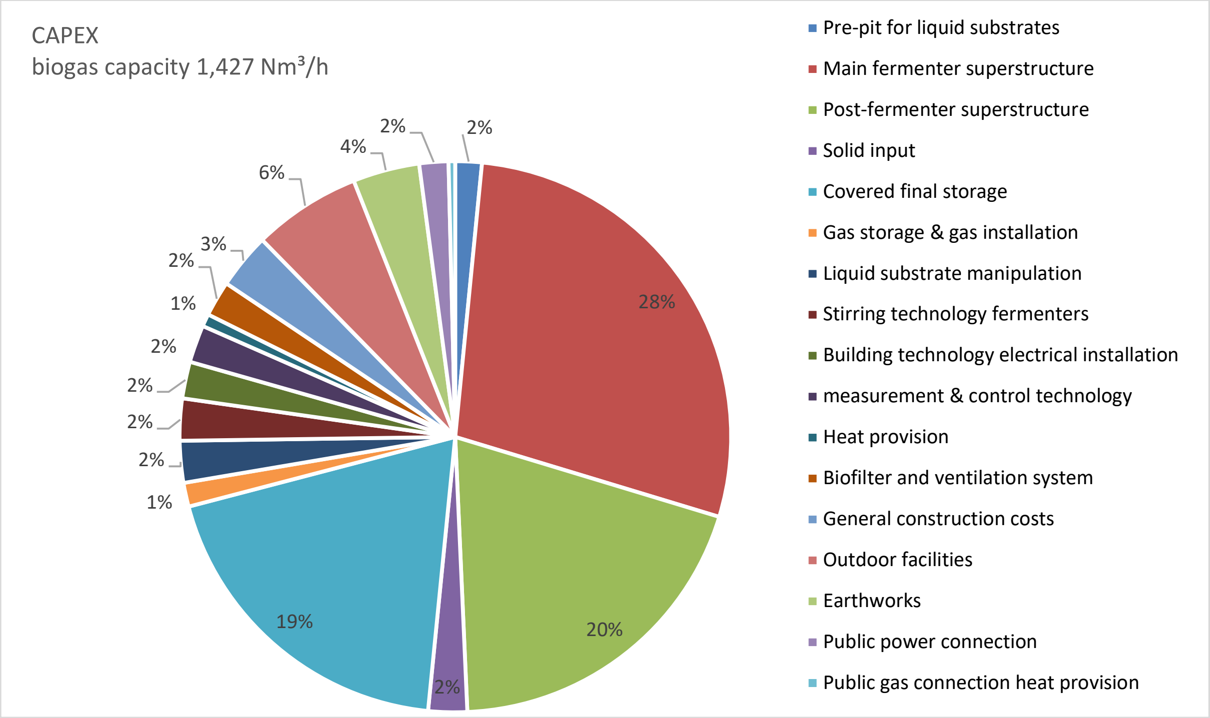


Figure 6 & 7: Share breakdown of costs for the biogas-based biorefinery case study. (see Table 3)[50,51,52]

To strengthen the economics, the main levers are **co-product valorization** and **industrial symbiosis.** In the EffiSludge setup, liquid digestate recycling displaces chemicals (**~100 % external N ≈ 750 kg N d^{-1}; ~50 % P ≈ 120 kg P d^{-1}**) and **halves aeration electricity** (≈ 39 → ~20 MWh d^{-1}). The **solid digestate (~55 t d^{-1})** is marketed as biofertilizer (**~€20/t**), and accepting regional residues (**~112 t d^{-1}**) yields **gate-fee revenues (~€10/t).** These sit atop the core **biomethane/LBG output of ~125 GWh a^{-1}**, which drives the bulk of revenues (**~€8.75 M a^{-1}**), alongside **OpEx ~€4.66 M a^{-1}** and capital charges on **~€25.4 M CapEx** (≈ €2.54 M a^{-1} straight-line; **~€3.3-3.5 M a^{-1}** incl. 5 % interest). Together, **product sales + avoided utilities + gate fees** provide the decisive margin.

Table 15: Simplified economic sensitivity — biogas-based biorefinery (illustrative) (Annual cash-margin change vs. base; positive is favorable. Base uses ~125 GWh a^{-1} biomethane and ~20 MWh d^{-1} auxiliary electricity import.)

Parameter	Unit	Base (updated)	Low scenario	High scenario	Δ Annual margin vs. Base (approx.)
Biomethane selling price	€/MWh	**70**	60	80	**± €1.25 M per ± €10/MWh** (125 GWh × Δprice)
Gate fee on incoming residues	€/t	**10**	0	30	Low: - €0.41 M (10⟶0); High: + €0.82 M (10⟶30)
Auxiliary electricity price	€/MWh	**100**	70	140	Low: + €0.22 M; High: - €0.22 M (± €30/MWh on ~7,300 MWh yr^{-1})
Solid biofertilizer price	€/t	**20**	10	40	Low: - €0.20 M; High: + €0.40 M (~20 kt yr^{-1})

Findings

Product-price sensitivity dominates: margins move most with the biomethane/LBG price (**base revenue ~€8.75 M yr^{-1}** from ~125 GWh yr^{-1}).

Symbiosis cuts operating exposure: inserting AD upstream **halves aeration electricity** (≈ 39 → ~20 MWh d^{-1}) and replaces **~100 % external N (~750 kg d^{-1}) and ~50 % P (~120 kg d^{-1})** via digestate recirculation—lowering utility/chemical costs.

Gate fees and fertilizer sales add resilience: ~112 t d^{-1} of regional residues yield **gate-fee income (~€10/t)**; **~55 t d^{-1}** solid digestate provides steady biofertilizer revenue (**~€20/t**).

Cost structure: with waste-based inputs, feedstock procurement is subordinate; **auxiliary energy and O&M dominate variable OPEX**; **fixed costs** reflect **~€25.4 M CapEx**; **OpEx ~€4.66 M yr^{-1}**.

Economic implications

Economic robustness hinges on **stable biomethane offtake** (grid injection/LBG contracts), **access to gate-fee-bearing residues**, and **industrial-symbiosis savings** (aeration power, nutrient substitution). At the documented scale and updated price basis (**€70/MWh, €10/t gate fees, €20/t fertilizer**)[53],[54] the plant achieves a **positive margin (~15.7 % with interest; ~24.7 % without)**; policy tools (renewable gas certificates, transport fuel credits) and **CO_2/by-product valorization** further de-risk the case.

Value-chain note. Bankability depends on paired agreements: (i) long-term gas offtake (grid or LBG), (ii) residue supply/gate-fee MoUs with local partners, and (iii) digestate markets or internal nutrient use at the mill—mirroring the interdependence observed in the case study's integrated mill-AD configuration.

Ecological implications

Figure 8 shows the cradle-to-gate indicators for the EffiSludge industrial symbiosis compared with a conventional, stand-alone WWTP reference. The integrated biogas route lowers greenhouse-gas (GHG) emissions from ~4,200 to ~1,900 t CO_2-eq per year (≈ 2,300 t CO_2-eq per year avoided; ~45% reduction) and halves the cumulated energy demand (CED) from ~52,560 to ~26,280 GJ per year. The main drivers are (i) captured biogenic methane, (ii) ~50% lower aeration electricity at the mill due to upstream AD, and (iii) nutrient recirculation that replaces external N/P dosing.

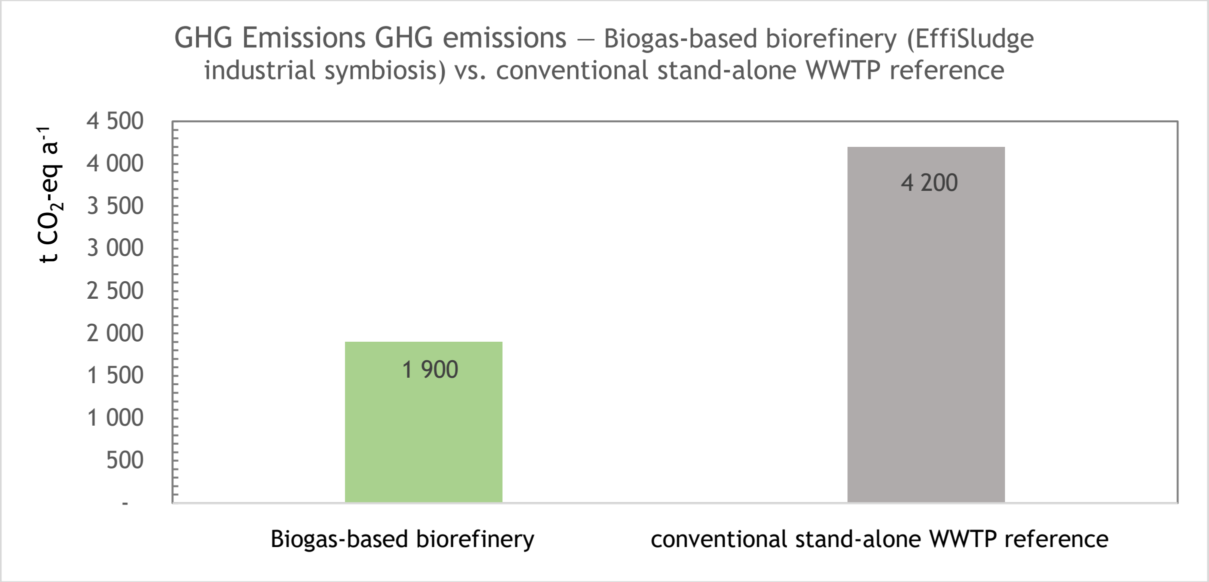


Figure 8: simplified comparison of annual GHG emissions — Biogas-based biorefinery (EffiSludge industrial symbiosis) vs. conventional stand-alone WWTP reference.

System boundary & method

- **Accounting scope:** *Cradle-to-gate* up to **plant gate** (substrate handling → AD/UASB → upgrading to biomethane → optional liquefaction to LBG → digestate separation/conditioning). **Distribution and end-use** are **excluded.**
- **Method:** simplified, **EU RED-aligned** GHG approach for biomethane; **CED** compiled using standard primary-energy accounting.
- **Reference case:** conventional WWTP treatment (aeration, **solid-liquid separation**, and typical **sludge treatment/disposal**) **without** AD integration.
- **Allocations/credits:**
    - **Included:** avoided **aeration power** (≈ 39 → ~20 $MWh \cdot d^{-1}$), **substituted N/P chemicals** via liquid-digestate recycle (≈100% N; ~50% P), operating energy for upgrading/liquefaction, **methane slip** in upgrading/handling, and internal utilities.
    - **Not included: downstream** effects (e.g., fossil fuel substitution in transport), product distribution/use beyond the plant gate, and **land-use change** (not relevant for waste-/residue-based feedstocks).

Table 16: Overview of GHG emissions and cumulated energy demand (cradle-to-gate). (EffiSludge industrial symbiosis vs. conventional stand-alone WWTP).

Indicator	EffiSludge (biogas-based)	Reference WWTP	Savings
GHG emissions	**1,900 t CO_2-eq yr^{-1}**	4,200 t CO_2-eq yr^{-1}	**2,300 t CO_2-eq yr^{-1} (≈45%)**
Cumulated energy demand (CED)	**26,280 GJ yr^{-1}**	52,560 GJ yr^{-1}	**26,280 GJ yr^{-1} (≈50%)**

Source: literature-based case study and TEE fact-sheet calculations for the EffiSludge industrial symbiosis.

Data basis & key assumptions

- **Scale:** industrial reference with **~125 GWh per year** biomethane and **~55 $t\cdot d^{-1}$** solid digestate; integrated-plant **aeration demand** ~**20 $MWh\cdot d^{-1}$** (vs. ~**39 $MWh\cdot d^{-1}$** in the reference).
- **Feedstocks:** pulp and paper **biosludge** plus regional fish/agri residues; **internal nutrient recycling** of ~**750 kg $N\cdot d^{-1}$** and ~**120 kg $P\cdot d^{-1}$**.
- **Emission factors:** drawn from **peer-reviewed/literature** sources (case-study base year), with site-typical power mix and standard factors for chemicals/transport; RED defaults or reviewed values where appropriate.
- **Uncertainty:** ±**15-25%** is typical for GHG/CED at this resolution due to site- and operation-specific variability. **Sensitivity** is highest to power-mix carbon intensity, **methane slip**, realized **aeration reduction**, energy use for upgrading/LBG, and **digestate management** practices.

Interpretation
The ~**45% GHG reduction** and ~**50% lower CED** primarily reflect **process integration** (placing AD before parts of the aerobic step) and **nutrient circularity**. EffiSludge shifts WWTP burdens away from electricity- and chemical-intensive operations toward **renewable gas** and **recoverable nutrient products**. The direction of change is robust across sites, while exact magnitudes remain **site-specific** (substrate mix, scale, power mix).

Table 17: Overview of TEE assessment results (biogas-based biorefinery).

Category	Result
Greenhouse gas emissions (plant)	**1,900 t CO_2-eq yr^{-1}** (reference WWTP: 4,200 t CO_2-eq yr^{-1}; savings 2,300 t CO_2-eq yr^{-1} ≈45%)
Cumulated energy demand (CED)	**26,280 GJ yr^{-1}** (reference 52,560 GJ yr^{-1}; ≈50% lower)
Annual costs (OPEX)	**€ 4,661,159 yr^{-1}**
Specific costs	**€0.52/kg biomethane (OPEX only); ≈€0.90/kg including finance costs (OPEX + depreciation/interest)**
Investment (CAPEX)	**€ 25,444,093**
Revenues (biomethane)	**€8,750,000/yr (125 GWh × €70/MWh)**
Specific revenues	**≈€0.97/kg biomethane (LHV basis); ≈€1.08/kg (HHV basis)**
Main products	**Biomethane/LBG ~342 MWh d^{-1} (~125 GWh yr^{-1});** **solid digestate ~55 t d^{-1}** (biofertilizer); liquid digestate recycled as N/P source
Utility/Nutrient synergies	Aeration electricity ≈**39 → ~20 MWh d^{-1}** (≈50% cut); external dosing **replaced by ~750 kg N d^{-1} (100%) and ~120 kg P d^{-1} (~50%)**

Source: literature-based case study and TEE fact-sheet calculations for the EffiSludge industrial symbiosis.

5. Conclusions & strategic outlook

This case study shows that an **industrial-symbiosis, biogas-based biorefinery** (EffiSludge type) is **technically mature (TRL 9)**, **environmentally advantageous**, and **economically viable under conservative, literature-based assumptions** when paired with stable offtake and site synergies.

Key Conclusions

- **Technical performance.** Co-digesting paper-mill biosludge with regional fish/agri residues in CSTR + UASB lines reliably yields ~342 MWh d^{-1} (~125 GWh y^{-1}) of biomethane; upgrading and liquefaction (to LBG) are standard operations at industrial scale. Digestate valorization (solid ~55 t d^{-1} as biofertilizer; liquid for nutrient recycle) underpins process robustness.
- **System integration benefits.** Inserting AD upstream of parts of the WWTP halves aeration electricity (~39→~20 MWh d^{-1}) and replaces ~100% external N (~750 kg d^{-1}) and ~50% external P (~120 kg d^{-1}) via digestate recirculation—directly lowering operating needs.
- **Environmental impact.** Within a cradle-to-gate scope (EU RED method), the integrated route reduces GHG emissions from ~4,200 to ~1,900 t CO_2-eq y^{-1} (≈2,300 t CO_2-eq y^{-1} avoided; ~45%) and halves the cumulated energy demand versus a stand-alone WWTP.
- **Economic viability.** With **CAPEX ≈ €25.4 M** and **OPEX ≈ €4.66 M/yr**, the plant's income at **€70/MWh** totals **~€9.56 M/yr** (≈ **€8.75 M** biomethane + **€0.41 M** gate fees + **€0.40 M** fertilizer). After capital charges (**~€3.3-3.5 M/yr** incl. 5% interest), the project delivers an **EBIT margin ~16%**—comfortably above 10%—with WWTP synergies (lower aeration, nutrient recirculation) further stabilizing costs.

Strategic Outlook

- **Bankable offtake + feedstock certainty.** Long-term gas offtake (grid injection/LBG for transport) and residue supply & gate-fee agreements with local partners are pivotal; aligning these contracts with the plant's nutrient-recycling scheme secures cash flow and operations.
- **Policy alignment.** RED-compliant biomethane, renewable gas certificates, transport fuel credits, and targeted industrial-symbiosis incentives (for energy-efficient wastewater treatment and nutrient recovery) can de-risk projects and accelerate replication.
- **Scaling & replication.** The configuration is modular and replicable where mills or similar anchor industries provide steady wet residues and have nutrient/utility needs. Broader roll-out should prioritize sites with high aeration loads and regional residue availability.
- **Innovation pathways.** Near-term options include biogenic CO_2 utilization (from upgrading/liquefaction), fertilizer product refinement (e.g., tailored N/P/K concentrates), and flexible dispatch between LBG, grid injection, and optional CHP depending on market signals.
- **Comparative edge.** Versus treating wastewater conventionally, the EffiSludge pathway converts liabilities into assets: renewable gas, fertilizer, lower plant energy, and lower GHGs—a compelling decarbonization lever for industry where electrification alone is insufficient.
- **Final remark.** By coupling **wastewater treatment, residue management, and renewable gas production** in one loop, biogas-based biorefineries operationalize the **circular bioeconomy** at industrial scale—delivering measurable climate benefits and resilient energy services while closing local nutrient cycles.

MORE DETAILED INFORMATION ON THE DATA BASIS AND THE METHOD APPLIED ARE AVAILABLE IN THE ACCOMPANYING REPORTS AT HTTPS://TASK42.IEABIOENERGY.COM/DOCUMENT-CATEGORY/REPORTS-PAPERS/

This case study was prepared by Johannes Lindorfer and colleagues from the Energieinstitut at the Johannes Kepler University Linz, Austria. Whilst the information in this publication is derived from reliable sources, and reasonable care has been taken in its compilation, IEA Bioenergy, its Task42 Biorefinery and the authors of the publication cannot make any representation of warranty, expressed or implied, regarding the verity, accuracy, adequacy, or completeness of the information contained herein. IEA Bioenergy, its Task42 Biorefinery and the authors do not accept any liability towards the readers and users of the publication for any inaccuracy, error, or omission, regardless of the cause, or any damages resulting therefrom. In no event shall IEA Bioenergy, its Task42 Biorefinery of the authors have any liability for loss of profits and/or indirect, special, punitive, or consequential damages.

