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.

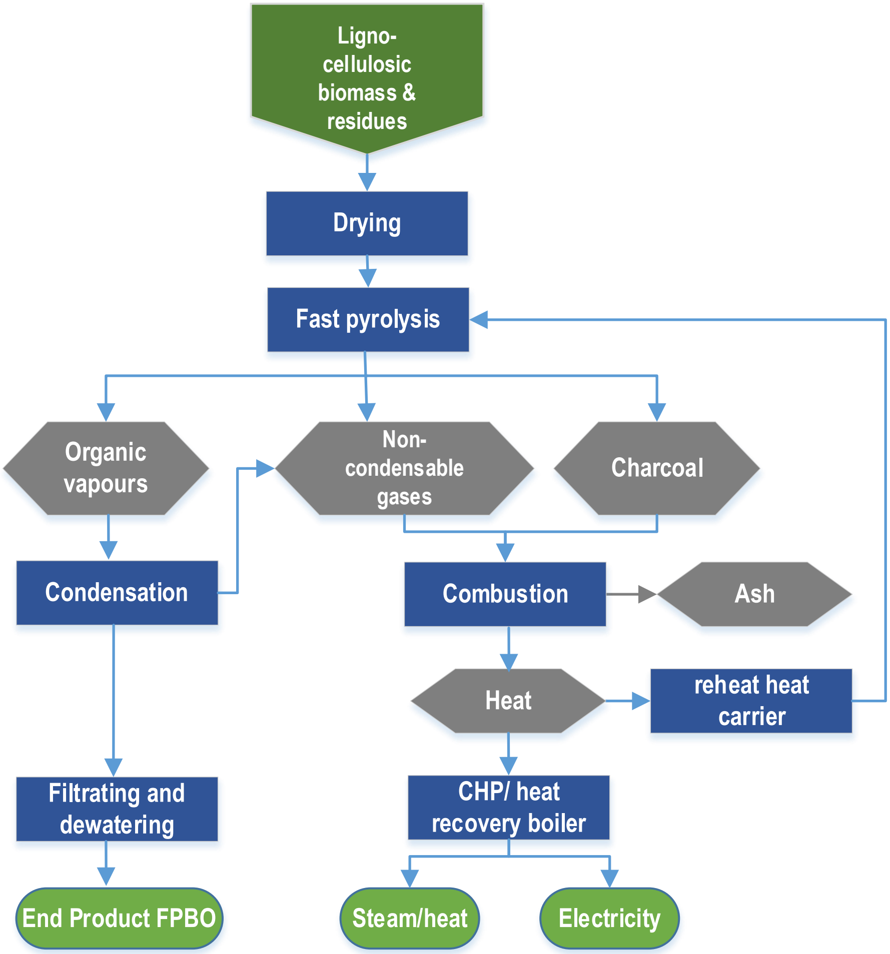


Figure 1: Basic flow chart of the fast pyrolysis plant case study

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.

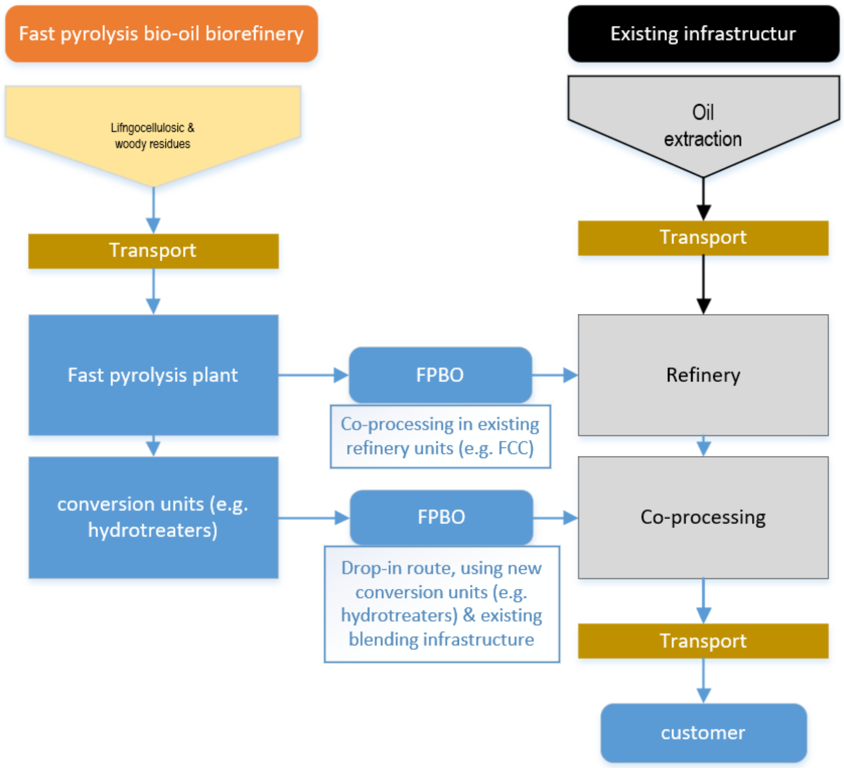
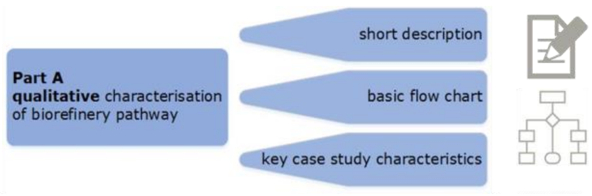


