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Techno-economic assessment of an integrated biorefinery for the production of advanced biofuels from the organic fraction of municipal solid waste

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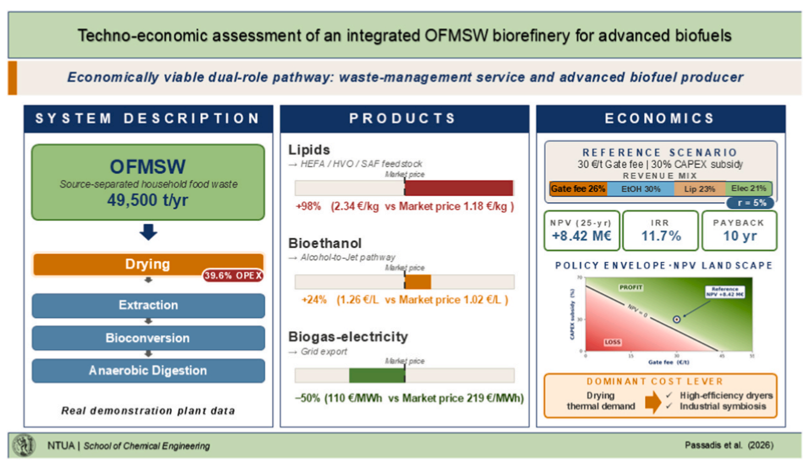
HIGHLIGHTS

- Demonstration-data-anchored TEA of an OFMSW lipids–bioethanol–biogas biorefinery.
- TEAs omitting general plant OPEX systematically overstate competitiveness.
- Reference scenario: NPV +8.4 M€, IRR 11.7%, 10-yr payback, P(NPV>0) = 90%.
- Break-even gate fees 6-25 €/t well below Greek landfill charge of 55 €;/t (2027).
- Drying = 39.6% of OPEX; high-efficiency drying or waste-heat symbiosis is the key lever.

GRAPHICAL ABSTRACT



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ABSTRACT

The organic fraction of municipal solid waste (OFMSW) is an abundant feedstock whose techno-economic potential remains poorly characterised: most published assessments rely on process simulation rather than operational data and omit general plant expenditures unavoidable at commercial scale. This work assesses a commercial-scale (49,500 t yr^{-1}) integrated biorefinery co-producing lipids, advanced bioethanol, and biogas. Process performance is scaled from a demonstration plant on source-separated household food waste, and capital, process, and general plant expenditures are explicitly modelled. A 25-year discounted cash flow model is combined with break-even mapping, deterministic sensitivity on fifteen parameters, levelised cost estimation, and Monte Carlo simulation on the eight dominant parameters. Capital investment is 16.68 M€ and annual

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operating expenditure 4.17 M€ yr^{-1}, with drying alone contributing 39.6% of OPEX. The project is not viable under market-only operation (NPV −15.50 M€); under a reference scenario of a 30 €/t gate fee and a 30% CAPEX subsidy it delivers a positive NPV of +8.42 M€ and an IRR of 11.74%. The levelised costs of 2.34 €/kg for lipids, 1.26 €/L for bioethanol, and 110 €/MWh for biogas-derived electricity place biogas in a competitive position, bioethanol within reach of the 2030 EU advanced-bioethanol price projection, and lipids above the used cooking oil benchmark. Thermal energy price and drying specific energy consumption emerge as the dominant drivers of project economics. Reducing the drying thermal demand, through high-efficiency dryers or industrial waste-heat symbiosis, is therefore the most impactful pathway to cleaner production for OFMSW biorefineries.

1. Introduction

The management of the Organic Fraction of Municipal Solid Waste (OFMSW) represents one of the most significant challenges for waste practitioners and policymakers across the European Union. Between 118 and 138 million tonnes of biowaste are generated annually in the EU, of which approximately 75 million tonnes originate from municipal sources (European Compost Network, 2023; Jensen et al., 2016). Despite this volume, a substantial fraction of OFMSW is still landfilled or incinerated, while composting and Anaerobic Digestion (AD), the dominant biological treatment routes, capture only part of the chemical and energetic value embedded in this heterogeneous feedstock. This situation calls for innovative treatment approaches that maximise resource recovery within a circular bioeconomy framework. Beyond diverting biowaste from landfill and the associated methane emissions, such approaches displace fossil-derived fuels and materials and return nutrients and energy to productive use, contributing to cleaner production across the waste-management and renewable-energy sectors (Hassanein, 2026; Renfrew et al., 2025; Ambaye et al., 2023).