Appendix: Data basis and calculations used in the TEE fact sheet

This appendix summarizes the key **assumptions, data, and calculation steps** underpinning the EffiSludge-style **biogas-based biorefinery** case study.

Nominal scale & operating hours. Industrial-scale plant co-located with a pulp & paper mill WWTP; continuous operation assumed (24/7). Feedstock handling capacity ~**20,000 t d^{-1}** mill wastewater plus **~112 t d^{-1}** regional fish/agri residues.

Process configuration. Two AD lines in parallel: **CSTR** for high-solids residues (dominant methane share) and **UASB** for wastewater; followed by **biogas upgrading** to biomethane and **liquefaction** to LBG at ~**-160 °C** (≈1/600 volume).

Biomethane output. Total energy output **~342 MWh d^{-1} ≈ 125 GWh a^{-1}** (representative best-practice scale, 2019). Contribution split: **~288 MWh d^{-1}** from CSTR co-digestion; **~55 MWh d^{-1}** (biogas-eq.) from UASB.

Digestate management & products. Solid digestate **~55 t d^{-1}** marketed as **biofertilizer**; liquid fraction partially evaporated (concentrate) and partially **recycled** to the WWTP as N/P source.

Utility/nutrient symbiosis (embedded in balance). AD placed upstream of part of the aerobic step **halves aeration electricity** (approx. **39** → **~20 MWh d^{-1}**). **External nutrients substituted** by digestate liquor: **~100 % of N (~750 kg N d^{-1})** and **~50 % of P (~120 kg P d^{-1})**. An **auxiliary electricity import** ~**20 MWh d^{-1}** is shown as secondary input.

Mass/energy accounting. Fact-sheet balances compiled in a transparent spreadsheet using published, site-specific and generic data; all flows normalized to common units (kg, MWh, d).

Environmental method & scope. Cradle-to-gate indicators (production up to plant gate; distribution/use excluded) calculated per **EU RED** simplified GHG approach; additional **Cumulated Energy Demand (CED)** compiled for the integrated system versus a conventional stand-alone WWTP reference.

Environmental results used. GHG: EffiSludge ~**1,900 t CO_2-eq a^{-1}** vs. reference ~**4,200 t CO_2-eq a^{-1}** ⇒ ~**2,300 t CO_2-eq a^{-1}** avoided (~**45** %). **CED:** EffiSludge ~**26,280 GJ a^{-1}** vs. reference ~**52,560 GJ a^{-1}** (≈**50** % lower).

Economic basis (illustrative, literature case). CAPEX ~€25.44 M, **OPEX ~€4.66 M a^{-1}**; **biomethane revenues ~€12.84 M a^{-1}** (biomethane green premium energy price basis ~€0.62/kg diesel-equivalent energy). Cost structure shows **variable costs > fixed OPEX** due to auxiliary energy;

feedstock costs subordinate because residues are processed (gate-fee potential).

Classification & framework. Structured per **IEA Bioenergy Task 42** fact-sheet methodology and **VDI 6310** concepts; indicators cover **Technical** (throughputs, yields, utilities), **Economic** (CAPEX/OPEX, specific costs/revenues), and **Environmental** (GHG, CED).

Caveats. Values represent a **2019 snapshot** of a real-world concept; plants are **site-specific** and require **case-by-case recalculation** for transferability.

Abbreviations: AD – Anaerobic Digestion; CSTR – Continuous Stirred-Tank Reactor; UASB – Up-flow Anaerobic Sludge Blanket; LBG – Liquefied Biogas (liquefied biomethane); WWTP – Wastewater Treatment Plant; CED – Cumulated Energy Demand.

Appendix C

3-PLATFORM BIOREFINERY (C5/C6 SUGARS, LIGNIN-ENERGY, VINASSE-BIOFERTILIZER) USING LIGNOCELLULOSIC BIOMASS STRAW FOR ADVANCED BIOFUEL PRODUCTION

This case study presents a comprehensive Technical, Economic, and Environmental (TEE) assessment of a lignocellulosic ethanol biorefinery that converts agricultural residues—primarily cereal straw—into second-generation (2G) bioethanol, process steam, and electricity. Biotechnological conversion of lignocellulose represents a key pathway for sustainable biofuel production and is increasingly viewed as central to circular economy strategies and net-zero emission targets.

The assessment is based on a commercial-scale biorefinery in Europe; however, it should be noted that the data are derived from literature and technology provider inputs and may not fully reflect actual operating conditions. The facility processes approximately 270,000 tonnes of straw annually, yielding around 50,000 tonnes of advanced ethanol. The plant operates with an integrated lignin-based combined heat and power (CHP) unit, supplying approximately 0.71 MJ steam and 0.15 MJ electricity per MJ ethanol, with an additional 0.13 MJ electricity sourced externally. Lignin, a major by-product of pretreatment and hydrolysis, is fully utilized on-site for process energy, enhancing overall system efficiency. Vinasse, another co-product (~1.54 t per t ethanol), is recycled as agricultural fertilizer or tested for energy applications such as co-firing or anaerobic digestion.

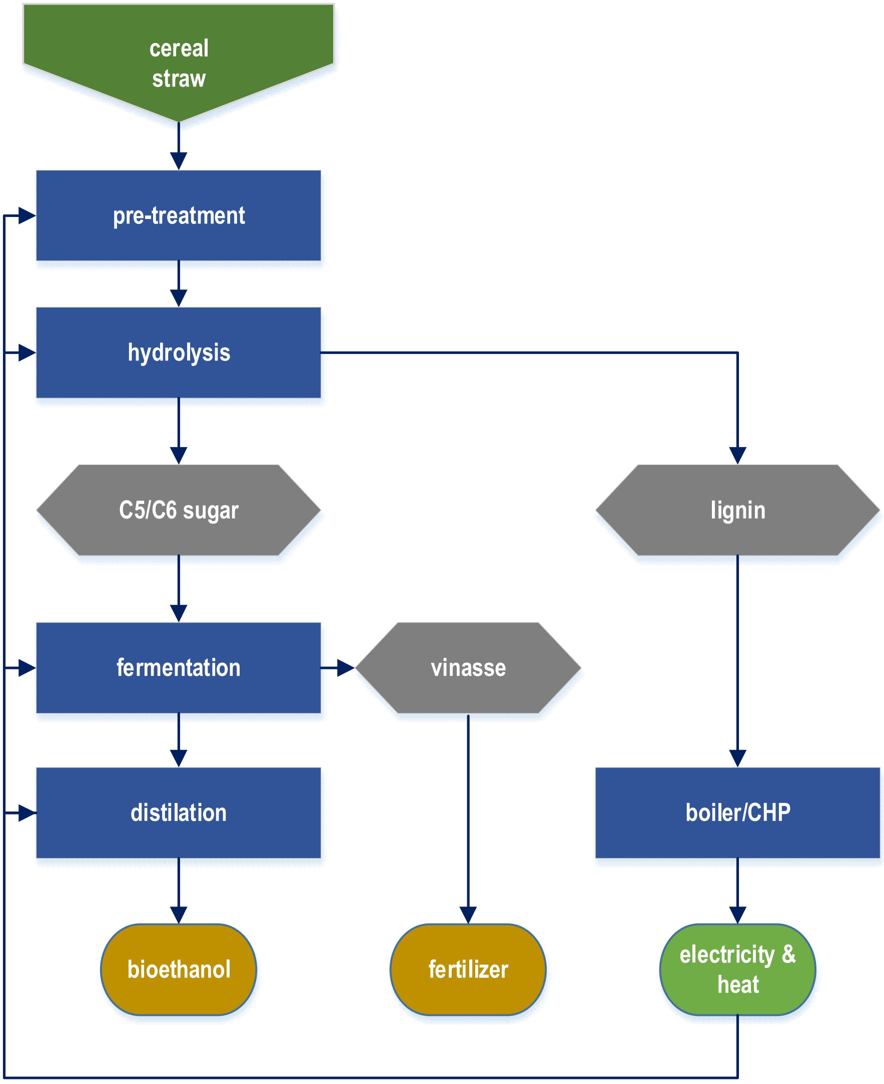


Figure 17: Basic flow chart of the advanced biofuel plant case study.

Economic analysis indicates annual revenues of approximately €48.7 million, including €46.2 million from ethanol sales (at €0.73/L) and €2.5 million from vinasse valorization, against total operating costs of roughly €48 million, resulting in a projected annual profit of €0.7 million. Capital expenditures, feedstock logistics, and chemicals inputs constitute the major cost shares, while internal energy generation reduces exposure to external energy prices. More favorable scenarios, such as optimized co-product valorization or policy support mechanisms, could further improve profitability.

Importantly, life cycle analysis (LCA) conducted under EU RED II and ISO 14040/44 frameworks indicates GHG emission reductions of up to 92% compared to fossil gasoline, particularly under scenarios using 100% renewable electricity. The biorefinery thus meets stringent sustainability criteria and demonstrates strong climate performance.

Demand for drop-in biofuels, sustainable aviation fuels, and renewable ethanol for chemical industries continues to grow. Integration of lignocellulosic ethanol into existing fuel and petrochemical infrastructures is emerging as a scalable and policy-aligned solution for industrial decarbonization.

This study highlights lignocellulosic ethanol as a technically mature, economically viable, and environmentally superior route for bioenergy valorization. While investment requirements and supply chain coordination remain challenges, the concept shows considerable promise, especially when embedded within regional circular value chains and supported by enabling policy frameworks.

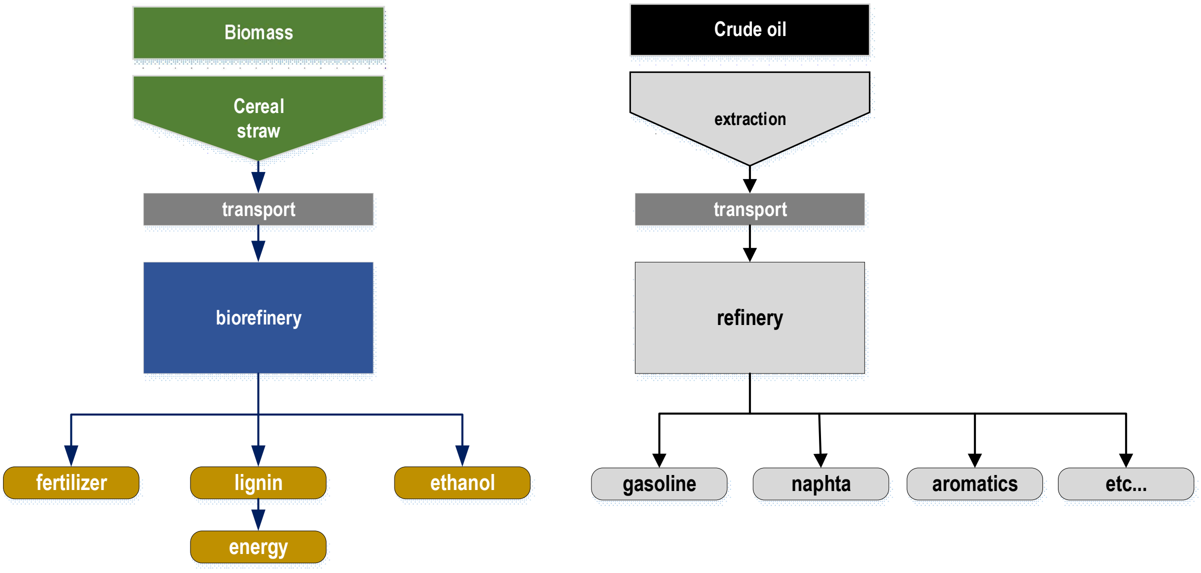


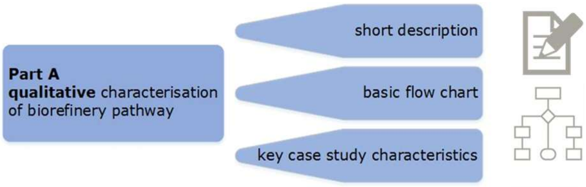
Figure 18: Comparison of biorefinery and petroleum refinery pathways for fuel and chemical production.

The figure illustrates the conceptual symmetry between **biorefineries** and **petroleum refineries** — both convert complex raw materials into fuels and chemical products.
However:

- **Biorefineries** rely on renewable, biological resources and yield **bio-based fuels** (e.g., ethanol).
- **Petroleum refineries** depend on **non-renewable fossil feedstocks** and produce **fossil-based fuels**.

This comparison highlights the transition toward sustainable fuel production and how biorefineries can complement or eventually substitute traditional refineries.

1. Introduction



Global energy systems are undergoing a fundamental shift driven by climate imperatives and the need to replace finite fossil resources with renewable alternatives. In this transition, biorefineries—industrial facilities that convert biomass into fuels, energy, and value-added co-products—are emerging as strategic assets for building a resilient, low-carbon bioeconomy. Among various biorefinery pathways, the enzymatic-thermochemical conversion of lignocellulosic residues into ethanol and renewable process energy offers particular promise for addressing hard-to-abate emissions while advancing circularity in agriculture and industry.

The 3-platform lignocellulosic ethanol biorefinery assessed in this case study exemplifies this approach. It utilizes underused cereal straw as feedstock and integrates three value streams: advanced bioethanol, on-site renewable energy from lignin combustion, and vinasse valorization. In this system, straw is pretreated and hydrolyzed enzymatically to release fermentable sugars, which are converted into ethanol via tailored microbial fermentation. The insoluble lignin fraction is combusted in a combined heat and power (CHP) unit to meet the plant's internal thermal and partial electrical demands. The remaining liquid residue, vinasse, is recovered as a nutrient-rich co-product and applied in agriculture or explored for energy uses such as anaerobic digestion or co-firing.

Unlike conventional biorefineries focused on single outputs, this lignocellulosic pathway demonstrates efficient polygeneration: it produces an advanced drop-in biofuel, reduces dependence on external energy inputs, and recycles co-products within regional nutrient and energy loops. With an annual input of approximately 270,000 tonnes of straw, the plant yields around 50,000 tonnes of ethanol, while internally generating up to 0.71 MJ of process steam and 0.15 MJ of electricity per MJ ethanol through lignin combustion. Vinasse is produced at about 1.54 tonnes per tonne of ethanol and reused on local fields to support regenerative farming.

Although many lignocellulosic biorefinery technologies have historically faced scalability and economic challenges, this case study demonstrates commercial-scale feasibility under real-world conditions. Annual revenues of ~€48.7 million (including ~€2.5 million from vinasse utilization) and operating costs of ~€48 million result in a projected annual profit of ~€0.7 million. Life cycle assessment (LCA), conducted under EU RED II and ISO 14040/44 frameworks, shows up to 92% GHG emission reductions compared to fossil gasoline—highlighting the pathway's alignment with net-zero goals.

This case contributes to:
- Demonstrating real-world performance of lignocellulosic ethanol systems at commercial scale;
- Identifying opportunities for energy integration and circular co-product utilization;
- Supporting transparent benchmarking under IEA Bioenergy Task 42 and VDI 6310 classification systems.

With growing demand for advanced biofuels in the transport, chemical, and industrial sectors—especially where electrification is impractical—the deployment of regionally embedded lignocellulosic ethanol biorefineries provides a viable and climate-aligned solution. The integration of feedstock flexibility, energy autonomy, and by-product valorization reinforces their role as enablers of sustainable, local bioeconomy value chains.

2. Method of assessment for fast pyrolysis biorefinery case study

2.1. CURRENT STATUS AND DEVELOPMENT TRENDS OF BIOREFINERIES

Modern biorefineries are evolving to convert a wide range of biomass feedstocks—including agricultural residues, woody biomass, and organic waste—into fuels, energy, and biobased products. Among the pathways under industrial implementation, lignocellulosic ethanol production stands out for its ability to valorize non-food crop residues and its alignment with EU policy objectives for advanced biofuels. Compared to thermochemical concepts such as pyrolysis or gasification, lignocellulosic ethanol offers distinct advantages through biological conversion processes, energy self-sufficiency via lignin-based combined heat and power (CHP), and co-product valorization within circular nutrient cycles.

To contextualize the performance of the lignocellulosic ethanol platform, the following table provides a comparative snapshot alongside two other prominent biomass conversion technologies. While these differ in conversion mechanism and final outputs, the comparison helps highlight relative strengths and trade-offs in energy efficiency, carbon intensity, and resource integration.

Table 18: Comparative overview of selected biorefinery pathways for advanced biofuels [55,56,57,58]

Metric	Lignocellulosic Ethanol	Fast Pyrolysis	Gasification-to-Fuels
TRL	8-9	6-9	5-6
Feedstock Type	Agro residues (straw)	Woody residues	Woody/agro biomass
Main Liquid Product	Ethanol (EtOH)	FPBO (bio-oil)	Syngas-derived fuels
Product Energy Yield	~65-75 %	~60-70 %	~45-55 %
Polygeneration Capability	Yes	Yes	Yes
Energy Efficiency (total)	~80-85 %	~85 %	~55-65 %
GHG Reduction (vs fossil)	~85-92 %	~96 %	~80-90 %
Drying Requirement	Moderate (20-30% DM)	Low (5-10% moisture)	Moderate
CAPEX (€/t EtOH or MWth)	~5,000-6,000 €/t EtOH	~750-1,200 k €/MWth	~2,000 k €/MWth
Product Upgrade Requirement	No (drop-in fuel)	Yes (stabilization)	Yes (Fischer-Tropsch)

Insights:
Lignocellulosic ethanol excels in circular co-product use (e.g. lignin-to-energy and vinasse-to-soil), high GHG savings, and compatibility with existing transport fuel infrastructure. Unlike thermochemical platforms, it requires less downstream upgrading. However, challenges remain in enzyme cost, logistics for bulk residues, and capital expenditure. Still, several commercial-scale facilities are validating its readiness across Europe and globally. These systems are especially well-suited for rural deployment where cereal straw is abundant and decentralized value creation is politically and economically desirable.