Figure 2: Fast Pyrolysis Bio-Oil as refinery feedstock-advanced biofuels: drop-in and co-processing.

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[1].
- **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 1: 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[2], 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 2: 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]

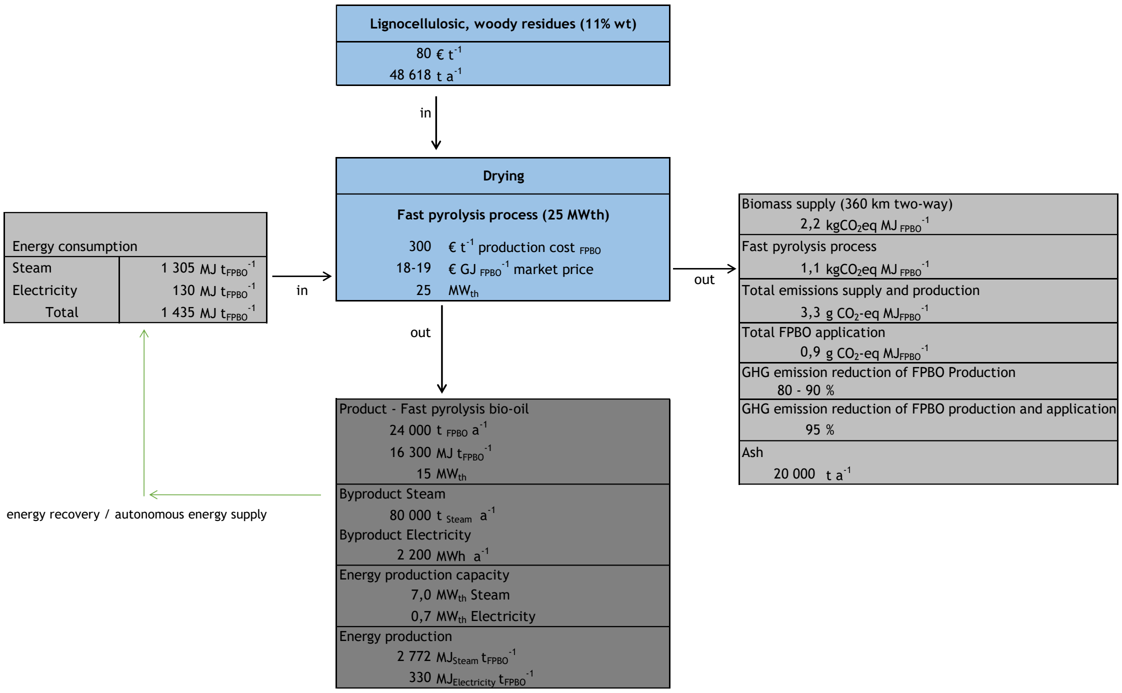


Figure 3: Overview of TEE assessment: Process pathway for fast pyrolysis bio-oil synthesis from lignocellulosic biomass. Based on own calculations with data from literature referenced at table 1 and additional sources[16],[17],[18]