The biorefinery concept enables the integrated conversion of OFMSW into multiple marketable products and energy carriers while minimising residual outputs (Arias et al., 2023; Rafey et al., 2026). Its compositional diversity, comprising carbohydrates, lipids and proteins, supports distinct conversion pathways. Individual pathways studied include bioethanol production via fermentation (Gegić et al., 2024; Singh et al., 2022), lipid recovery for biodiesel (Musharavati et al., 2024; Gaeta-Bernardi and Parente, 2016) and biogas generation through AD (Moreno et al., 2021; Karimi and Karimi, 2018). More recently, integrated multi-product configurations combining biochemical and thermochemical routes have been proposed (Molina-Peñate et al., 2024; Ladakis et al., 2022).

Beyond waste management, OFMSW biorefinery products address the demand pull of EU policy: ReFuelEU Aviation and FuelEU Maritime mandate progressive uptake of waste-derived lipids (Annex IX Part A) for HEFA/HVO and Alcohol-to-Jet pathways, while REPowerEU targets 35 billion m^3 of biomethane by 2030. An integrated biorefinery that co-produces liquid biofuel alongside biogas therefore serves both the transport-decarbonisation and renewable-gas agendas (Detsios et al., 2023; European Parliament and Council, 2023a, 2023b; European Commission, 2022).

Techno-economic assessment (TEA) is widely employed in early-stage biorefinery research to identify cost drivers and guide process optimisation (Scown et al., 2021). A growing body of TEA studies has addressed biofuel production from OFMSW and food waste, employing a range of economic indicators from simple cost estimation to discounted cash flow analysis (Molina-Peñate et al., 2024; D'Adamo et al., 2023; Chen et al., 2022; Meng et al., 2021; Muhammad and Rosentrater, 2020; Gaeta-Bernardi and Parente, 2016). Yet these studies derive their process inputs from laboratory experiments, literature data, or process simulation rather than sustained pilot or demonstration scale operation. Papagianni et al. (2024) found that only 5% of 150 reviewed biofuel case studies used pilot- or demonstration-scale data. Three gaps compound this. First, most analyses omit general plant expenditures such as labour, supervision, insurance, and maintenance, which are substantial at commercial scale (Peters et al., 2003); the resulting underestimation yields optimistic projections that may partly explain the scarcity of final investment decisions for OFMSW biorefineries. Second, although gate fees (Meng et al., 2021) and biogas incentive tariffs (D'Adamo et al., 2023) have been examined individually, none has mapped the combined gate-fee and capital-subsidy support needed for viability across biorefinery configurations. Third, no existing TEA addresses the integrated co-production of extractable lipids, bioethanol, and biogas, or the economic interactions between these streams, within a single OFMSW biorefinery.

In a companion study, Passadis et al. (2025), assessed the operational energy and cost performance of a demonstration-scale biorefinery processing source-separated household food waste into lipids, bioethanol, and biogas. That study established the process-level feasibility, but its scope was limited to operational expenditures at demonstration scale. The present study extends that foundation to a comprehensive TEA of a scaled-up biorefinery processing almost 50,000 tonnes of wet OFMSW per year, a commercially relevant scale representative of a medium-sized European municipality. The specific objectives are: (i) to develop a techno-economic model incorporating capital and operating expenditures, with yields and energy demands grounded in demonstration-scale data; (ii) to evaluate viability through Net Present Value (NPV), Internal Rate of Return (IRR), payback period, and the Levelised Cost Of each Fuel or Electricity (LCOF/LCOE); (iii) to determine the minimum gate fee and capital subsidy levels required for viability through break-even and sensitivity analyses, (iv) to benchmark the LCOF/LCOE against current EU market prices. The novelty of this work is therefore threefold: to our knowledge it is the first TEA of an integrated OFMSW biorefinery co-producing lipids, bioethanol, and biogas; its process performance is grounded in demonstration-scale operational data rather than simulation; and it explicitly includes general plant expenditures and maps the combined gate-fee and capital-subsidy support required for viability.