2.2. KEY CHALLENGES IN ASSESSMENT

The assessment of integrated biorefinery systems faces several systemic and methodological hurdles:

- Limited public availability of high-quality operational data, particularly for commercial-scale biological conversion processes;

- Methodological inconsistencies in GHG accounting and life cycle assessment (LCA);
- Differing assumptions on allocation and system boundaries, which hinder comparability.

This study addresses these issues using standardized guidelines:

- **ISO 14040/44** for LCA framework and energy/environmental indicators[59]
- EU **Renewable Energy Directive (RED II/III)** for biofuel GHG criteria and sustainability thresholds[60]
- **VDI 6310** for biorefinery classification and economic evaluation standards[61]

2.3. CLASSIFICATION SYSTEM USED

To ensure comparability and modular adaptability, the lignocellulosic ethanol biorefinery is classified according to the IEA Bioenergy Task 42 four-axis framework:

1. **Feedstock:** lignocellulosic residues (e.g. cereal straw);
2. **Platform:** sugar fermentation platform (C5/C6 conversion);
3. **Products:** advanced bioethanol, renewable electricity and heat, vinasse-based soil enhancers or energy carriers;
4. **Processes:** enzymatic hydrolysis, fermentation, CHP combustion.

This classification system supports pathway transparency and enables alignment with future scaling or technological evolution (e.g., SAF production or lignin valorization into materials).

2.4. THE TEE ASSESSMENT FRAMEWORK

The Technical, Economic, and Environmental (TEE) framework applied here builds on established methods developed within IEA Bioenergy and prior research (e.g. Lindorfer et al., 2019).[62] It encompasses:

- **Technical Indicators:**
  Feedstock-to-fuel yield (mass and energy basis), internal energy integration via CHP, polygeneration of fuels and co-products;
- **Economic Indicators:**
  At 50 kt/a capacity the project requires ~€240 million CAPEX; annual operating expenses (ex-CAPEX) are ~€24 million (feedstock €11.5 M, enzymes/chemicals €7.5 M, labour €3.0 M, energy/other €2.0 M); with a capital charge of ~€24 million/y, total costs are ~€48.0 million/y versus ~€48.7 million/y in revenues (incl. ~€2.5 M from vinasse), yielding a net margin of ~€0.7 million/y at €0.73/L ethanol and €42/t - the results are **highly sensitive** to these assumptions
- **Environmental Indicators:**
  Life-cycle GHG performance (up to 92% reduction vs fossil gasoline under RED II), primary energy demand per MJ ethanol, and circularity of nutrient and energy flows.

All data are consolidated into a transparent, spreadsheet-based model incorporating site-specific inputs (e.g. straw logistics, energy sourcing), literature-based defaults, and public LCA databases, enabling reproducibility and scenario analysis.

3. CASE STUDY ANALYSIS – PART A: BIOREFINERY PLANT

3.1. OVERVIEW AND SYSTEM BOUNDARY

This case study focuses on a commercial-scale lignocellulosic ethanol biorefinery located in Europe, which converts agricultural residues—primarily cereal straw—into advanced bioethanol, process steam, and electricity. The assessment applies a cradle-to-gate system boundary, encompassing all process stages from feedstock supply through to the delivery of bioethanol and co-products.

Table 19: Key technical characteristics of the lignocellulosic ethanol biorefinery case study.

Key Parameter	Characteristic
Raw Material	Lignocellulosic biomass (e.g., cereal straw)
Process	Pretreatment, enzymatic hydrolysis, fermentation, CHP
Main Products	Bioethanol, process steam, electricity, vinasse
Capacity	~270,000 tonnes of straw/year
Ethanol Output	~50,000 tonnes/year (~63 million liters/year)
Energy Efficiency (total)	~80-85 % (via internal lignin CHP)[63]
TRL Level	8-9
Geographic Location	Europe

3.2. PROCESS DESCRIPTION

The biorefinery process is designed to convert lignocellulosic agricultural residues—such as cereal straw—into second-generation ethanol and process energy. The plant accepts non-edible, low-moisture biomass and processes it through a series of thermochemical and biochemical stages. First, the biomass is mechanically pretreated and subjected to steam-based fractionation to separate the fiber matrix. Enzymatic hydrolysis then converts cellulose and hemicellulose into fermentable sugars (C5 and C6), followed by microbial fermentation to produce ethanol.

The solid lignin-rich residue remaining after hydrolysis and fermentation is combusted in a combined heat and power (CHP) unit. This internal energy recovery system provides the thermal energy required for pretreatment and distillation, and supplies a portion of the plant's electricity demand. Surplus heat and electricity may be made available for export depending on process configuration and energy balance.

Another significant output is vinasse—a liquid fermentation residue—produced at a rate of approximately 1.54 tonnes per tonne of ethanol. It is either recycled to local farmland as a nutrient-rich soil conditioner or considered for energy recovery (e.g., co-firing or anaerobic digestion), supporting regional circularity goals.

The biorefinery qualifies as a polygeneration unit, delivering three primary outputs: ethanol, process steam, and electricity. While thermal and electrical energy are largely used internally, the option for external supply enhances the overall energy efficiency and integration potential. The ethanol product is delivered off-site for blending into transport fuels, where it displaces fossil gasoline and contributes to RED II/III renewable energy targets.

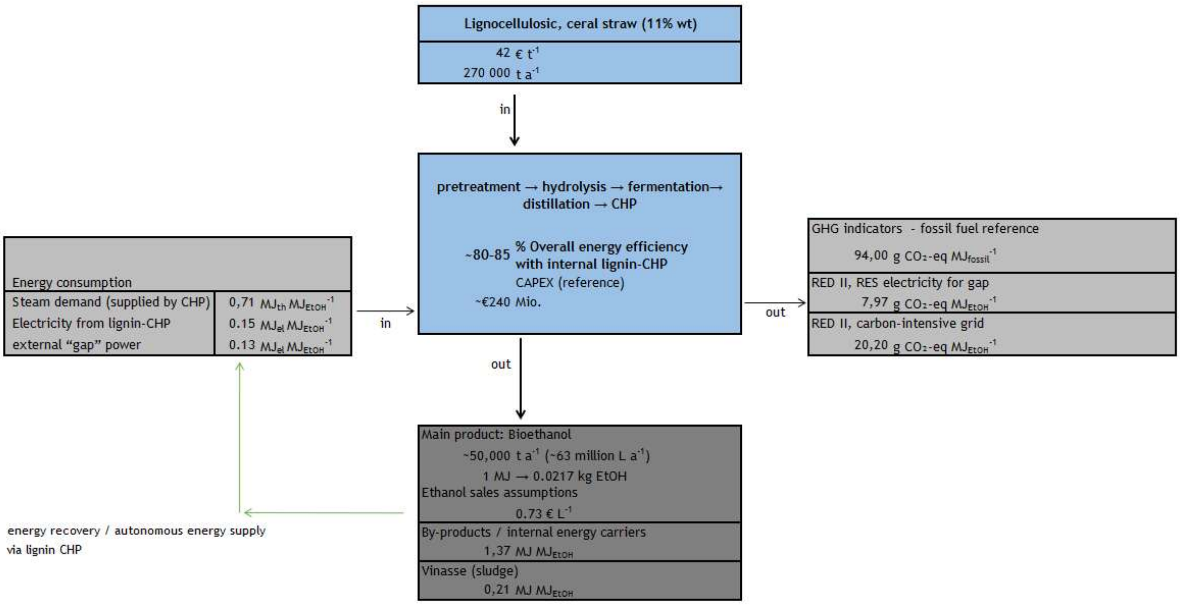


Figure 19: Overview of TEE assessment - Process pathway for lignocellulosic ethanol production from agricultural residues. Based on own calculations with data from literature referenced at table 1 and supplementary sources[64]

The process begins with the collection and mechanical conditioning of lignocellulosic biomass, such as cereal straw. After initial size reduction, the biomass undergoes steam-based pretreatment to break down the complex fiber matrix and enhance enzyme accessibility. Following this, enzymatic hydrolysis converts cellulose and hemicellulose into fermentable sugars. These are fermented to ethanol using specialized microbial strains. The solid lignin-rich residue is combusted in an on-site combined heat and power (CHP) system to generate process energy. The liquid residue (vinasse) is collected for agricultural or energetic reuse.

The core process steps include:

- **Pretreatment:** Steam explosion or liquid hot water treatment to deconstruct biomass structure
- **Enzymatic Hydrolysis:** Enzymatic breakdown of polysaccharides into monomeric sugars (C5 and C6)
- **Fermentation:** Bioconversion of sugars to ethanol
- **Distillation:** Separation and purification of ethanol
- **CHP Combustion:** Lignin burned in CHP to supply steam and electricity
- **Vinasse Recovery:** Liquid fermentation residue reused in agriculture or valorized for energy

System Design Benefits:

- Integrated co-generation of process steam and electricity from lignin
- Internal energy self-sufficiency with optional export potential
- Circular use of co-products (e.g., vinasse to soil, lignin to energy)

3.3. MASS AND ENERGY BALANCE

At full capacity, the biorefinery processes approximately **270,000 tonnes of straw per year**, equivalent to **~30.8 tonnes/hour (wet basis) at 8,760 h/a**. From this, it produces around **50,000 tonnes/year of bioethanol**, accompanied by internally generated **process steam and electricity** from lignin combustion. Vinasse is generated as a major liquid co-product.

Annual Outputs:

- **Bioethanol:** ~63 million liters/year (~50,000 tonnes/year), energy content ~1,350 TJ/year (LHV(EtOH)=27 MJ/kg
- **Process Steam:** ~959 TJ/year (mainly from lignin CHP)
- **Electricity:** ~203 TJ/year (partial internal use, partial grid supply)
- **Vinasse:** ~77,000 tonnes/year (~1.54 t per t ethanol)

By-Products:

- **Lignin (input to CHP):** ~70,000 t/year (dry basis)
- **Ash:** Minor, removed from combustion residue
- **Water:** Released primarily as vapor during distillation and combustion (no separate wastewater stream)

Table 3 summarizes the key characteristics of the considered case study.

Annual Outputs:

- **Bioethanol:** ~63 million liters/year (~50,000 tonnes/year), energy content ~1,700 TJ/year
- **Process Steam:** ~1,200 TJ/year (mainly from lignin CHP)
- **Electricity:** ~180 TJ/year (partial internal use, partial grid supply)
- **Vinasse:** ~77,000 tonnes/year (~1.54 t per t ethanol; 10 wt% solids)

By-Products:

- **Lignin (input to CHP):** ~70,000 tonnes/year (dry basis)
- **Water:** Released primarily as vapor during distillation, combustion and wastewater stream
- **Ash:** Minor, removed from combustion residue

Table 20: Key characteristics case study.

3-platform biorefinery (C5/C6 sugars, lignin-energy, vinasse-biofertilizer) using lignocellulosic biomass straw for advanced biofuel production							
State of technology		Industrial (TRL 9)					
Country		Europe					
Main data source		Literature (sources referenced in table 1 & [65],[66]					
Products				**Auxiliaries**			
	Bioethanol	1,350	TJ a^{-1}		the residual	~176	TJ a^{-1}
		50	kt a^{-1}		electricity is		
	CHP supplies				imported (RES best		
	Steam	~959	TJ a^{-1}		case or national		
	Electricity	~203	TJ a^{-1}		grid)		
Costs				**Feedstock**			
	Investment Dep.	24	Mio. € a^{-1}		Cereal straw	270	kt a^{-1}
	Feedstock	11.5	Mio. € a^{-1}				
	Auxiliaries	7.5	Mio. € a^{-1}	**Conversion rates (Efficiencies)**			
	Labour	3.0	Mio. € a^{-1}		Feedstock to EtOH	18.5	wt%
	energy/other	2.0			Overall Energy efficiency through CHP	80-85	%

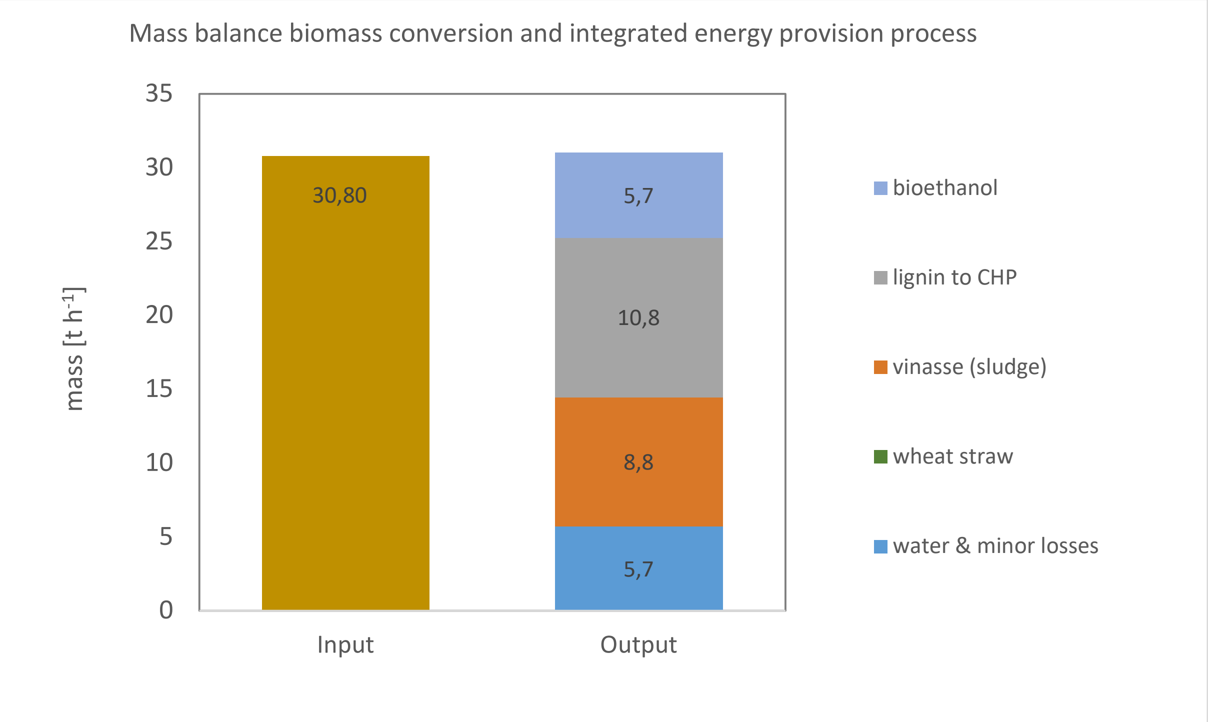


Figure 20: Simplified balance of mass of input and output stream (Mass flows are shown for ***full year*** *operation).*

PART B: VALUE CHAIN ASSESSMENT

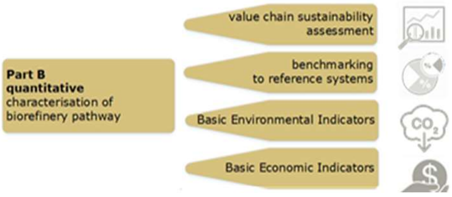


Figure 5 illustrates the annual revenue and cost structure of the lignocellulosic ethanol biorefinery. Revenues are primarily derived from the sale of advanced ethanol (~€46.2 Mio/a), complemented by additional income from vinasse valorization (~€2.5 Mio/a). On the cost side, the largest shares stem from capital charges, enzymes/chemicals, and feedstock procurement; total annual operating costs are ~€48.0 Mio/a. Internal process energy from lignin-CHP reduces exposure to external energy prices. Overall, the figure highlights a positive operating margin of ~€0.7 Mio/a, underscoring the importance of co-product valorization (vinasse to agriculture/energy) and energy integration for economic viability.

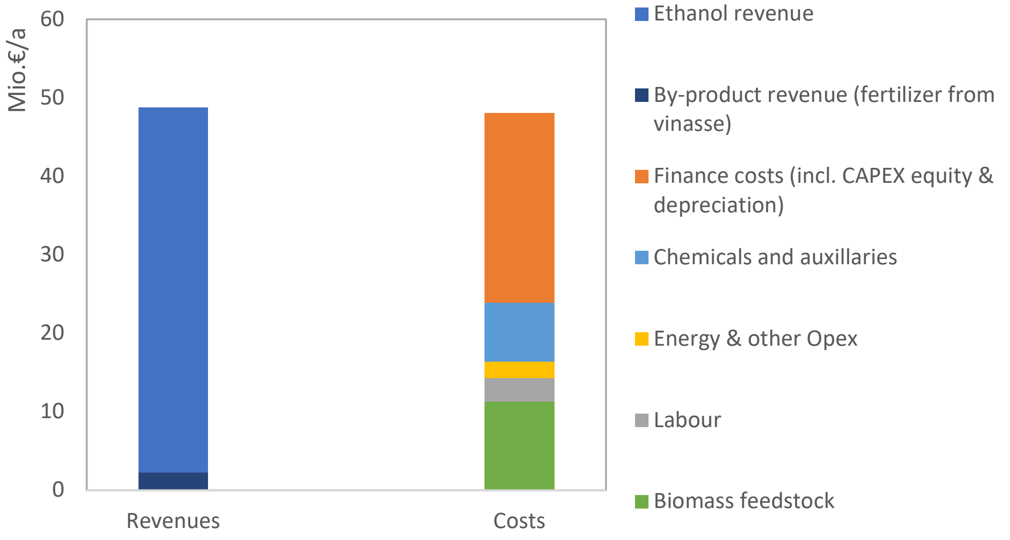


Figure 21: Costs and revenues — lignocellulosic ethanol biorefinery (case study).
Revenue ≈ €48.7 M/a; Costs ≈ €48.0 M/a; Operating margin ≈ €0.7 M/a.