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

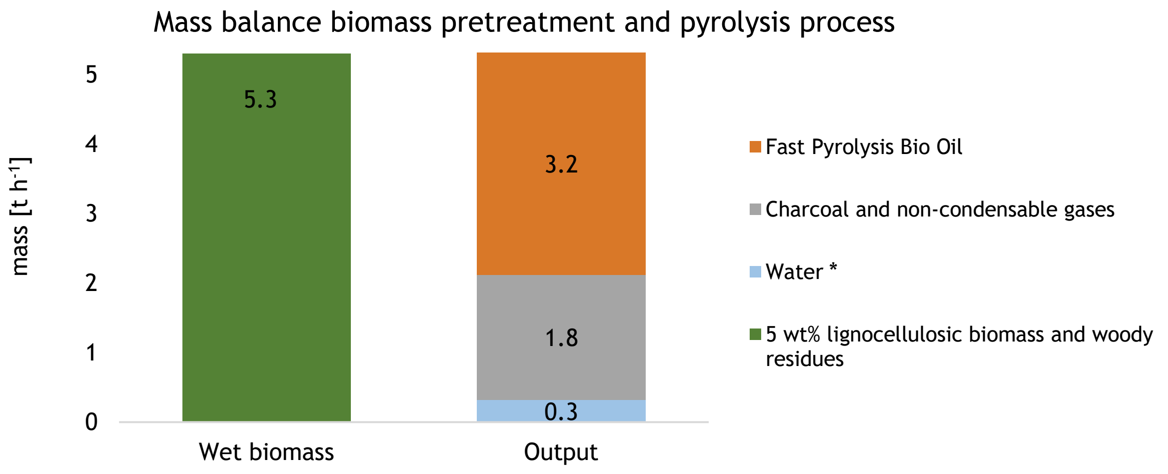
At full capacity:

- **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 3 summarizes the key characteristics of the considered case study.

Table 3: 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 4: Simplified balance of mass of input and output stream.

PART B: VALUE CHAIN ASSESSMENT

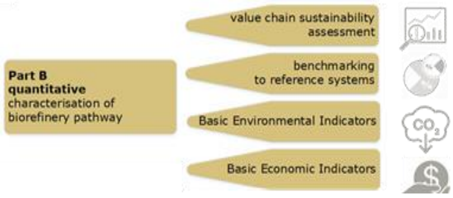


Figure 5 illustrates the annual revenue and cost structure of the fast pyrolysis biorefinery case study. The revenues are primarily derived from the sale of FPBO, complemented by approximately 12 % from electricity and steam exports. On the cost side, the largest share is attributed to biomass feedstock 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.

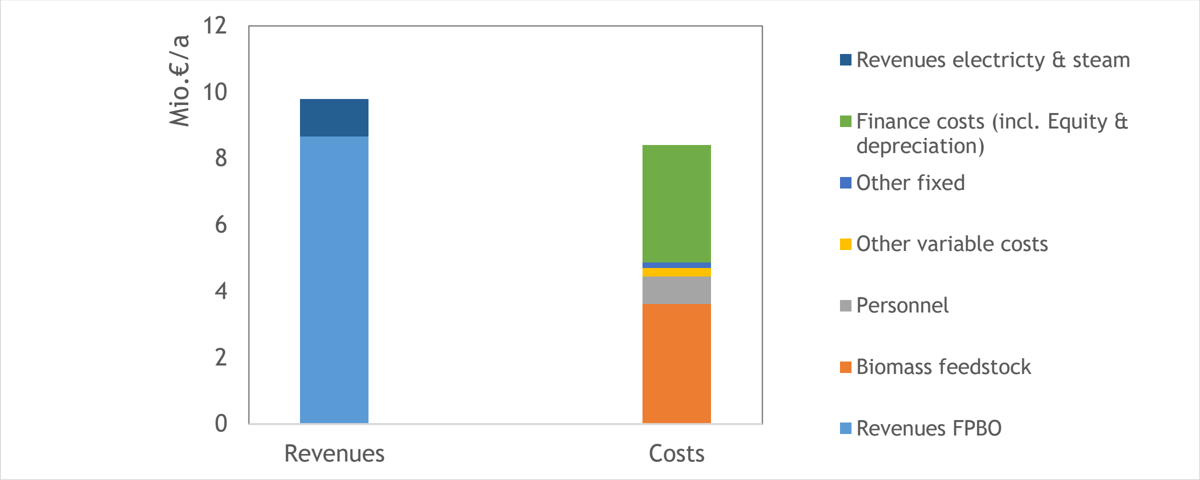


Figure 5: Costs and revenues case study of fast pyrolysis bio-oil production biorefinery plant.