2. Methodology

2.1. System description and scale-up basis

The biorefinery configuration analysed in this study has been described in detail in a companion study which presented the demonstration-scale mass and energy balances, process yields, and conversion efficiencies used as the basis for the present TEA (Passadis et al., 2025). Unless otherwise stated, all process parameters were adopted from that work. The key process specifications and balance values relevant to the present analysis are summarised in Supplementary §S1. The system processes source-separated household food waste (simplified as OFMSW) through four sequential units: (i) a rotary drum dryer; (ii) a hexane-based solid-liquid extraction unit for lipids recovery; (iii) a bioconversion unit where the defatted residue undergoes simultaneous saccharification and fermentation (SSF) followed by thermal distillation to produce bioethanol at 95% v/v purity; and (iv) a mesophilic (40 °C) AD unit coupled with a combined heat and power (CHP) engine.

The TEA is based on a commercial-scale plant located in Greece that processed 150 t/d of wet food waste over 330 operating days per year, corresponding to an annual throughput of 49,500 t/yr (Supplementary

§S3). Two aspects of the commercial-scale configuration differ from the demonstration plant and warrant explanation: the drying energy performance and the anaerobic-digestion reactor type. The drying specific energy consumption (SEC) is adopted as 0.80 kWh/kg H_2O, below the 1.20 kWh/kg H_2O measured at the non-optimised demonstration dryer, which would not be representative of a commercial-scale baseline. This value is consistent with reported and commercial performance for indirect, heat-integrated dryers (Havlík and Dlouhý, 2020; Huber, 2023; Martynenko and Alves Vieira, 2023). Even where such a value is not a characteristic of a given drying technology, it can be attained within the wider system through heat integration and the valorisation of available waste heat; it therefore remains a valid benchmark against which to evaluate the drying step. A detailed justification, including the demonstration-dryer characteristics and the values reported by each source, is provided in Supplementary §S3.

In addition, the AD unit was modelled as a continuously stirred tank reactor (CSTR). Although the stillage leaving bioconversion has a total solids content of 20.3%, the feed reaching the digester in continuous operation has a total solids content of approximately 14.7%, which lies within the wet-digestion regime (TS < 15%). The CSTR is the configuration conventionally applied to wet digestion at this solids content, whereas plug-flow designs are characteristic of high-solids and dry digestion (typically 20–40% TS) (Prasanna Kumar et al., 2024); the commercial unit was therefore specified as a CSTR rather than the PFR used at demonstration scale. The feed was conditioned further to approximately 10% TS to improve mixing and loading conditions (Supplementary §S3). The digester was sized at an organic loading rate of 3.2 kg VS m^{-3} d^{-1}, within the 2–6 kg VS m^{-3} d^{-1} range typical of CSTR biogas processes (Schnürer et al., 2016), corresponding to a hydraulic retention time of 30 days. On the basis of this conservative loading and residence time, together with the pre-processed character of the feed (Supplementary §S3), the demonstration-scale specific biogas yield of 0.31 m^3 kg^{-1} VS was retained as a design assumption. The key plant design parameters and feedstock properties are summarised in Table 1, and the corresponding annual mass balance tracing the 49, 500 t yr^{-1} wet feedstock is presented in Table 2.

2.2. Cost estimation and revenue assumptions

2.2.1. Capital expenditure estimation

Equipment costs for the drying, lipids extraction, bioconversion, and distillation units were estimated using the power-law scaling relationship (Equation (1)) (Peters et al., 2003):

Table 1
Key plant design parameters and feedstock properties.

Parameter	Value	Source
Plant configuration		
Plant capacity (t/d)	150	*Design basis*
Annual throughput (t/yr)	49,500	
Feedstock properties		
Initial moisture (% w.b.)	75.9	S2 of Supplementary Material
Lipids content (% d.b.)	11.2	
Starch content (% d.b.)	7.7	
Cellulose content (% d.b.)	14.6	
Volatile solids (%)	90.5	
Process performance		
Drying SEC (kWh/kg H_2O)	0.80	Martynenko and Alves Vieira (2023)
Lipids extraction efficiency (%)	85	S1 of Supplementary Material
Starch/cellulose hydrolysis (%)	95/85	
Fermentation efficiency (%)	96	
Distillation SEC (kWh/L EtOH)	2.2	
AD biogas yield (m^3/kg VS)	0.31	
CHP electrical/thermal efficiency (%)	37/49	Ciuła et al. (2022)

Table 2
Summarised commercial-scale annual mass balance (49,500 t yr^{-1}wet OFMSW, 330 operating days).