Chum et al. (2011)[67] and Giwa et al. (2022)[68] emphasize that regional variability in feedstock supply chains strongly affects techno-economics; the same applies here: delivered straw costs and logistics can materially shift levelized ethanol costs. In this case study, self-sufficient process energy from lignin (CHP) provides both environmental and economic benefits, while scale, learning (enzymatic packages), and competition can further drive down supply-chain costs. The cost allocation used here reflects high CAPEX share (~50%), feedstock (~24%), chemicals and auxiliaries (~16%), consistent with cellulosic ethanol literature and the study's assumptions. (see figure 6).

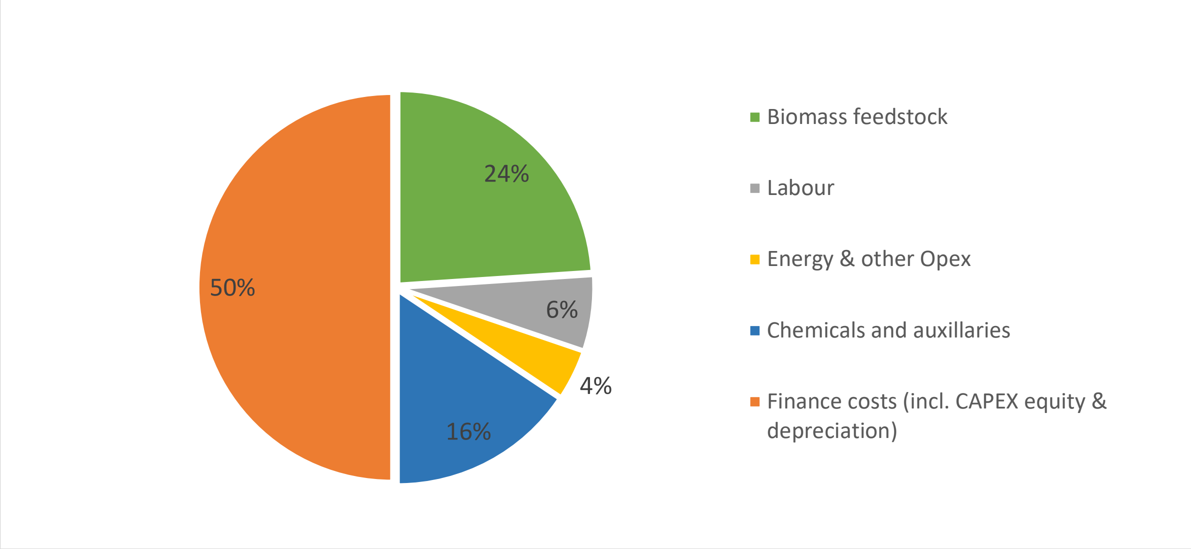


Figure 22: Share breakdown of costs (illustrative, linked to Table 3). Cost drivers: CAPEX (depreciation/finance), chemicals and auxiliaries (, feedstock; other fixed/variable items minor.

Economic sensitivity and key drivers.

At an ethanol selling price of **0.73 €/L** and a delivered straw cost of **€42 /t**, the lignocellulosic ethanol plant achieves an **annual margin of approximately €0.70 million**. Profitability is highly sensitive to both the ethanol market price and feedstock cost: each **€0.01/L** change in ethanol price alters the margin by about **€0.63 million per year**, and each **€10/t** variation in straw cost changes the margin by roughly **€2.7 million per year** (for 63.3 million L EtOH and 270 kt straw per year). The **price break-even** at this feedstock level is around **€0.719 /L**, while the **cost break-even** at 0.73 €/L corresponds to a straw price of ≈ **€44-45 /t**.

A small price reduction to **0.725 €/L** lowers the margin to ≈ **€0.38 M/y**, and **0.72 €/L** brings it to near zero. Conversely, cheaper straw (e.g., **€32/t**) or moderate price improvements rapidly increase profitability, whereas higher straw prices (e.g., **€52/t**) lead to losses of several million euros.

Table 21: Mini sensitivity table - lignocellulosic ethanol biorefinery profitability (illustrative)

Scenario	Ethanol (€/L)	Straw (€/t)	Margin (M€/y)
Current case	**0.730**	**42**	**+ 0.70**
Price - 0.005 €/L	0.725	42	+ 0.38
Price - 0.010 €/L	0.720	42	+ 0.07
Break-even (price)	**≈ 0.719**	42	**≈ 0.00**
Straw + €10/t	0.730	52	- 2.00
Straw - €10/t	0.730	32	+ 3.40

(Margins rounded to two decimals.)

Stability levers and system implications.

Maximizing **on-site lignin utilization in the CHP** and **valorizing vinasse** are the two most effective stabilizers of the lignocellulosic ethanol business case. Lignin-to-CHP delivers process steam and a significant share of electricity, **buffering energy-market volatility**, raising **energy self-sufficiency**, and **preserving high GHG savings**. Vinasse is primarily deployed as a **fertilizer** (closing nutrient loops); where appropriate, it can also be routed to **energy options** (e.g., co-digestion with other substrates or co-firing) to add revenue flexibility. In contrast to thermochemical pathways that may export solid carbon at the expense of local heat supply, this configuration **prioritizes energy autonomy**, converting lignin internally to minimize external energy exposure and to maintain a strong emissions profile.

Findings (economic sensitivity).

- **Even small shifts can erase the margin:** at the current case (0.73 €/L, ~€42/t straw), a **price drop of only ~€0.011/L** (≈1.5 c/L) or a **straw cost increase of ~€2.6/t** is enough to push the **~€0.70 M/year** margin to ~zero.
- **Moderate ethanol price improvements** via e.g. green premium pricing materially lift operating results but again - **even modest changes** in straw price or ethanol price can erode margins quickly; the results are **highly sensitive** to these assumptions.
- The most robust returns arise from **lower-cost residue sourcing** combined with **modest price uplift** and steady co-product valorization.

Implications.
Economic resilience depends on (i) **feedstock availability and logistics** (multi-supplier contracting, seasonal buffers), (ii) **stable offtake** for ethanol (long-term supply agreements), and (iii) **supportive policy instruments** (e.g., RED II/III compliance, recognition of verified GHG savings, carbon crediting/guarantees of origin). Together, these measures reduce downside risk around the break-even region and support bankability. As with any advanced biofuel facility, **synchronized offtake and feedstock contracts** are prerequisites—plants should proceed to FID only when **both** long-term residue supply **and** product offtake are secured.

The following diagram (Figure 7) shows a simplified flow chart of the lignocellulosic ethanol pathway and the fossil benchmark. As with any advanced biofuel installation, synchronized offtake and feedstock contracts are critical: plants are built only when both residue supply and product offtake are secured long-term.

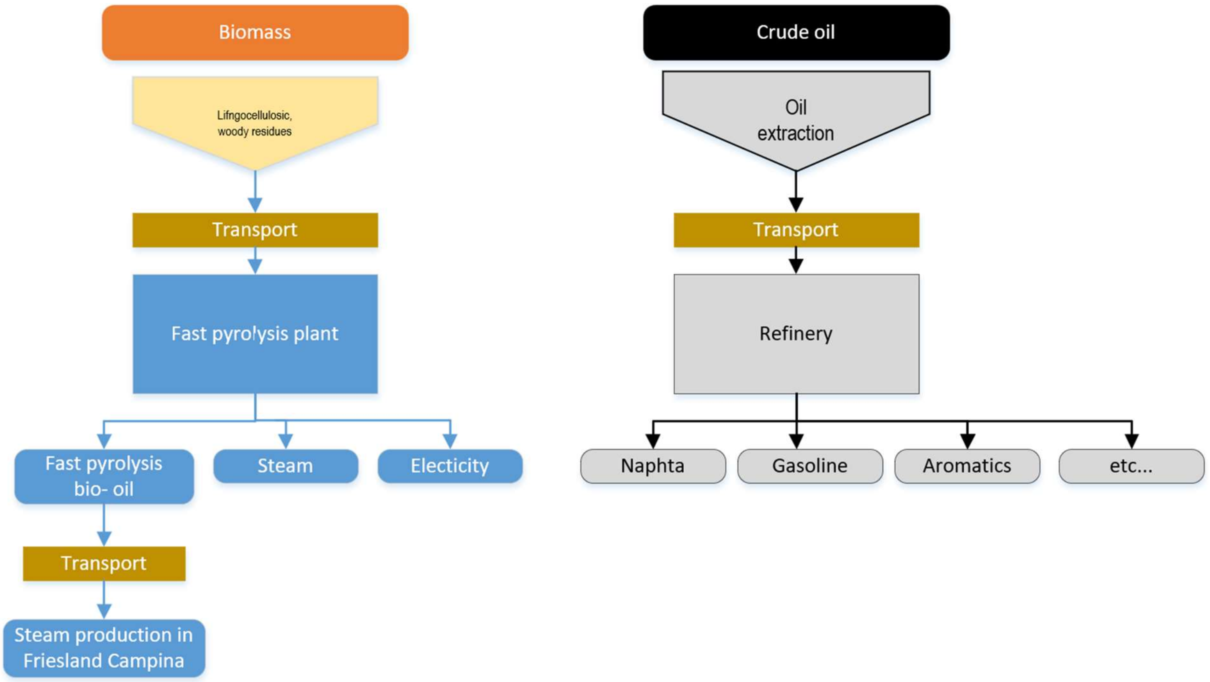


Figure 7: Flow chart to visualize the lignocellulosic ethanol plant in comparison to the oil extraction refinery reference system.

Figure 8 presents the environmental results (GHG and energy). In line with the RED II calculation, total allocated GHG emissions can be as low as **~7.97 g CO_2-eq/MJ EtOH** (assuming renewable electricity for the "electricity gap"), corresponding to **~92%** savings vs. the fossil comparator (**94 g**

CO_2-eq/MJ). Using a national grid mix with high proportions of non-renewables for the electricity gap increases allocated emissions to **~20.2 g CO_2-eq/MJ**. Under ISO 14040/44 scenarios, best-case GWP values of **~11.4 g CO_2-eq/MJ** (wind electricity) correspond to **~88%** savings vs. fossil gasoline. These results underline the importance of renewable electricity sourcing and vinasse management for optimum performance.

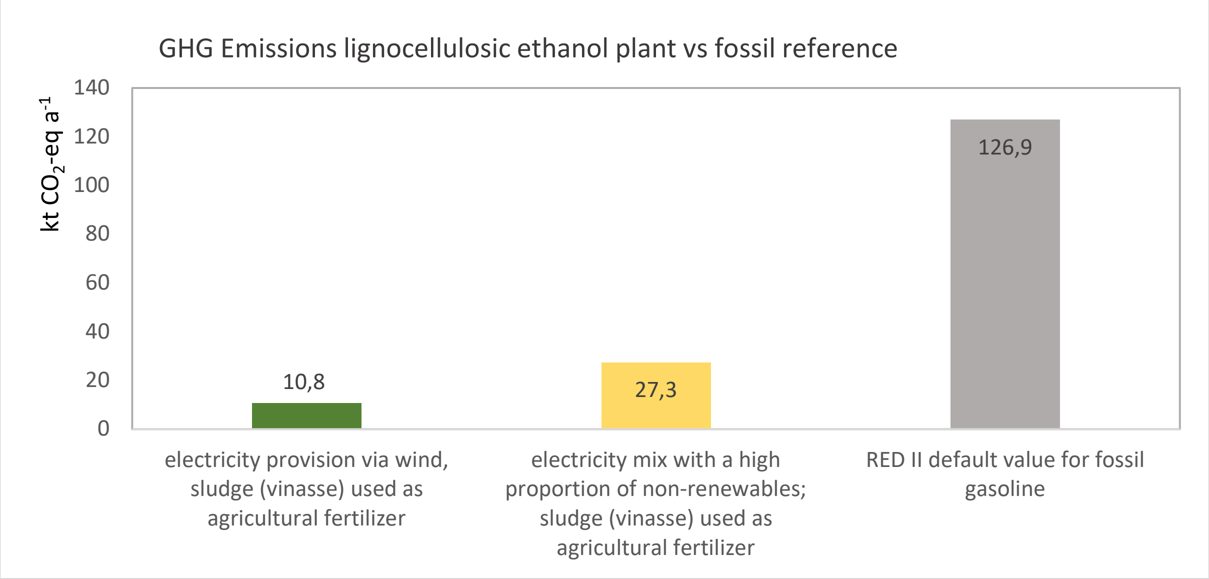


Figure 8: Comparison of annual GHG emissions — lignocellulosic ethanol plant vs fossil reference (illustrative). Reduction potential: ~79-92% depending on methodology and power mix.

Table 5: Overview of GHG emissions — production & application (RED II-III framing, allocated to ethanol).

Component / variable (RED II)	Value (g CO_2-eq/MJ EtOH)	Notes
e_{ec} (feedstock cultivation/harvest)	3.77	Residues (no LUC)
e_p (processing) — RES electricity	3.65	Electricity gap via RES
e_p (processing) — grid mix with a high proportion of non-renewables	18.5	local grid for gap
e_{td} (transport & distribution)	2.24	Feedstock & product logistics
e_u (use phase)	0	Biogenic (per RED II)
E (total, unallocated)	**9.69 (RES)**	Before allocation
E (allocated to ethanol)	**7.97 (RES)**	**~92% saving vs 94**
E (allocated, grid mix with high proportions of non-renewables)	**20.2**	**~79% saving vs 94**

Source: case-study calculations and RED II method

Table 22: Overview of TEE assessment results — lignocellulosic ethanol biorefinery (case study).

Category	Biorefinery (EtOH case)	Reference System (Fossil)	Notes
GHG emissions	8-11 g CO_2-eq/MJ (best-case, allocated)	94 g CO_2-eq/MJ	RED II vs ISO variants
Primary energy demand	0.67-0.71 MJ/MJ EtOH (best-case to baseline)	—	Wind ≈ best; grid mix higher
Annual costs	€48.0 M/a	—	OPEX estimate
Annual revenues	€48.7 M/a (EtOH + vinasse)	—	Price €0.73/L assumed
Operating margin	€0.7 M/a	—	Revenues - costs
Energy efficiency	80-85% (with lignin-CHP polygeneration)	—	Integration lowers auxiliary energy

Notes on water and residues: Water is largely integrated in product and flue-gas streams (distillation and CHP). Ash is a minor output from lignin combustion. Vinasse is ~1.54 t per t ethanol and is recycled agronomically or explored for energy use; lignin (~1.9 t/t EtOH wet basis in the design data) is fully utilized on-site for process energy.

5. Conclusions & strategic outlook

This case study shows that **lignocellulosic (2G) ethanol** production from cereal straw is **technically mature, environmentally superior, and close to break-even** under realistic market assumptions—especially when renewable electricity is secured and long-term supply/offtake contracts are in place.

Key Conclusions

- **Technical Performance**: The plant converts **~270,000 t/a straw** into **~50,000 t/a ethanol** (≈63 million L/a). With **full on-site lignin-CHP**, overall energy efficiency reaches **~80–85 %**, supplying all process steam and a substantial share of electricity. **Lignin is combusted on-site** (not exported); **vinasse** is primarily used as **fertilizer**, with optional energy routes (co-digestion/co-firing) as a flexibility lever.
- **Environmental Impact**: Allocated **RED II** GHG intensities are **~7.97 g CO_2-eq/MJ** when the electricity gap is covered by **renewables** (≈**92 %** savings vs. the 94 g/MJ fossil comparator) and **~20.2 g/MJ** with a carbon-intensive grid. **ISO 14040/44** best-case results of **~11.4 g/MJ** correspond to **~88 %** savings. The design therefore **exceeds EU thresholds** and sustains high savings through energy self-sufficiency.
- **Economic Viability**: At **0.73 €/L** ethanol and **~€42/t** straw, the plant yields an **annual margin ≈ €0.70 M** (CAPEX charge assumed **€24 M/a**). The case is **highly sensitive**: each **€0.01/L** price change shifts margin by ≈ **€0.63 M/a**; each **€10/t** straw change shifts margin by ≈ **€2.7 M/a**. Moderate price uplift, lower delivered straw costs, and additional co-product revenues strengthen the result.

Strategic outlook

- Policy & certification.

Bankability improves with RED II/III compliance, renewable PPAs/GoOs, carbon crediting for verified GHG savings, and stable mandates for advanced biofuels.

- Supply & offtake discipline.

Multi-supplier straw logistics, seasonal buffers, and long-term ethanol offtake are prerequisites; projects should reach FID only when both sides are secured.

- System integration.

On-site lignin-CHP remains the anchor for energy autonomy and GHG performance. Where feasible, RES for the electricity gap (wind/solar PPAs) locks in top-quartile emissions.

- Innovation pathways.

Incremental gains come from enzyme/chemical intensity reduction, heat integration, vinasse valorization options, and digital operations to optimize energy dispatch vs. grid CO_2 intensity.

- Comparative edge.

Versus other advanced biofuel routes, lignocellulosic ethanol combines mature biology, high, verifiable GHG savings, and scalable residue use, making it a robust near-term decarbonization option for the liquid fuels pool (E5/E10/E85, ETBE) and for chemical value chains.

Final remark.

By coupling residue-based feedstock with on-site renewable energy generation, lignocellulosic ethanol biorefineries operationalize the circular bioeconomy—delivering local fuels with deep GHG cuts while reinforcing regional energy security.

MORE DETAILED INFORMATION ON THE DATA BASIS AND THE METHOD APPLIED ARE AVAILABLE IN THE ACCOMPANYING REPORTS AT HTTPS://TASK42.IEABIOENERGY.COM/DOCUMENT-CATEGORY/REPORTS-PAPERS/

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Appendix: Data basis and calculations used in the TEE fact sheet

This appendix consolidates the **assumptions, calculation methods, and key results** for the lignocellulosic (2G) ethanol case based on the most recent TEE assessment.