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).

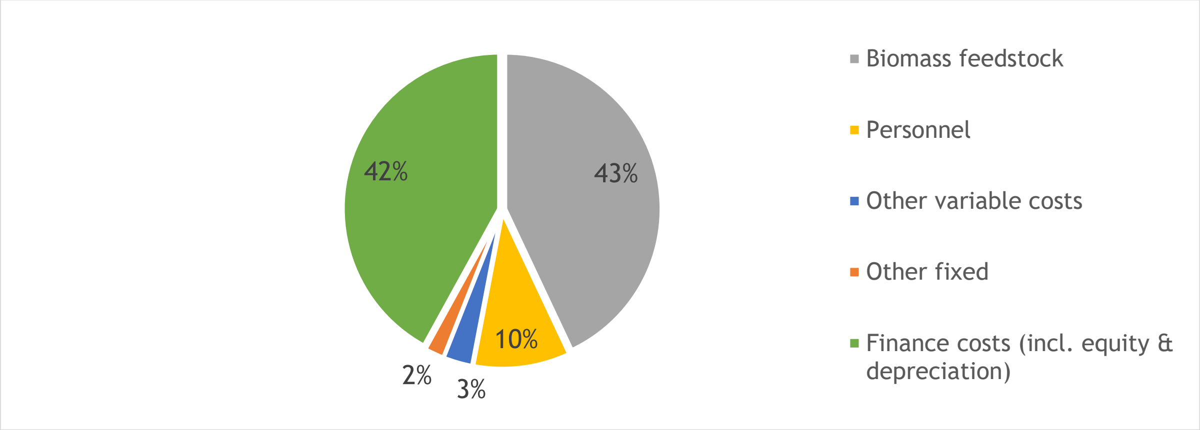


Figure 6: Share breakdown of costs of the fast pyrolysis bio-oil case study. (see Table 3)

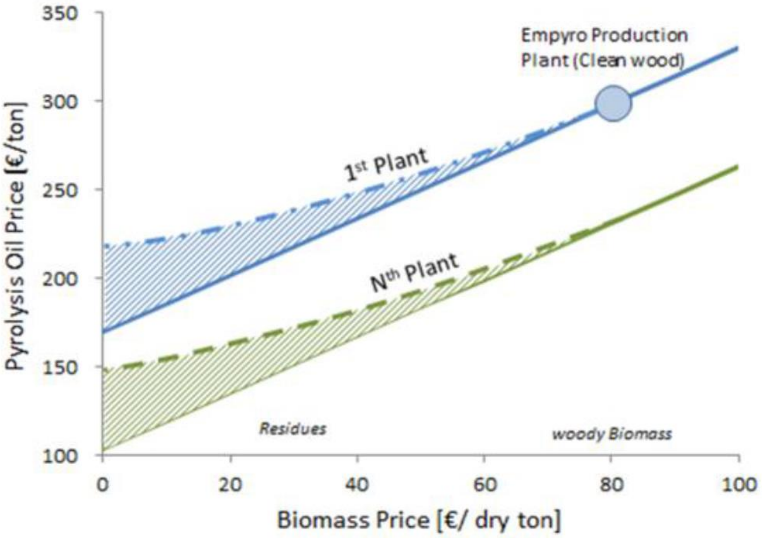


Figure 7: Correlation curves between FPBO price and biomass price.[24]

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 4: 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 8). 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]