Stream	Quantity	Unit
Feedstock – wet OFMSW	**49,500**	t yr^{-1}
Dry solids (24.2% w.b.)	11,979	t yr^{-1}
Water content (75.8%w.b.)	37,521	t yr^{-1}
Drying		
Water evaporated	36,190	t yr^{-1}
Dried solids to extraction	13,310	t yr^{-1}
Lipid extraction		
Lipids	1140	t yr^{-1}
Defatted residue to bioconversion	10,839	t yr^{-1}
Hexane losses	47.8	t yr^{-1}
Bioconversion		
Bioethanol	1672	m^3 yr^{-1}
Fermentation CO_2	1263	t yr^{-1}
Added process water	32,516	t yr^{-1}
Stillage to AD	40,772	t yr^{-1}
Anaerobic digestion	96	
Biogas	2.48×10^6	m^3 yr^{-1}
Net electricity	5184	MWh yr^{-1}
Added process water	47,336	*t yr^{-1}*
Solid digestate	5576	*t yr^{-1}*
Liquid effluent to treatment	43,201	*t yr^{-1}*
Liquid effluent recycled to digester	28,800	*t yr^{-1}*

Detailed unit-level balances are provided in Supplementary §S1 & §S3.

$$C_2 = C_1 \times \left(\frac{Q_2}{Q_1}\right)^n \quad (1)$$

where C_1 is the known equipment cost at the demonstration scale, C_2 is the estimated cost at the target scale, Q_1 and Q_2 are the respective capacities (t/d), and n is the scaling exponent, set to 0.6 (the six-tenths rule). The 150× ratio between demonstration (1 t/d) and commercial (150 t/d) scale lies beyond the approximately one-order-of-magnitude range over which the six-tenths correlation is most reliable (Peters et al., 2003). In the absence of vendor-quoted commercial costs, a uniform exponent of $n = 0.6$ was retained at this screening level. The resulting capital-cost uncertainty bounded through a ±30% perturbation of total capital investment in the sensitivity analysis (Supplementary §S4).

The demonstration-scale equipment costs were derived from procurement records at 1 t/d capacity. Total installed costs were estimated using the Peters factorial method (Peters et al., 2003), with the individual cost factors listed in Table 3. This factorial was applied exclusively to the liquid biofuel units; for the AD/CHP unit a turnkey installed cost of 5000 €/kW was adopted, in the upper range of European AD/CHP costs, reflecting the additional pre-treatment and contamination-handling required for OFMSW (Motola et al., 2023).

The estimate CAPEX is developed on a greenfield, standalone basis. Storage infrastructure is captured within the buildings and service-facility factors of the Peters build-up, contamination and pre-treatment handling within the AD/CHP turnkey cost, and ATEX-compliant provisions for hexane handling within the scaled extraction-unit equipment cost; permitting and any additional safety systems beyond these are not capitalised and are acknowledged as screening-level exclusions.

2.2.2. Operating expenditure estimation

Annual OPEX was disaggregated into process-specific costs and general plant costs (Table 3). Process OPEX comprises thermal and electrical energy, consumables (hexane, enzymes, yeast, and process water), and equipment maintenance. Solvent recovery is reflected through the closed-loop hexane system, with make-up limited to the recovery losses; dedicated treatment of the non-recycled liquid effluent of AD and odour-control operation are not separately costed and are acknowledged as screening-level exclusions. General plant OPEX covers

Table 3
Cost estimation parameters.

Parameter	Value	Reference
CAPEX estimation (Peters factorial)		
Scaling exponent, n	0.6	(Peters et al., 2003)
Installation	25% of equip.	
Service facilities and yard	11% of equip.	
Buildings	20% of equip.	
Land	2.3% of equip.	
Indirect costs	15% of direct	
Working capital	15% of FCI	
AD/CHP turnkey cost[a]	5000 €/kW	European Commission (2019)
Process OPEX		
Equipment maintenance	3%/yr of equip.	Peters et al. (2003)
Drying allocation (lipids/ethanol)	80/20%	
General plant OPEX[b]		
Operating labour	15% of process OPEX	Peters et al. (2003)
Supervisory and clerical	15% of labour	
Laboratory charges	15% of labour	
Operating supplies	5% of maintenance	
Plant overhead	5% of total OPEX	
Fixed charges (insurance, taxes)	5% of total OPEX	
Utility and consumable prices		
Grid electricity	0.10 €/kWh	Greek Energy Market[c]
Thermal energy	0.059 €/kWh	Passadis et al. (2025)
Hexane	660 €/m^3	Current European market[d]
Enzymes (amylase/cellulase)	1.00 €/L	Felekis et al. (2023)
Yeast	1.20 €/kg	Felekis et al. (2023)
Process water	1.00 €/m^3	EYDAP[e]