- **System definition & capacity**
- **Feedstock:** Agricultural residues, primarily **cereal straw**.
- **Nominal production: 50,000 t EtOH·a^{-1}** (≈ **63.3 million L·a^{-1}**).
- **Straw demand: 270,000 t·a^{-1}** (≈ **5.4 t straw per t EtOH**).
- **Operating-hours basis for hourly figures:** unless stated otherwise, **8,760 h·a^{-1}** (→ 5.71 t EtOH·h^{-1}; 30.8 t straw·h^{-1}).
- **Mass balance (per 1 t EtOH; rounded)**
- **Input:** ~**5.4 t** wet straw (≈10% moisture).
- **Outputs: 1.0 t EtOH**, **1.9 t lignin** (to CHP, basis to be reported consistently as wet or dry), **1.54 t vinasse** (≈10 wt% solids), ~**1.0 t water & minor losses**.
- **Mass-based conversion: ≈18.5 wt%** (EtOH mass / straw mass).
- **Energy basis & utilities**
- **Lower heating values:** EtOH **27 MJ·kg^{-1}**, straw ≈**17 MJ·kg^{-1}** (for cross-checks).
- **Annual ethanol energy: 50,000 t × 27 GJ·t^{-1} = 1,350 TJ·a^{-1}.**
- **Process energy intensity (per MJ EtOH):**
    - **Steam demand (supplied by CHP): 0.71 MJ_th/MJ → ~959 TJ·a^{-1}.**
    - **Electricity from lignin CHP: 0.15 MJ_el/MJ → ~203 TJ·a^{-1}.**
    - **Electricity gap (import): 0.13 MJ_el/MJ → ~176 TJ·a^{-1}** (covered by **RES** in best case, or **national grid mix**).
- **Total plant energy efficiency (LHV): ~80-85%**, enabled by **full on-site lignin-CHP** (steam +

partial power self-supply).

- **Environmental performance (method-separated)**
- **RED II (allocated to ethanol):**
    - **Best case (RES for electricity gap): 7.97 g CO_2-eq·MJ^{-1} → ≈92%** saving vs fossil comparator (94 g·MJ^{-1}).
    - **Grid case (carbon-intensive mix): 20.2 g CO_2-eq·MJ^{-1} → ≈79%** saving.
- **ISO 14040/44 (cradle-to-gate, best case): ~11.4 g CO_2-eq·MJ^{-1} → ≈88%** saving vs fossil gasoline.
- **Use-phase:** Biogenic CO_2 from ethanol use is **counted as zero** in both methods.
- **Vinasse handling:** Base case **agricultural fertilizer** (nutrient recycling); energy routes (co-digestion/co-firing) optional and scenario-dependent.

Economics

- **CAPEX (installed): ~€240 million** for **50 kt·a^{-1}** capacity.
- **Annual operating expenses (ex-CAPEX): ~€24.0 M·a^{-1}**, comprising:
    - **Feedstock: €11.5 M·a^{-1}** (~€42/t delivered).
    - **Auxiliaries & chemicals: €7.5 M·a^{-1}.**
    - **Labour: €3.0 M·a^{-1}.**
    - **Energy & other OPEX: €2.0 M·a^{-1}.**
- **Capital charge (depreciation/equity): ~€24.0 M·a^{-1}.**

Revenues:

- **Ethanol: €46.2 M·a^{-1} (€0.73/L** × 63.29 M L).
- **Vinasse valorization: €2.5 M·a^{-1}.**
- **Total revenues: €48.7 M·a^{-1}.**

- **Total costs: €48.0 M·a^{-1} → Net margin: ~€0.7 M·a^{-1}** (near break-even).
- **Sensitivity (first-order)**
- **Price sensitivity: ±€0.01/L** EtOH → **±€0.63 M·a^{-1}** margin.
- **Feedstock sensitivity: ±€10/t** straw (on 270 kt·a^{-1}) → **±€2.7 M·a^{-1}** margin.
- **Break-even points at €42/t straw:** price **≈€0.719/L**; at €0.73/L price: straw **≈€44-45/t.**

Appendix D

4-PLATFORM (ISOBUTENE, C5-STREAM, LIGNIN, VINASSE) BIOREFINERY PLANT USING WOODY RESIDUES FOR THE PRODUCTION OF SUSTAINABLE AVIATION FUEL, LIGNIN-BLEND ASPHALT, ETBE, FERTILIZER, PROCESS STEAM AND ELECTRICITY

This case study presents a comprehensive Technical, Economic, and Environmental (TEE) assessment of a **second-generation lignocellulosic biorefinery** that converts residual softwood sawdust into **sustainable aviation fuel (SAF)** via a wood-to-sugars platform, **fermentation to bio-isobutene (IBN)**, and **oligomerization/hydrogenation to isoparaffins**. All results and diagrams presented here are based on **high-level approximations** intended to illustrate the conceptual SAF pathway rather than provide detailed engineering design data.[69] The configuration valorizes multiple co-products—**lignin** (on-site boiler/CHP energy and/or asphalt binder[70]), **C5-sugar-to-ethanol**, **fermentation sludge** (K/Ca fertilizer credit), and **microbial biomass** (animal feed)—consistent with circular-bioeconomy principles. At commercial scale, engineered balances envisage **~415 kt·a^{-1}** dry sawdust input and indicative outputs of **~30.2 kt·a^{-1} SAF**, **~165 kt·a^{-1} lignin (dry)**, **~28 kt·a^{-1} ethanol**, **~89.2 kt·a^{-1} fertilizer sludge**, and **~6.8 kt·a^{-1} microbial biomass**; in lignin-CHP layouts, ~105.8 kt·a^{-1} lignin is used energetically to meet process heat demand.

The assessment applies a **cradle-to-gate** boundary and certification-grade accounting (EU **RED II/RED III**[71] energy-based allocation for energy products with **avoided-burden** credits for non-energy co-products; **CORSIA** referenced[72]), with scenarios varying process-energy supply (**natural-gas vs. lignin boiler/CHP**) and electricity mix (**EU-28 vs. high-RES**). Utilities choices dominate results: in the **lignin-CHP + RES** best case, SAF achieves **~6.6 g CO_2-eq/MJ** (≈ 93 % below the 94 g CO_2-eq/MJ RED II comparator); ISO-style scenarios span **~18-56 g CO_2-eq/MJ** depending on utilities and co-product handling.

Economically, the concept is **CAPEX-intensive** (installed cost order-of-magnitude **~€598 M**) with **feedstock** as the second-largest cost block; Using current, conservative EU pricing, a SAF selling price of ~€2,200 t^{-1} at the reference output (~30.2 kt a^{-1}) yields ~€66.4 Mio a^{-1} from SAF alone; including conservative co-product revenues (lignin ~€11.8 M, ethanol ~€14.0 Mio, microbial biomass ~€1.36 Mio, fertilizer sludge ~€0.89 Mio, and modest power export ~€1.0 M) brings total revenues to ~€94-95 Mio a^{-1} against **~€85 Mio a^{-1}** in annual costs—i.e., a modest **~€9-10 Mio a^{-1}** margin that remains sensitive to SAF price realization and co-product offtake.

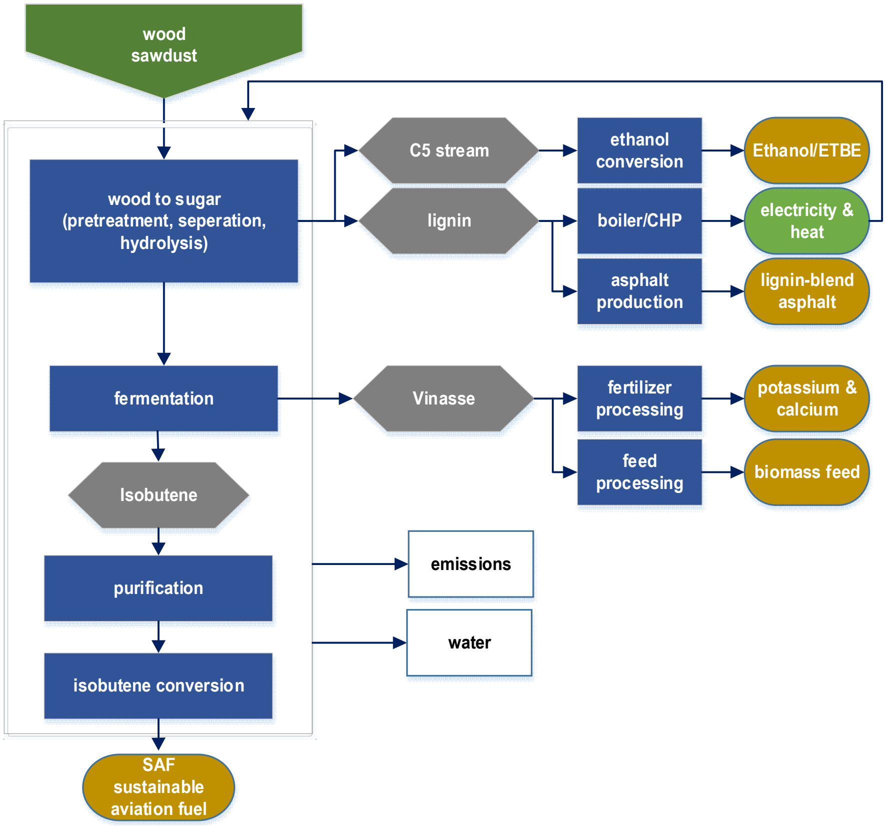
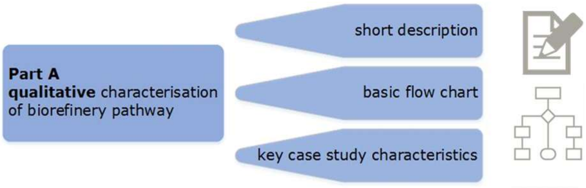


*Figure 23: Basic flow chart of the **second-generation lignocellulosic biorefinery** that converts residual softwood sawdust into **sustainable aviation fuel (SAF)** case study.*

1. Introduction

Deep decarbonization of aviation is emerging as a priority within the broader transition of global energy systems. Because long-haul air travel remains hard to electrify, **drop-in sustainable aviation fuels (SAF)** are central to near- and medium-term climate strategies in Europe and beyond.[73] This case study examines an innovative **second-generation (2G) lignocellulosic biorefinery** that converts residual softwood (sawdust) into SAF via a wood-to-sugars platform, fermentation to **bio-isobutene**, and downstream oligomerization/hydrogenation to **isoparaffins** suitable for jet fuel blending. The pathway valorizes multiple by-product streams—**lignin**, **C5 sugars (to ethanol)**, **fermentation sludge (as Ca/K fertilizer)**, and **microbial biomass (as animal feed)**—consistent with circular-bioeconomy principles.



Technologically, the concept integrates proven unit operations into a novel configuration: pretreatment and enzymatic hydrolysis liberate C6/C5 sugars; the C6 fraction is fermented to gaseous isobutene; upgrading yields SAF-range isoparaffins. **Lignin** can be used **on-site** as a process energy carrier (boiler or CHP) and/or **off-site** as a **bitumen substitute**—a design choice that materially affects both energy self-sufficiency and life-cycle performance.

The study applies a **transparent Technical, Economic, and Environmental (TEE)** lens, anchored in **ISO 14040/14044** life-cycle assessment and aligned with **EU RED II** and **CORSIA** certification frameworks. **Energy-based allocation (LHV)** is used to distribute burdens among energy products (SAF, lignin, ethanol), complemented by a **hybrid "avoided-burden" treatment** for non-energy co-products (fertilizer, animal feed). Scenario analysis varies **process energy provision** (fossil vs. lignin boiler/CHP) and **electricity mix** (EU-28 average vs. high-RES), capturing the strong influence of grid intensity on results.

At commercial scale, the engineered balances envisage **~415 kt/y dry sawdust** input, with by-product valorization and on-site auxiliaries sized accordingly. Depending on the final product slate, annual outputs include **~30 kt SAF** (alternative campaigns can produce ION or ETBE). Logistics favor regional feedstock sourcing to minimize transport burdens.

Headline environmental findings underline the value of **lignin-to-energy integration** and **renewable electricity**: in the **SAF + Lignin-CHP + RES** case, cradle-to-gate emissions reach **~6.6 gCO_2-eq/MJ**, corresponding to **~93%** reduction relative to the RED II fossil reference; ISO-based scenario work finds similarly low values when the grid is decarbonized. Across layouts, **SAF pathway emissions** span roughly **~18–56 gCO_2-eq/MJ**, with the lowest values achieved when **lignin supplies process heat** and **RES covers power demand**.

Beyond climate metrics, **primary energy demand (PED)** and **energetic/exergetic efficiencies** are quantified to locate process bottlenecks and improvement levers. The analysis confirms that **co-product utilization** (especially lignin) is critical to system-level efficiency and that country-specific electricity footprints can dominate comparative results—reinforcing the case for **on-site CHP** and **high-RES power** procurement.

In sum, this SAF case study demonstrates a **scalable, multi-product, residue-based biorefinery** with credible pathways to **>90% GHG reduction** under favorable energy supply assumptions. It provides decision-grade evidence on **design choices (boiler vs. CHP, on- vs. off-site lignin use, grid mix)**, establishes **comparable LCA baselines** under RED II/CORSIA, and surfaces **process-level targets** to accelerate deployment of net-zero-aligned industrial biorefineries in regions rich in underutilized woody residues.

2. Method of assessment for sustainable aviation fuel oriented biorefinery case study

2.1. CURRENT STATUS AND DEVELOPMENT TRENDS OF SAF ORIENTED BIOREFINERIES

Advanced biorefineries are shifting from single-product concepts to **multi-product value chains** that prioritize drop-in **sustainable aviation fuel (SAF)**[74] while valorizing co-products such as **lignin, C5-sugar-to-ethanol, organic fertilizer (Ca/K credits), and microbial protein**. In this case, residual **softwood sawdust** is deconstructed to C6/C5 sugars, fermented to **bio-isobutene (IBN)**, and upgraded via **oligomerization/hydrogenation to SAF-range isoparaffins**. The route is at **demonstration scale** and is being advanced for **ASTM D7566**[75] annex inclusion; certification analyses follow **EU RED II** and **CORSIA** GHG frameworks.[76]

To situate this pathway among today's SAF options, the table below compares **ASTM-recognized** routes by blend limits and typical feedstocks (indicative). Our pathway ("wood-to-IBN SIP-like isoparaffins") is under consideration and thus shown as **emerging**:

SAF pathway (ASTM name)	Max blend (vol%)	Typical feedstocks / notes
FT-SPK (Annex 1)	50	Lignocellulosic residues via gasification/FT.
HEFA-SPK (Annex 2)	50	Waste lipids/vegetable oils (e.g., UCO).
SIP (Annex 3)	10	Fermented sugars → iso-paraffins (sugar platforms).
ATJ-SPK (Annex 5)	50	Alcohols (ethanol/isobutanol) to jet.
CHJ (Annex 6)	50	Hydrothermolysis of lipids.
Wood-to-IBN isoparaffins (this case)	—*	Residual softwood → sugars → **bio-IBN** → iso-paraffins; in ASTM D7566 evaluation.

*Blend limit to be defined upon ASTM approval.

Market drivers & trends. EU **RefuelEU Aviation** sets indicative SAF blend targets of **5% by 2030, 32% by 2040, 63% by 2050**, catalyzing scale-up across multiple pathways. Cost challenges persist, but **scale effects and co-product valorization** are identified levers for competitiveness.[77]

What differentiates this biorefinery. The concept integrates **on-site energy provision from lignin (boiler/CHP)** and targets a **RES electricity mix**, both of which shift cradle-to-gate GHG from ~56 down to **~18-19 gCO₂e/MJ (ISO)**, and to **~6.6 gCO₂e/MJ (RED II, best-case LI-CHP + RES)** when allocation and credits are applied as specified.

2.2. KEY CHALLENGES IN ASSESSMENT

Data sparseness at demo scale. Novel steps (e.g., **IBN fermentation yields**, purification energy, and IBN-to-jet upgrading) still rely partly on project data and literature proxies, requiring transparent assumptions in the LCI.

Methodological consistency. ISO 14040/44 prioritizes system expansion; **RED II** mandates **LHV-based energy allocation**; **CORSIA** introduces its own comparator and rules. Reconciling these within one model—and deciding where to apply **credits vs. allocation**—materially affects results.[78]

Boundary and scenario sensitivity. Electricity carbon intensity (EU-28 vs. high-RES 2050), choice of **lignin use** (energy vs. asphalt binder), and **on-site CHP coverage** dominate both **GWP** and **PED** outcomes; consistent scenario design is essential for fair comparison.

Economic realism. CAPEX intensity, feedstock price exposure, and product slate selection (e.g., campaign to **ION** when margins are stronger) remain critical; early analyses show CAPEX and feedstock dominate cost structure at demo scale.

Assessment of biorefinery systems is complicated by:

- Limited availability of high-quality data, especially for low-TRL systems
- Methodological inconsistencies in Life Cycle Assessment (LCA)
- Allocation and system boundary decisions that affect comparability

This study addresses these issues using standardized guidelines:

- ISO 14040 series for LCA methodology[79]
- EU Renewable Energy Directive (RED III) for GHG accounting[80]
- VDI 6310 for classification and economic parameters[81]

2.3. CLASSIFICATION SYSTEM USED

We apply **IEA Bioenergy Task 42**'s poly-hierarchical classification to ensure comparability and modular growth:

- **Feedstock:** Residual softwood sawdust (regional EU supply).
- **Platforms: C6/C5 sugars → bio-isobutene (gaseous)** as the intermediate platform
- **Processes:** Pretreatment & enzymatic hydrolysis → fermentation (bio-IBN) → purification → **oligomerization/hydrogenation** to SAF; **lignin boiler/CHP** and off-site auxiliaries.
- **Products: SAF (main)**; **lignin** (energy/binder), **ethanol (from C5)**, **fertilizer credits (Ca/K)**, **microbial protein (animal feed)**; plus **steam/electricity** from CHP.

This map supports pathway evolution (e.g., shifting lignin between energy/material markets, or alternating SAF/ION/ETBE campaigns) without losing comparability.

2.4. THE TEE ASSESSMENT FRAMEWORK

We build on the **TEE** approach (Technical-Economic-Environmental) with a **transparent, Excel-based fact-sheet** on prior work by Lindorfer et al. (2019)[82] and consolidating open literature, engineered balances, and certification-grade calculations.

Technical. Mass/energy balances for a **~415 kt/a (dry) sawdust** input; product campaigns of **~30 kt/a SAF** (alternatively ION or ETBE); on-site energy variants (**NG boiler/CHP** vs **lignin boiler/CHP**), and EU-28 vs **RES** electricity. **KPIs** include unit yields, **PED** (allocated/non-allocated), and energetic/exergetic efficiencies at product and system level.