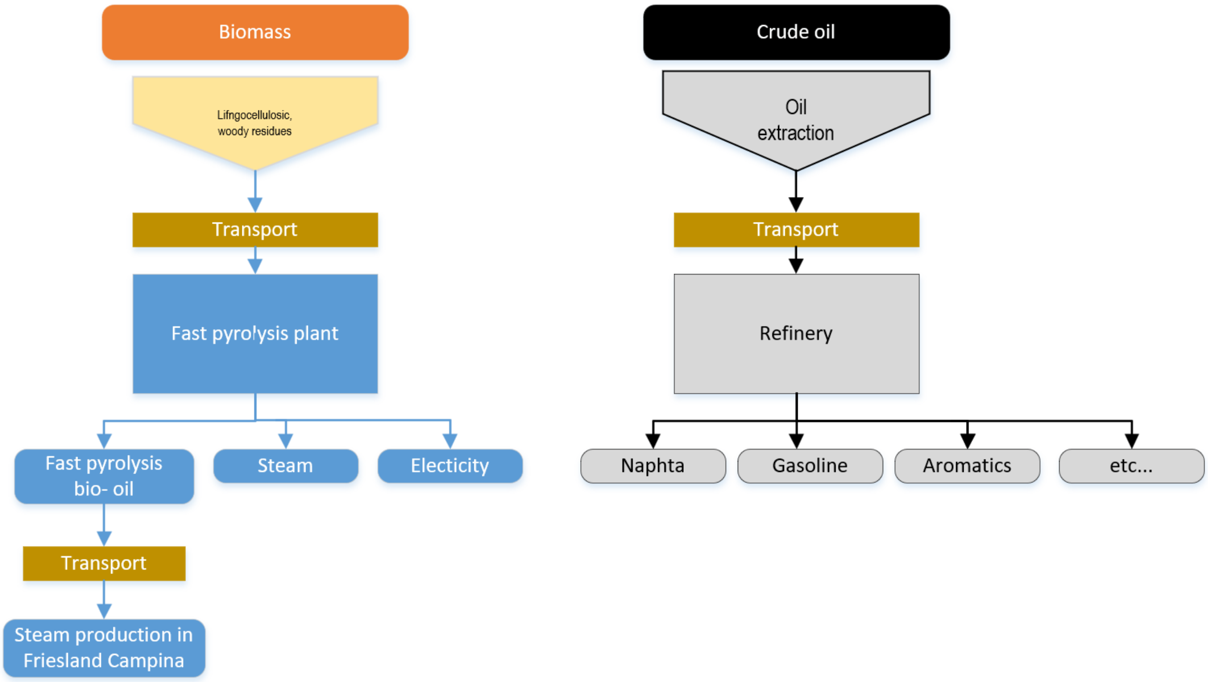


Figure 8: Flow chart to visualize the fast pyrolysis plant in comparison to the oil extraction refinery reference system.

The results of the environmental assessment based on GHG emissions and annual cumulated energy demand are shown in Figure 9. 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.

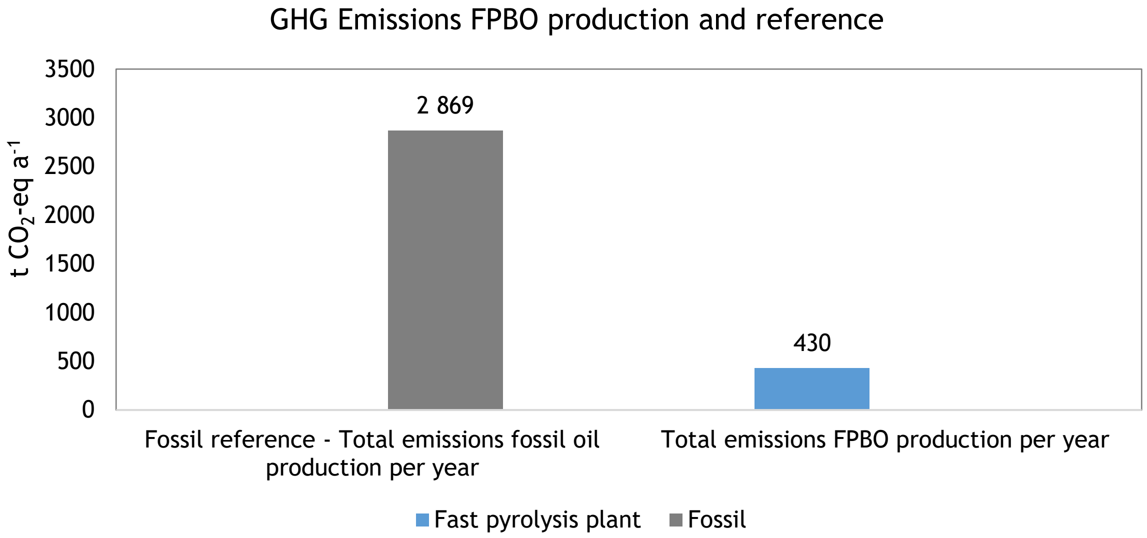


Figure 9: Comparison of Annual GHG Emissions - Fast Pyrolysis Plant vs. Fossil Reference

Table 5: 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 6: 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[3]. 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 A: 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.

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