[a] Upper range reflecting additional pre-treatment requirements for OFMSW (European Commission, 2019).
[b] Applied to liquid biofuel units only; AD/CHP carries industry-specific OPEX (CHP maintenance 15 €/MWh, digestate handling 3 €/t, biologicals 25,000 €/yr).
[c] RAAEY: Regulatory Authority for Energy, Waste and Water, Greece.
[d] Based on current European Market prices of hexane.
[e] Based on the most recent data of the relevant Greek authority for water supply (EYDAP).

operating labour, supervisory and clerical staff, laboratory charges, operating supplies, plant overhead, and fixed charges, estimated using the factorial approach applied to the liquid biofuel units (Peters et al., 2003). The AD/CHP unit carries its own industry-specific OPEX structure including CHP maintenance, digestate handling and transport, and biological additives. Drying energy cost was allocated 80% to lipids and 20% to bioethanol. This allocation, on the basis of physical causality, reflects the operational rationale of the drying stage: moisture reduction below 10% w.b. is a prerequisite for efficient hexane-based lipids extraction, which constitutes the primary driver of the drying unit's energy demand. The defatted residue subsequently entering the bioconversion unit benefits from the drying step but does not impose the same stringent moisture requirement, justifying the lower allocation share.

2.2.3. *Financial analysis framework*

The economic viability of the biorefinery was evaluated through a 25-year Discounted Cash Flow (DCF) analysis (Peters et al., 2003; Short et al., 1995). All financial parameters are summarised in Table 4. The NPV was calculated based on Equation (2):

$$NPV = -I_0 + \sum_{t=1}^{N} \frac{NCF_t}{(1+r)^t} \tag{2}$$

where I_0 is the net capital investment after subsidy (€), NCF_t is the after-tax net cash flow in year t (€/yr), r is the real discount rate, and N is the project lifetime (years). The detailed cash flow structure including the income statement and tax treatment is provided in the supplementary material (Table S7a and S7b). The payback period is defined as the earliest year in which the cumulative NPV turns positive.

Table 4
Revenue and financial assumptions.

Parameter	Value	Reference
Revenue Assumptions		
Lipids (€/kg)	1.18	Prykhodko (2025) [a]
Bioethanol (€/L)	1.02	European Commission (2024) [b]
Biogas (€/MWh)	219	Hellenic Parliament (2016) [c]
Solid digestate [d] (€/kg)	0.01	-
Gate fee[e] (€/t)	0-55	-
Financial parameters		Analysis parameters
Discount rate (%)	5	
Project lifetime (years)	25	
Corporate tax rate (%)	22[f]	
Depreciation (%)	8	
CRF (yr^{-1})	0.071	
Policy instruments (sensitivity range)		
CAPEX subsidy (%)	0-70	

[a] UCO market price, December 2024.
[b] Projected advanced bioethanol: 2016 €/toe ≈ 1.02 €/L.
[c] Corresponds to the Reference Price applicable to biogas plants with installed capacity ≤ 1 MW under Article 4 of Law 4414/2016, disbursed through the Feed-In Premium mechanism.
[d] European Compost Network Data Report 2022: Compost and Digestate for a Circular Bioeconomy. European Compost Network, Bochum, Germany.
[e] Sensitivity range: Greek municipalities face escalating landfill charges reaching 55 €/t by 2027 (Law 4819/2021), making alternative treatment economically attractive even at lower gate fees.
[f] Greek corporate tax.

The LCOF/LCOE was calculated for each product using the Capital Recovery Factor (CRF) approach, assuming constant annual operation and performance throughout the project lifetime (i.e., no equipment degradation). This assumption is supported by the absence of components subject to intrinsic performance decay, such as catalysts or membranes; equipment performance is sustained by the routine maintenance included in the operating expenditure, while the 330-day annual operating basis already reflects downtime and maintenance outages.