Economic. High-level indicators (**CAPEX/OPEX**, minimum selling price, revenue split, IRR) reflect demo-scale realities: **CAPEX share ~largest cost block**, feedstock the second, corresponding to a dry sawdust price of roughly **50-55 €/t** in the Baltic context, with sensitivity to product slate (e.g., near-term **ION** margins vs SAF).

Environmental.

- **Standards: ISO 14040/44** LCA as backbone; **RED II** (fossil comparator **94 gCO₂e/MJ**, **LHV energy allocation**); **CORSIA** (comparator **89 gCO₂e/MJ**, ≥10% reduction).
- **Allocation & credits: Energy-based allocation** among energy products (SAF, ethanol, lignin) plus **hybrid avoided-burden credits** for non-energy co-products (fertilizer, animal feed).
- **Scenario findings (headline): LI-CHP + RES** delivers ~**6.6 gCO₂e/MJ (RED II)** for SAF (≈**93%** reduction vs 94), while ISO scenario work spans ~**18.7-56 gCO₂e/MJ** depending on energy supply and co-product handling.

Model transparency. The fact-sheet compiles feedstock logistics, utilities, and product slates into a **reproducible** structure for benchmarking across sites and years; it also flags the **dominance of electricity carbon intensity** and **lignin routing** on GHG/PED outcomes—guiding design toward **lignin-to-CHP** and **high-RES power**.

3. CASE STUDY ANALYSIS – PART A: BIOREFINERY PLANT

3.1. OVERVIEW AND SYSTEM BOUNDARY

This case study examines a **commercial-scale, second-generation (2G) lignocellulosic biorefinery** designed to produce **sustainable aviation fuel (SAF)** from **residual softwood (sawdust)**. The facility—engineered around a **Baltic state** siting concept—converts sawdust to **C6/C5 sugars**, ferments C6 sugars to **bio-isobutene (IBN)**, and upgrades IBN via **oligomerization/hydrogenation** to **SAF-range isoparaffins**. Co-products are deliberately valorized: **lignin** (as on-site energy carrier and/or bitumen substitute), **C5-sugar-to-ethanol**, **fermentation sludge** (K/Ca fertilizer credit), and **microbial biomass** (animal feed credit), consistent with circular-bioeconomy principles.

The assessment applies a **cradle-to-gate** boundary: it includes **feedstock logistics (regional sawdust supply and transport), pretreatment and hydrolysis, fermentation, IBN purification, SAF conversion, utilities (boiler/CHP), and off-site auxiliaries.** Product distribution beyond the plant gate is excluded except where required for scenario-specific logistics accounting in the fact-sheet. **GHG accounting** follows **EU RED II** (energy-based allocation, fossil comparator 94 gCO₂e/MJ) and, for SAF scenarios, **CORSIA**; **ISO 14040/44** scenarios are provided to benchmark methodological sensitivity. Key drivers varied in scenarios are **process-energy provision (natural gas vs. lignin; boiler vs. CHP)** and **electricity mix (EU-28 vs. high-RES).**

Table 23: Key technical characteristics of the SAF biorefinery case study (fact-sheet basis).

Key parameter	Characteristic
Primary feedstock (dry)	Residual softwood (sawdust), **~415 kt·a^{-1}** regional supply concept.
Core platform	Wood-to-sugars (pretreatment + enzymatic hydrolysis) → **bio-isobutene (gaseous)** fermentation → IBN purification → **isoparaffins (SAF)** via oligomerization/hydrogenation.
Main product	**SAF** (isoparaffins), **~30.2 kt·a^{-1}** (campaign mode).
Co-products (indicative)	**Lignin ~165 kt·a^{-1} (dry)**; **ethanol ~28 kt·a^{-1}** (from C5 sugars); **sludge ~89.2 kt·a^{-1}** (fertilizer credit); **microbial biomass ~6.8 kt·a^{-1}** (animal-feed credit).
Utilities concept	**Lignin boiler/CHP** covers thermal demand; electricity from CHP and/or grid (EU-28 or high-RES scenarios).
Location concept	**Europe, Baltic States (demo concept)**; regional sawdust logistics emphasized.
Technology status	Demonstration / pre-commercial integration of proven unit ops into novel configuration; ASTM D7566 annex evaluation targeted.
Headline GHG results (SAF)	**RED II, SAF LI-CHP + RES: ~6.6 gCO$_2$e/MJ** (≈**92.9%** reduction vs. 94). **ISO scenarios: ~18-56 gCO$_2$e/MJ** depending on energy supply and allocation/credits.

System boundary note. The "off-site (auxiliaries)" system—storage, conveyance, pumps, blowers, heat exchangers, etc.—is explicitly modeled because it materially contributes to utilities and handling burdens at commercial scale.

3.2. PROCESS DESCRIPTION

The process route in this case study follows a **lignocellulosic sugar platform** rather than fast pyrolysis. Residual **softwood sawdust** is deconstructed to **C6/C5 sugars**, the **C6 fraction** is fermented to **gaseous bio-isobutene (IBN)** using engineered *E. coli*, and purified IBN is upgraded via **oligomerization and hydrogenation** to **SAF-range isoparaffins** suitable for blending under ASTM D7566 (annex under evaluation). Along the chain, multiple by-products are valorized: **lignin** (as process energy via boiler/CHP and/or as a **bitumen substitute**), **C5-to-ethanol**, **fermentation sludge** providing **K/Ca fertilizer credits**, and **microbial biomass** as **animal-feed protein**—key levers for both environmental and economic performance.

Process sequence (SAF campaign):

- **Feed handling & deconstruction.** Regional sawdust is received and conditioned; **pretreatment + enzymatic hydrolysis** liberate C6/C5 sugars and separate a **lignin-rich solids** stream. C5 sugars are routed to **ethanol**; lignin is directed either **on-site to boiler/CHP** for process heat/power or **off-site** to substitute asphalt binder, depending on the scenario.

- **Fermentation (bio-IBN).** The **C6 sugar liquor** is fermented with engineered *E. coli* to **gaseous isobutene**; **sludge** (fertilizer K/Ca) and **biomass** (animal-feed protein) arise as co-products. IBN is then **purified** via an adsorption/desorption column system.

- **Conversion to SAF.** Purified IBN is **oligomerized and hydrogenated** to **isoparaffins** in the jet-range. The same conversion train can be campaigned to **ION** or **ETBE** for market flexibility, but **SAF** is the reference product in this study.

- **Utilities & energy integration.** Thermal demand is covered by **natural-gas or lignin boiler**, or by **NG/lignin-CHP**; electricity is supplied by **on-site CHP and/or grid** (EU-28 mix or high-RES scenario). Utilities choices are decisive for cradle-to-gate results.

System design benefits (vs. single-product routes):

Polygeneration with targeted co-product valorization (lignin, ethanol, fertilizer, animal feed) to lift overall energy/exergy performance.

Internal energy self-sufficiency via lignin-to-boiler/CHP, reducing exposure to high-carbon grids; scenarios demonstrate strong sensitivity to the electricity mix.

Certification-aligned accounting. The pathway is modeled for **RED II/CORSIA** using **LHV-based energy allocation** across energy products and **avoided-burden** credits for non-energy co-products—matching the fact-sheet used for TEE results.

Indicative flows at commercial scale (Europe/baltic concept, SAF campaign): ~415 $kt\cdot a^{-1}$ dry sawdust in; outputs ~**30.2 $kt\cdot a^{-1}$** SAF, ~**165 $kt\cdot a^{-1}$ lignin (dry)**, ~**28 $kt\cdot a^{-1}$ ethanol**, ~**89.2 $kt\cdot a^{-1}$ fertilizer sludge**, **~6.8 $kt\cdot a^{-1}$ microbial biomass**. In **LI-CHP + RES** layouts, **~105.8 $kt\cdot a^{-1}$ lignin** is used energetically to meet heat demand.

Environmental headline (cradle-to-gate, SAF): With **lignin-CHP** and **RES electricity**, emissions reach **~6.6 gCO_2-eq/MJ (RED II)**—**≈92.9%** below the 94 gCO_2-eq/MJ fossil comparator; ISO scenarios span **~18–56 gCO_2-eq/MJ** depending on utilities and allocation/credits.

3.3. MASS AND ENERGY BALANCE

At **commercial scale**, the reference layout processes **~415 kt a^{-1}** (dry) **residual softwood sawdust** into **SAF-range isoparaffins** via C6/C5 sugar extraction, IBN fermentation, and oligomerization/hydrogenation. Co-products are deliberately valorized: **lignin** (as process energy via boiler/CHP and/or off-site as **bitumen substitute**), **ethanol** from C5 sugars, **fermentation sludge** (K/Ca fertilizer credit), and **microbial biomass** (animal-feed protein).

Annual mass flows (indicative, SAF campaign):
- **SAF: ~30.2 kt a^{-1}** (plant reference product)

- **Lignin (total): ~165 kt a^{-1} (dry)**; of this, **~105.8 kt a^{-1}** is used **energetically** in the **LI-CHP + RES** best-case to cover thermal demand, with the remainder available for off-site material substitution.

- **Ethanol (from C5): ~28 kt a^{-1}** (credit via energy allocation)

- **Sludge (fertilizer K/Ca): ~89.2 kt a^{-1}; Microbial biomass (animal feed): ~6.8 kt a^{-1}.**

Utilities intensities (per unit SAF): electricity ≈ **0.99 MJ_{el} / MJ_{SAF}**, steam ≈ **1.266 MJ_{th} / MJ_{SAF}** (conversion + purification dominate), which makes the **utilities concept** (lignin boiler/CHP vs. fossil boilers; EU-28 vs. high-RES grid) the decisive lever for cradle-to-gate impacts.

Lignin-to-energy requirement: to close the site heat balance, the plant needs ≈ **2.74 t lignin / t_{SAF}** with a lignin **boiler**, or ≈ **3.50 t lignin / t_{SAF}** with **CHP** (higher electric self-sufficiency). Choice of utilities set-up trades off **grid imports** vs. **on-site renewable share** and strongly shifts both **GHG** and **primary energy** allocation.

Allocation snapshot (EU RED II, LHV-based, per t SAF): the energy allocation splits roughly **SAF**

22.3%, **lignin 63.3%**, **ethanol 12.6%**, **animal-feed biomass 1.7%**—driving the distribution of burdens and credits in the fact-sheet.

Environmental headline (for context): in the **LI-CHP + RES** scenario, **SAF** reaches **~6.6 gCO_2-eq / MJ (RED II)**—a **~92.9%** reduction vs. the **94 gCO_2-eq / MJ** fossil comparator. ISO-based scenarios span **~18-56 gCO_2-eq / MJ** depending on energy supply and co-product handling.

Table 24: Summary of main parameters for the SAF case study biorefinery.

Item	Value / note
Feedstock (dry sawdust)	**~415 kt a^{-1}** regional supply concept; trucked (~50 km typical).
Main product (SAF)	**~30.2 kt a^{-1}** isoparaffins (ASTM D7566 annex under evaluation).
Co-products	**Lignin ~165 kt a^{-1} (dry)**; **Ethanol ~28 kt a^{-1}**; **Sludge ~89.2 kt a^{-1}**; **Biomass ~6.8 kt a^{-1}.**
Utilities intensity (SAF block)	**0.99 MJ_{el} / MJ_{SAF}**, **1.266 MJ_{th} / MJ_{SAF}**.
Lignin for site energy	**~105.8 kt a^{-1}** (LI-CHP + RES best-case); equivalently **2.74-3.50 t lignin / t_{SAF}** (boiler vs. CHP).
Energy allocation (RED II)	**SAF 22.3%**, **Lignin 63.3%**, **Ethanol 12.6%**, **Animal-feed 1.7%** (per t SAF).
System energy set-ups	**NG boiler/CHP** or **lignin boiler/CHP**; grid: **EU-28** or **high-RES** scenario.
State of technology / site concept	**Demo integration**; **Europe/Baltic state** layout for logistics/energy benchmarking.

Interpretation. This **SAF-oriented sugar platform** trades a liquid energy carrier at the gate for **drop-in jet fuel**, with **utilities design and lignin routing** dominating both the **mass** (lignin use) and **energy** (electricity/steam) balances—and, consequently, **GHG** and **PED** outcomes

Table 25: Key characteristics case study.

4-PLATFORM (Isobutene, C5-stream, lignin, vinasse) biorefinery plant using woody residues for the production of sustainable aviation fuel, lignin-blend asphalt, ETBE, fertilizer, process steam and electricity							
State of technology				Demo			
Country				Europe/Baltic states			
Main data source				Literature			
Products	Isooctane	1	MJ_{ION} MJ_{ION}^{-1}	Primary energy demand			
		30.5	Kt a^{-1}	Isooctane	Electricity	0.843	MJ_{el} MJ_{IBN}^{-1}
	ETBE	0.81	MJ_{ETBE} MJ_{ETBE}^{-1}		Steam	1.229	MJ_{el} MJ_{IBN}^{-1}
		35	Kt a^{-1}	ETBE	Electricity	0.54	MJ_{el} MJ_{ETBE}^{-1}
	SAF	1	MJ_{SAF} MJ_{SAF}^{-1}		Steam	0.841	MJ_{th} MJ_{ETBE}^{-1}
		35	Kt a^{-1}	SAF	Electricity	0.99	MJ_{el} MJ_{SAF}^{-1}
					Steam	1.266	MJ_{th} MJ_{SAF}^{-1}
Total emissions	ION BC	80.1	gCO_2eq MJI_{ION}^{-1}	Feedstock saw dust (dry)	Isooctane	5.78	MJ_{DM} MJ_{IBN}^{-1}
Total emissions	ION LI- CHP RES	5.6	gCO_2eq MJ_{ION}^{-1}			415	Kt a^{-1}
Savings	Compared to fossil fuel reference of 94 gCO_2eq MJ^{-1}	94.1	%		ETBE	5.771	$MJ_{DM}MJ_{ETBE}^{-1}$
GHG Emissions	ETBE BC	69.4	gCO_2eq MJ_{ION}^{-1}			415	Kt a^{-1}
Total emissions	ETBE BC RES	25.6	gCO_2eq MJ_{ION}^{-1}		SAF	5.889	MJ_{DM} MJ_{SAF}^{-1}
Savings	Compared to fossil fuel reference of 94 gCO_2eq MJ^{-1}	72.8	%				
Total emissions	SAF BC	88.5	gCO_2eq MJ_{ION}^{-1}				
	SAF LI-CHP RES	6.6	gCO_2eq MJ_{ION}^{-1}				
Savings	Compared to fossil fuel reference of 94 gCO_2eq MJ^{-1}	92.9	%				

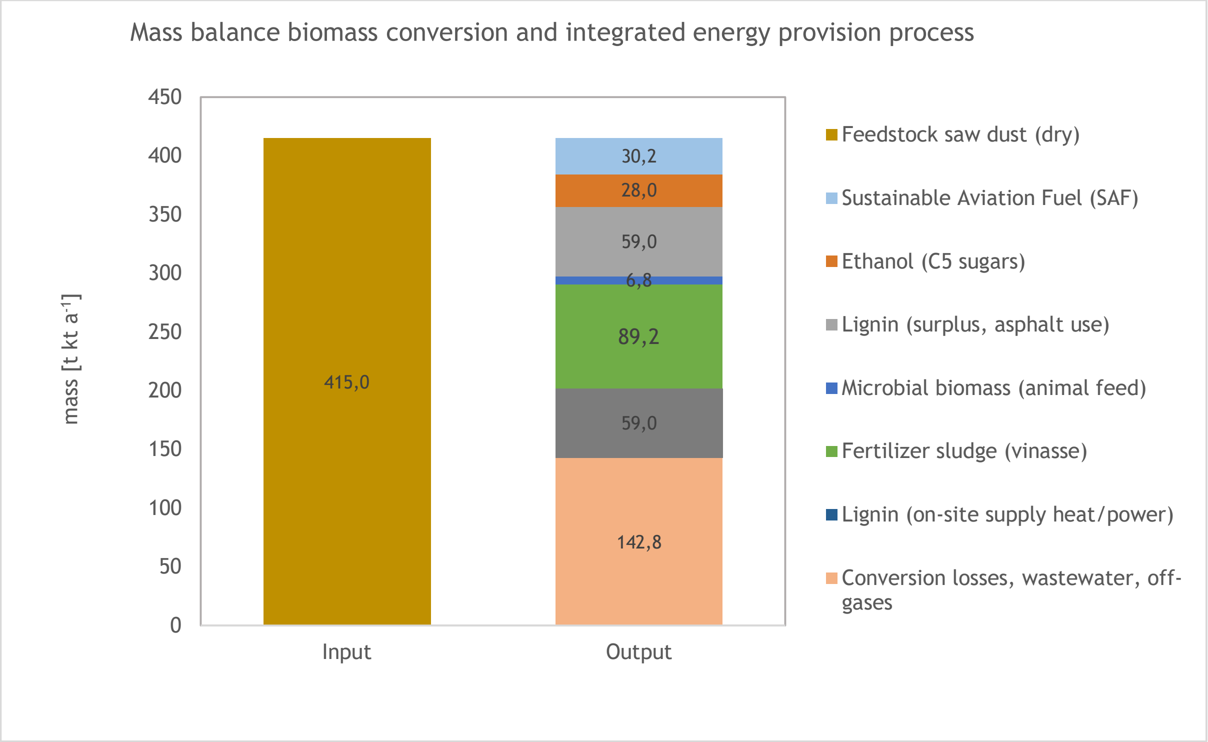
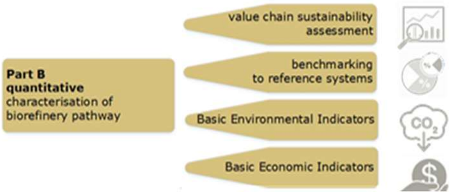


Figure 24: Simplified balance of mass of input and output streams.

PART B: VALUE CHAIN ASSESSMENT



In the **SAF configuration**, revenues are led by SAF but materially supported by co-products. At the reference scale (**~30.2 kt SAF a^{-1}** from **~415 kt a^{-1}** dry sawdust), the plant also generates **~165 kt a^{-1} lignin (dry)**, **~28 kt a^{-1} ethanol (from C5 sugars)**, **~89.2 kt a^{-1} fertilizer sludge (vinasse, K/Ca)**, and **~6.8 kt a^{-1} microbial biomass**; in lignin-CHP layouts, about **~105.8 kt a^{-1}** of the lignin is used on-site to supply process heat/power (utilities intensity ≈ **0.99 MJ_{el}/MJ_{SAF}** and **1.266 MJ_{th}/MJ_{SAF}**), with the remainder available for material markets (e.g., asphalt binder).

Using a **conservative EU pricing** basis, **SAF at ~€2,200 t^{-1}** yields **~€66.4 M a^{-1}** from SAF alone; adding cautious co-product monetization (surplus lignin, ethanol/ETBE route or direct fuel-grade ethanol, animal-feed biomass, a small fertilizer credit, and modest power export) brings total revenue to **~€94-95 M a^{-1}**. Against **~€85 M a^{-1}** in annual costs, corresponding to a dry sawdust price of roughly **50-55 €/t** in the Baltic context, this implies a **modest ~€9-10 M a^{-1} operating margin**—still **sensitive** to SAF price realization and offtake for co-products.[83]

On the **cost side**, the structure is **CAPEX-led** (installed cost **~€598 M**); capital charges are about **~42 %** of annualized cost, **feedstock ~26 %**, with the balance across **utilities/chemicals/maintenance, labor, and overheads**—hence the decisive role of the utilities concept (**lignin boiler/CHP vs. fossil; EU-28 grid vs. high-RES power**) for both **OPEX** and **GHG**.

In certification accounting (RED II), the best-case **lignin-CHP + RES** setup achieves **~6.6 g CO_2-eq/MJ** (≈ **93 %** below the **94 g** fossil comparator); ISO scenarios span **~18-56 g CO_2-eq/MJ**, reflecting the strong sensitivity to energy supply and co-product handling.

In the SAF configuration, **revenues are dominated by SAF sales**, with the **minimum selling price (MSP) ≈ 2,200 € t⁻¹** used as the benchmark in the fact-sheet model. At the reference scale (~**30.2 kt SAF a⁻¹**), this corresponds to ~**84.8 M€ a⁻¹** in product revenue; co-product valorization (ethanol from C5 sugars, fertilizer credits from sludge, animal-feed protein, and optional exported electricity) is treated in the margin through allocation/credits rather than as primary sales lines.

Strategically, **bankable SAF offtake**, **secured sawdust contracts**, and **policy value pass-through** (e.g., mandates/credits) remain pivotal; co-product routing (especially **lignin-to-energy**) and a low-carbon electricity mix materially improve both margins and compliance.

Table 26: Approximated revenue table based on simplified mass and energy balance and literature values[84,85]

Stream	Output (kt/yr)	price assumed (€ per tonne)	Revenue (Mio.€/yr)
SAF (main product)	30.2	2,200	**66.4**
Lignin (surplus)	59.0	200	**11.8**
Ethanol (C5 stream)	28.0	500	**14.0**
Microbial biomass (animal feed)	6.8	200	**1.36**
Fertiliser sludge (vinasse)	89.2	10	**0.89**
Energy export (electricity/steam)	-	-	**1.0**
Total Revenue	-	-	**≈ 94.5**

Figure 3 illustrates the annual **revenue-cost structure** of the SAF-oriented biorefinery. In the **conservative EU/Baltic context**, SAF remains the lead revenue stream (≈**€66.4 M a⁻¹** at ~€2,200 t⁻¹ for ~30.2 kt a⁻¹ output), while **co-products**—surplus **lignin** routed to asphalt binder markets, **ethanol** from the C5 stream (direct sale or ETBE route), **microbial biomass** (animal feed), a small **fertilizer** credit from vinasse, and limited **power export**—lift total revenues to about **€94-95 M a⁻¹**. On the **cost side**, the structure is **CAPEX-led** (installed CAPEX ≈ **€598 M**), with capital charges contributing ~**42 %** of annualized costs, **feedstock** ~**26 %**, and the remainder spread across **utilities/chemicals/maintenance, labor, and overheads**—hence the central role of the **utilities concept** (lignin boiler/CHP vs. fossil; EU-28 grid vs. high-RES power) in both **OPEX** and **GHG** performance. Under these assumptions, total annual costs of ≈**€85 M a⁻¹** yield a **modest ~€9-10 M a⁻¹** operating margin that is **sensitive** to realizable SAF price and co-product offtake.

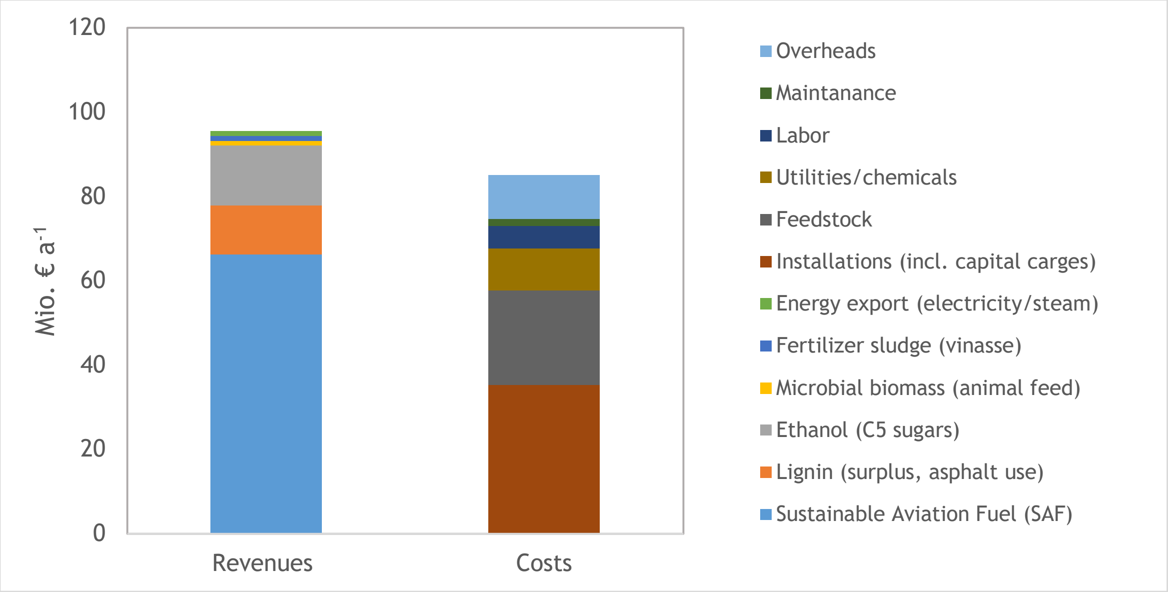


Figure 25: Revenues and costs estimated for sustainable aviation fuel oriented case study.

Recent literature shows that **regional feedstock economics** are a primary determinant of lignocellulosic biorefinery performance: differences in raw-material price and logistics strongly shape TEA outcomes, corresponding to a dry sawdust price of roughly **50-55 €/t** in the Baltic context. While **self-supplied process energy** from co-products (notably **lignin** to boiler/CHP) delivers both environmental and cost benefits. In our SAF case, the **cost pie** mirrors this: approximately **~42 % capital charges**, **~26 % feedstock**, with the **balance** across **utilities/chemicals/maintenance, labor, and overheads**—underscoring that the **utilities concept** (lignin boiler/CHP vs. fossil utilities; EU-28 grid vs. high-RES power) is pivotal for both **OPEX** and **GHG** results. A first-order sensitivity confirms that margins are **highly elastic** to **dry sawdust price** and **realizable SAF price/MSP**: a combined shock of **+25 % feedstock / −10 % SAF price** pushes the plant **negative**, whereas moderate MSP uplift and/or discounted feedstock swings restore a slim positive margin. This is consistent with our broader findings that **lignin-to-energy** and **low-carbon electricity** materially stabilize costs and enable certification-grade performance (best-case **LI-CHP + RES ≈ 6.6 g CO_2-eq/MJ**, ~93 % below RED II's 94 g comparator).

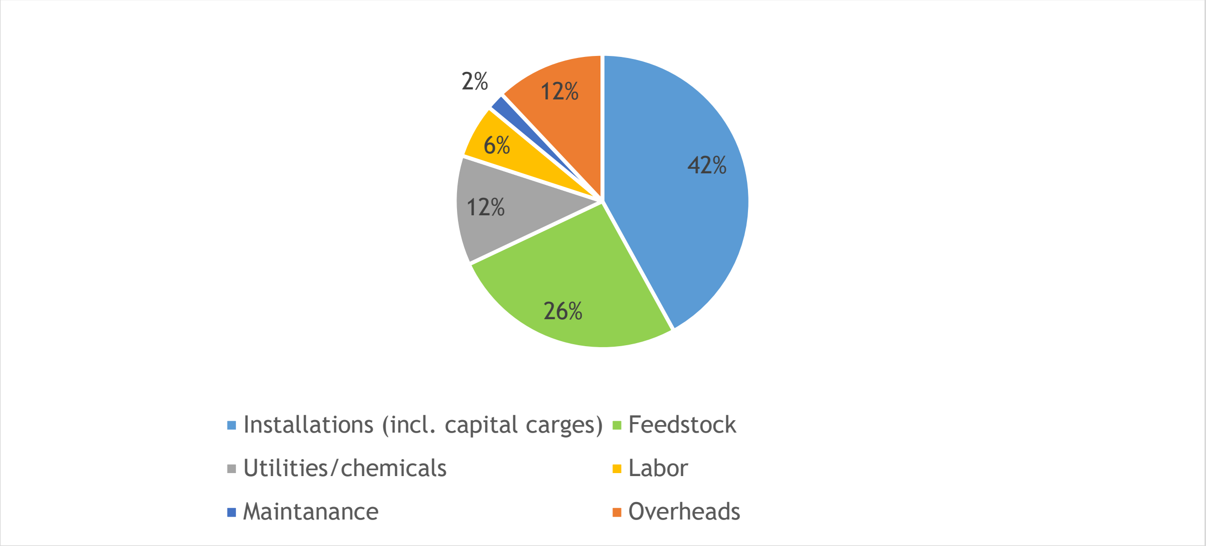


Figure 26: Cost share (SAF configuration. (see Table 3)

The shares in Figure 4 reflect the structure above: **~42 % installation/capital**, **~26 % feedstock**, remainder split across **OPEX (utilities, chemicals, maintenance), labor, and overheads**. Because pretreatment/hydrolysis and upgrading are energy intensive (**≈ 0.99 MJ_{el}/MJ_{SAF}** and **≈ 1.266 MJ_{th}/MJ_{SAF}**), choosing **lignin-boiler/CHP with RES power** limits fossil exposure and supports both **cost** and **GHG** performance; conversely, reliance on fossil boilers and/or carbon-intensive grids raises both.

Base: as-is feedstock; MSP per scenario. **Optimistic:** feedstock −20 %; MSP +10 %. **Pessimistic:** feedstock +25 %; MSP −10 %. **Outcome: breakeven/slim +** at base, **notable margin** in the optimistic case, and **negative** under the combined adverse shock—mirroring prior evidence that regional feedstock markets dominate TEA variance and that **on-site lignin energy** provides both environmental and economic hedges.

Table 27: *Simplified sensitivity (conservative, SAF configuration).*

Parameter	Base	Optimistic	Pessimistic
Sawdust cost (€/t, dry)	55	44 (−20%)	69 (+25%)
SAF price / MSP (€/t)	2,200	2,420 (+10%)	1,980 (−10%)
Total revenue (M€/yr)	95.5	102.1	88.8
Total cost (M€/yr)	85.0	80.6	90.5
Net margin (M€/yr)	+10.5	+21.5	−1.7

Assumptions & notes:

- Outputs: ~30.2 kt/yr SAF; co-products monetized conservatively (lignin, ethanol/ETBE, feed, fertilizer, modest power export).
- Base revenues: SAF €2,200/t ⇒ €66.4 M/yr; plus co-products ⇒ €95.5 M/yr total.
- Base costs: €85.0 M/yr (cost pie ≈ 42% capital, 26% feedstock, balance OPEX/labor/overheads).
- Feedstock sensitivity: feedstock is ~26% of total cost (≈€22.1 M/yr).
    - Optimistic (−20%): cost ↓ by ~€4.42 M to €80.6 M/yr.
    - Pessimistic (+25%): cost ↑ by ~€5.53 M to €90.5 M/yr.
- SAF price sensitivity applies only to SAF revenue (base €66.4 M):
    - +10% ⇒ +€6.64 M; −10% ⇒ −€6.64 M.
- Co-product revenues are held constant across scenarios (conservative).

The plant **tips negative** under the combined **+25% feedstock / −10% SAF price** shock (−€1.7 M/yr). Moderate improvements (e.g., **+10% SAF price** and/or **−20% feedstock cost**) lift the margin to **€20 M+**. This underscores the dominance of **feedstock economics** and **SAF price realization**, and the stabilizing role of **lignin-to-energy** and **low-carbon utilities** on both OPEX and certification-grade GHG results.

Strategic levers for economic viability (SAF):

Co-product strategy. Route **lignin to boiler/CHP** to cover site heat (and part of power) and claim **RED II energy-allocation benefits**; market **excess lignin** as **bitumen substitute** when energy demand is covered. Ethanol (from C5), fertilizer, and animal feed provide additional credits.

Utilities decarbonization. LI-CHP + RES scenarios minimize GHG (~**6.6 gCO_2e MJ^{-1}**, ~**92.9 %** vs. fossil reference) and reduce exposure to fossil energy price shocks; designs with fossil utilities show higher emissions and often higher variable costs.

Scale & learning. Larger trains and maturing vendor ecosystems **shift CAPEX and OPEX down over time**, closing part of the price gap to fossil jet.

Value-chain/market implications

- **Offtake matters.** Bankable **SAF offtake** (airlines/fuel suppliers) is essential to underwrite the capital stack; campaign flexibility toward **ION or ETBE** can improve early-years cash flow but may conflict with SAF mandate opportunities.

- **Policy alignment.** The case study is modeled against **EU RED II** allocation rules; trajectory to **RED III / CORSIA** compliance plus **RefuelEU-style** mandates are critical to close the price gap in the medium term.

- **Design choice = economics.** Selecting **LI-CHP + RES** not only enables the **~6.6 gCO_2e MJ^{-1}** cradle-to-gate result but also **stabilizes OPEX**, improving resilience to fuel-price volatility.

Bottom line: In today's market, the **SAF campaign** shows **tight economics but clear decarbonization value. Capital efficiency**, **co-product monetization**, and **renewable utilities integration** are the decisive levers for investment-grade viability.

Figure 8 presents a simplified flow diagram of the **SAF pathway** (residual softwood → C6/C5 sugars → bio-isobutene → oligomerization/hydrogenation → **SAF-range isoparaffins**) alongside a **fossil jet benchmark.** Beyond the headline product, the figure highlights the **bankability triad** that must be locked in **before FID**: (i) **long-term SAF offtake** with airlines/fuel suppliers (typically take-or-pay, indexed to jet price with floors/ceilings and pass-through of policy credits), (ii) **secure feedstock supply** from regional sawmills (volume/quality specs and price indexation), and (iii) a **utilities strategy**—preferably **lignin-to-boiler/CHP with RES power**—to stabilize OPEX and underpin GHG performance. The project only closes if these legs are **contracted in parallel**: airlines will not sign meaningful SAF offtakes without credible plant delivery and cost visibility, while investors will not fund the plant without binding offtakes and de-risked feedstock. Co-product routing (lignin to energy or material markets, C5-to-ethanol, fertilizer and animal-feed credits) is shown because it materially supports margins and compliance. In practice, **synchronized agreements**—SAF offtake, feedstock contracts, and utilities/credit arrangements—have been **decisive for value-chain formation**, replacing the "oil boiler + fuel guarantee" logic of fast-pyrolysis heat markets with **aviation-grade, certification-aligned offtakes** and embedded policy instruments.

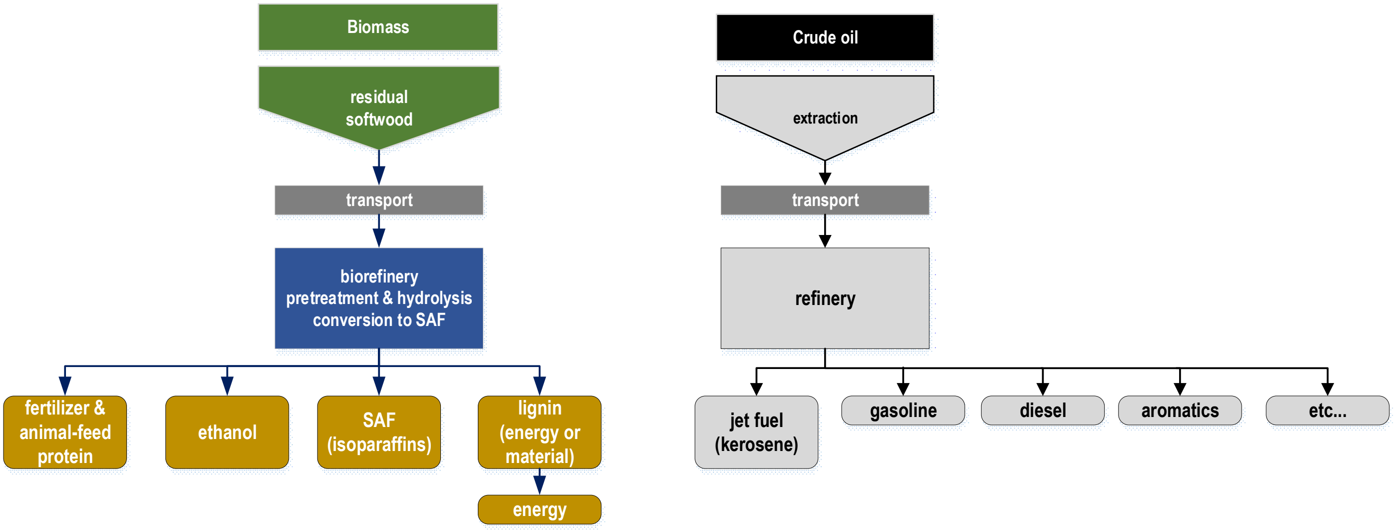


*Figure 27: Flow chart of the **wood-to-IBN SAF biorefinery** with co-product valorization and policy/market interfaces, shown against a **fossil jet refinery reference** (functional equivalence at the blended jet-fuel gate).*

Figure 9 compares the **wood-to-IBN → SAF** biorefinery with a fossil jet benchmark. In our ISO 14040/44 cradle-to-gate LCA, **SAF pathway emissions span ~18.7-56 g CO_2-eq/MJ**, driven primarily by the **wood-to-sugars** unit, **off-site auxiliaries**, and—most critically—the **utilities set-up** (lignin-to-energy vs. fossil heat; EU-28 power vs. high-RES mix). Switching to **renewable electricity (RES)** and using **lignin for process heat/CHP** consistently shifts results to the low end of the range. Under certification accounting (**EU RED II**), the best-case **SAF LI-CHP + RES** scenario achieves **~6.6 g CO_2-eq/MJ**, i.e., **~92.9%** below the **94 g CO_2-eq/MJ** fossil comparator. All scenarios also satisfy **CORSIA**'s ≥10% reduction vs. **89 g CO_2-eq/MJ** fossil jet, with the same design levers (lignin-to-energy, RES power) delivering the largest margins. On energy use, the **allocated PED** is **~2.8-4.2 MJ/MJ SAF** (renewable share up to **~82%** in lignin-CHP designs), while the **non-allocated biorefinery PED** is **~10.7-13.1 MJ/MJ SAF**. Overall, **electricity carbon intensity** and **lignin routing** are the dominant determinants of both **GWP** and **PED**; without a low-carbon grid, several layouts fail RED II savings, whereas **LI-(B/CHP)+RES** configurations meet or exceed the target.

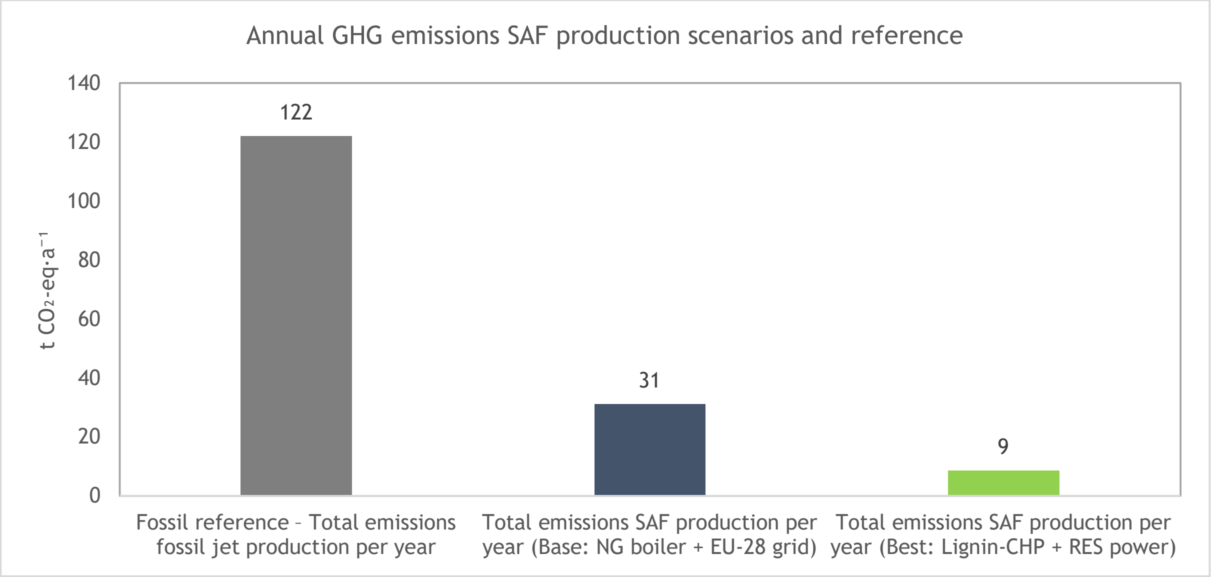


Figure 28: Annual GHG Emissions of SAF production scenarios under base and best utilities scenarios relative to fossil jet fuel.

Table 28: Overview of GHG emissions and reductions in the SAF case (production & application).

Contribution to GHG (cradle-to-gate)	Base caseNG boiler + EU-28 grid	Best caseLignin-CHP + RES power
Biomass supply & transport	1.8	1.8
Pretreatment & enzymatic hydrolysis	5.2	1.3
Fermentation (bio-IBN) & purification	3.1	0.9
IBN upgrading to SAF (oligomerization/hydrogenation)	2.0	0.6
Utilities (process heat & electricity)	10.5	1.9
Off-site auxiliaries (handling, storage, services)	1.3	0.5
Product transport to blender/airport (regional)	0.2	0.2
Co-product credits (fertilizer & animal-feed protein)*	**−0.2**	**−0.6**
Total — SAF production (cradle-to-gate)	**23.9**	****6.6**
Tank-to-wake combustion (biogenic CO₂ under RED II)	0.0	0.0
Total — production & application (RED II view)	**23.9**	**6.6**
Fossil jet comparator (RED II)	**94**	**94**
GHG reduction vs. fossil jet	**74.6 %**	**92.9 %**

* Co-product handling follows your hybrid approach: energy-based allocation among energy products (SAF, ethanol, lignin) and avoided-burden credits for non-energy co-products (fertilizer and animal-feed protein).

Notes for the caption:

- The **best-case result (6.6 g CO_2-eq/MJ)** corresponds to **lignin-to-CHP with renewable electricity (RES)**; the **base case** uses **natural gas utilities and EU-28 average grid electricity**.
- If you also report **ISO 14040/44** results, keep those in the text/Figure 9 (range ~18–56 g CO_2-eq/MJ) to show methodological sensitivity; Table 5 stays **RED II** for certification comparability.

*Table 29: Overview of the TEE assessment results — **SAF** case study.*

Block	Metric	BaseNG boiler + EU-28 grid	BestLignin-CHP + RES
Greenhouse-gas emissions	g CO_2-eq per MJ SAF (cradle-to-gate, RED II)	**23.9**	**6.6**
	Annual GHG — biorefinery (t CO_2-eq·a^{-1})*	**31,100**	**8,600**
	Fossil jet comparator (t CO_2-eq·a^{-1}; 94 g/MJ)	122,000	122,000
	Savings vs fossil jet	**~74.6 %**	**~92.9 %**
Cumulated energy demand (PED)	Allocated PED (MJ/MJ SAF)	**~4.2**	**~2.8**
	Annual allocated PED (TJ·a^{-1})	**~5,450**	**~3,630**
	Renewable share of PED	**moderate**	**high (lignin + RES)**
Costs	Annual costs (M€·a^{-1})**	**~82-86**	**~78-82**
	Specific revenue SAF (€/t SAF)	**~2,200**	**~2,200**
	Investment (installed CAPEX, M€)	**~598**	**~598**
Revenues	Annual SAF revenue at MSP (M€·a^{-1})†	**~66.4**	**~66.4**
	Specific revenue (€/t SAF)	**2,200**	**2,200**
	Specific revenue (€/L SAF, $\rho \approx 0.775$ kg·L^{-1})	**~2.16**	**~2.16**

* Annual GHG totals = (g CO_2-eq/MJ) × (1.298×10^9 MJ·a^{-1}); fossil reference uses **94 g CO_2-eq/MJ**.

** Cost bands reflect financing assumptions; capital charges dominate the total, with feedstock as the second-largest block.

† MSP used for the fact-sheet baseline; co-product effects (ethanol, fertilizer, animal-feed protein, optional power export) are handled by allocation/credits rather than shown as independent sales lines.

Reading notes.

- The **Best** layout (lignin-CHP + RES) delivers the certification-oriented **6.6 g CO_2-eq/MJ** cradle-to-gate result and materially lowers **PED** by displacing fossil utilities with **lignin** and low-carbon power.
- The **Base** layout is margin-constrained and sensitive to both **sawdust price** and **grid carbon intensity**; moving to **lignin-CHP** improves both **GHG** and **OPEX stability**.
- Investment-grade viability hinges on **bankable offtake**, **secure feedstock contracts**, and **co-product valorization**—especially the routing of **lignin** to on-site energy.

5. Conclusions & strategic outlook

Key conclusions

Technical performance

- The demonstrator-scale, residue-based **wood-to-IBN → SAF** biorefinery is **technically feasible** and operable in continuous mode.
- At the reference scale (**~415 $kt\cdot a^{-1}$ dry sawdust**), the plant delivers ~**30.2 $kt\cdot a^{-1}$ SAF** with campaign flexibility to **ION/ETBE**, while **lignin** supplies process heat (boiler) or heat+power (CHP).
- **Co-product valorization**—lignin (energy or bitumen substitute), **C5-to-ethanol**, **fertilizer** (K/Ca from sludge), and **animal-feed protein**—is integral to mass/energy closure and site economics.
- The **utilities concept** (lignin-CHP vs. fossil, RES vs. EU-28 grid) is the dominant design lever for both **GHG** and **OPEX**.

Environmental impact

- **Cradle-to-gate GHG** for SAF spans ~**18-56 g CO_2-eq/MJ (ISO)** depending on utilities and allocation; under **RED II** accounting, the **lignin-CHP + RES** layout achieves ~**6.6 g CO_2-eq/MJ**, i.e., ~**93%** below the **94 g CO_2-eq/MJ** fossil comparator.
- All modeled layouts meet **CORSIA**'s reduction threshold; **electricity carbon intensity** and **lignin routing** are the principal drivers.
- **Primary energy demand (PED)** is lowest—and the renewable share highest—when **lignin supplies process energy** and grid imports are **RES-based**.

Economic viability

- Economics are **tight but bankable** with the right conditions: **long-term SAF offtake**, **secured sawdust contracts**, **policy credit stacking**, and **lignin-to-energy** integration.
- **CAPEX** dominates annualized costs; **feedstock** is the second-largest component. The baseline **MSP ~2,200 €/t SAF** yields a **slim operating margin** that is highly sensitive to **feedstock price** and **achieved SAF price**.
- Co-product credits (ethanol, fertilizer, animal feed, optional power export) improve the margin but do not replace the need for **policy support** and **efficient financing**.

Strategic outlook

Policy integration

- **RefuelEU-style SAF mandates**, **GHG-based credits (RED/CORSIA)**, and **ETS/CBAM interactions** are pivotal to closing the price gap to fossil jet.
- Contract structures that pass through **policy value** (e.g., book-and-claim, base-price floors, indexation to jet) de-risk revenue and enable financing.

Scale-up pathway

- Replicable **train-based designs** and **regional clusters** (co-located with sawmills, logistics hubs, and grid interconnects) are the fastest route to scale.
- Moving from **boiler to CHP**, increasing **on-site RES**, and standardizing vendors reduce both **GHG** and **unit costs** over time.

Innovation levers

- **Higher hydrolysis and fermentation yields**, **lower-severity upgrading**, and **catalyst longevity** directly cut utilities demand.
- **Green H_2 integration** and **power-to-heat** (as grids decarbonize) further lower cradle-to-gate emissions.
- Continued progress toward **ASTM D7566 annex inclusion** for IBN-derived isoparaffins expands market access and blend limits.

Comparative positioning

- Versus **HEFA**, the pathway avoids lipid-feedstock constraints and ILUC exposure; versus **FT-biomass**, it offers **modular integration** and strong co-product synergies; versus **ATJ-ethanol**, it benefits from **solid-residue feedstock security** and diversified product campaigns (SAF/ION/ETBE).

Final remark

- The **wood-to-IBN SAF** biorefinery demonstrates a credible, **residue-based** route to deep aviation decarbonization. With **bankable offtake**, **secured feedstock**, and **renewable utilities**, the concept delivers **>90% GHG savings** under certification accounting and establishes a pragmatic blueprint for **industrial-scale, circular-bioeconomy deployment**.

Abbreviations

ATJ – alcohol-to-jet (SAF pathway based on alcohols such as ethanol or isobutanol); BC – base case; CAPEX – capital expenditure; CBAM – Carbon Border Adjustment Mechanism; CHP – combined heat and power; CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation; ETBE – ethyl tert-butyl ether; FID – final investment decision; GHG – greenhouse gas(es); GWP – global warming potential; IBN – isobutene (bio-isobutene); IEA – International Energy Agency; IRR – internal rate of return; ISO – International Organization for Standardization; LCA – life cycle assessment; LCI – life cycle inventory; LHV – lower heating value; LI-CHP – lignin-fired combined heat and power; MSP – minimum selling price; NG – natural gas; OPEX – operating expenditure; PED – primary energy demand; RED II / RED III – Renewable Energy Directive II / III; RES – renewable electricity supply / renewable energy sources; SAF – sustainable aviation fuel; SARPs – Standards and Recommended Practices (ICAO); SIP – synthetic iso-paraffins (ASTM D7566 Annex 3); TEA – techno-economic assessment; TEE – Technical-Economic-Environmental assessment; TRL – technology readiness level.

MORE DETAILED INFORMATION ON THE DATA BASIS AND THE METHOD APPLIED ARE AVAILABLE IN THE ACCOMPANYING REPORTS AT HTTPS://TASK42.IEABIOENERGY.COM/DOCUMENT-CATEGORY/REPORTS-PAPERS/

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Appendix: Data basis and calculations used in the TEE fact sheet

This appendix summarises the key assumptions, calculations, and primary sources underpinning the case study.

Table A1. Key assumptions, calculations, and references used in the SAF case study (residual softwood → sugars → bio-isobutene → isoparaffins).

Block	Parameter	Symbol / unit	Value (base case)	Value (best case)	Notes
Capacity & operation	Nominal operating hours	$h\cdot a^{-1}$	8,000	8,000	Planned on-stream factor for commercial operation
	Feedstock throughput (dry sawdust)	$kt\cdot a^{-1}$	**~415**	**~415**	Regional softwood residues (sawmill/sanding dust); dry basis
	Main product output (SAF isoparaffins)	$kt\cdot a^{-1}$	**~30.2**	**~30.2**	Reference SAF campaign; other campaigns possible (ION/ETBE)
	SAF energy output (LHV≈43 $MJ\cdot kg^{-1}$)	$TJ\cdot a^{-1}$	**~1,298**	**~1,298**	30.2 kt × 43 $GJ\cdot t^{-1}$
Co-products	Lignin (total produced)	$kt\cdot a^{-1}$ (dry)	**~165**	**~165**	Portion used for process energy vs. sold depends on utilities concept
	Lignin used for site energy	$kt\cdot a^{-1}$	—	**~105.8**	Best case uses lignin in CHP to meet heat (+part power)
	Ethanol (from C5 sugars)	$kt\cdot a^{-1}$	**~28**	**~28**	Energy product under RED allocation
	Fermentation sludge (fertilizer credit)	$kt\cdot a^{-1}$	**~89.2**	**~89.2**	Credited via avoided mineral fertilizer (K/Ca)
	Microbial biomass (animal-feed credit)	$kt\cdot a^{-1}$	**~6.8**	**~6.8**	Credited as protein feed
Utilities & energy	Utilities concept	—	**NG boiler + EU-28 grid**	**Lignin-CHP + RES power**	Two bounding designs used throughout the TEE analysis
	Electricity intensity (SAF block)	MJ_{el} per MJ_{SAF}	**~0.99**	**~0.99**	Same process need; supply differs (grid vs. CHP/RES)
	Annual electricity demand	$GWh\cdot a^{-1}$	**~357**	**~357**	0.99 × 1.298×10^{9} MJ ÷ 3.6

	Steam/thermal intensity (SAF block)	MJ_{th} per MJ_{SAF}	**~1.266**	**~1.266**	Conversion + purification dominate
	Annual steam/thermal demand	$GWh_{th}\cdot a^{-1}$	**~456**	**~456**	1.266 × 1.298×10^9 MJ ÷ 3.6
GHG performance (RED II accounting)	Fossil comparator	g CO_2-eq·MJ^{-1}	**94**	**94**	RED II reference for aviation
	SAF cradle-to-gate	g CO_2-eq·MJ^{-1}	**~23.9**	**~6.6**	Base vs. best utilities designs
	Reduction vs. fossil	%	**~74.6%**	**~92.9%**	Relative to 94 g CO_2-eq·MJ^{-1}
LCA scope & allocation	Boundary	—	Cradle-to-gate	Cradle-to-gate	Production only; use phase biogenic under RED
	Allocation among energy products	—	LHV-based	LHV-based	For SAF, ethanol, lignin
	Credits for non-energy co-products	—	Avoided-burden	Avoided-burden	Fertilizer & animal-feed protein
Economics (fact-sheet baseline)	Installed CAPEX	M€	**~598**	**~598**	Order-of-magnitude, installed cost
	MSP (SAF)	€·t^{-1}	**~2,200**	**~2,200**	Reference price used to balance base-year cash flows
	Annual SAF revenue at MSP	M€·a^{-1}	**~66.4**	**~66.4**	30.2 kt × 2,200 €·t^{-1}
	Feedstock price (dry sawdust)	€·t^{-1}	**~53-55** (illustrative)	**~80**	Sensitivity driver in TEA
	Cost structure (high level)	share of annualized cost	**CAPEX ≈42%; feedstock ≈26%; rest OPEX**	Similar shares	Financing assumptions drive CAPEX share
Standards & certification	Regulatory frameworks	—	RED II, CORSIA	RED II, CORSIA	Accounting and comparators as reported
	ASTM status	—	Emerging annex for IBN-derived isoparaffins	Emerging	Target pathway for D7566 inclusion

Abbreviations: LHV—lower heating value; RES—renewable electricity mix; CHP—combined heat and power; TEA—techno-economic analysis; TEE—Technical-Economic-Environmental.

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