The CRF is given by Equation (3):

$$CRF = \frac{r\,(1+r)^N}{(1+r)^N - 1} \tag{3}$$

where, r is the real discount rate and N is the project lifetime. The LCOF/LCOE for each product j is then (Equation (4)):

$$LCOF_j = \frac{CRF \times CAPEX_j + OPEX_j}{P_j} \tag{4}$$

where $CAPEX_j$ is the allocated capital cost for product j (€), $OPEX_j$ is the allocated annual operating cost (€/yr), and P_j is the annual production of product j (kg/yr, L/yr, or MWh/yr). Cost allocation follows the physical-causality basis described in Section 2.2.2, with drying costs split 80:20 between lipids and bioethanol; unit-specific costs are assigned entirely to their corresponding product. General plant OPEX was distributed across products in proportion to their direct OPEX share. The LCOF is reported both with and without general plant OPEX to enable comparison with the literature, where indirect costs are frequently omitted. Equivalently, the IRR is the discount rate at which the sum of discounted net cash flows equals zero (Equation (5)):

$$\sum_{t=0}^{N} \frac{NCF_t}{(1+IRR)^t} = 0 \tag{5}$$

The product selling prices, financial parameters, and policyinstrument ranges used in the cash-flow model are summarised in Table 4.

2.2.4. Sensitivity and uncertainty analysis

The robustness of the economic assessment was evaluated through a multi-level framework progressing from policy mapping to parametric sensitivity to stochastic risk analysis.

2.2.4.1. Break-even analysis and scenario definition. The unsubsidized base case (zero gate fee, zero CAPEX subsidy) was first evaluated to establish the economic gap that waste-management revenue and public capital support must jointly close. A break-even analysis was then conducted to identify the gate fee-subsidy combinations yielding NPV = 0. The gate fee is the charge paid by municipalities for the treatment of their OFMSW and is bounded above by the prevailing landfill tax. It was varied from 0 to 55 €/t, with the upper bound corresponding to the Greek landfill charge applicable from 2027 (Hellenic Parliament, 2021). The CAPEX subsidy, which represents direct public capital support analogous to the Greek National Strategic Reference Framework (NSRF) programme for circular-economy projects, was varied from 0 to 70%. The combined effect of these two instruments was visualised as two-dimensional heatmaps of NPV and IRR, while a one-dimensional representation of NPV versus gate fee at two representative subsidy levels (0% and 30%) was additionally prepared to visualise the individual break-even points. A reference scenario of 30 €/t gate fee with 30% CAPEX subsidy was then selected from the viable region, representing a conservative and realistic configuration for a Mediterranean EU Member State.

2.2.4.2. Deterministic sensitivity. A one-at-a-time (OAT) local sensitivity analysis was conducted around the reference scenario on fifteen key parameters (Table 5). Each parameter was varied by ±30% of its reference value while all others were held constant, and the resulting NPV was recorded. For parameters identified as dominant cost drivers, their combined effect with gate fee was further examined through two-dimensional NPV heatmaps, allowing the minimum market conditions required at different process performance levels to be identified. The LCOF of each product was calculated both with and without general plant OPEX to quantify the effect of indirect cost inclusion on production cost estimates, as these costs are frequently omitted in the literature.

2.2.4.3. Stochastic risk analysis. The deterministic sensitivity isolates the individual influence of each parameter but cannot capture the joint effect of multiple parameters varying simultaneously, as occurs in practice. To quantify the combined uncertainty of the most economically relevant inputs, a Monte Carlo simulation with 10,000 iterations was performed following standard TEA convention (Humbird et al., 2011; Vicari et al., 2012). The eight parameters identified as dominant drivers by the deterministic tornado (Fig. 3) were selected for stochastic treatment. Each parameter was sampled independently from a triangular probability distribution with its mode set equal to the reference value and its bounds set at ±30% of the reference, matching the perturbation envelope used in the deterministic analysis. Triangular distributions are standard under limited distributional information. The model was evaluated for each sampled combination, producing a distribution of 10,000 NPV outcomes from which the probability of a positive NPV together with the median NPV and the 5th-95th percentile range were derived as measures of overall investment risk.

Table 5
Parameters included in the one-at-a-time (OAT) deterministic sensitivity analysis.

Parameter	Base	Low (−30%)	High (+30%)	Unit
Gate fee	30	21	39	€/t
CAPEX subsidy	0.30	0.21	0.39	-
Lipids selling price	1.18	0.826	1.534	€/kg
Bioethanol selling price	1.02	0.714	1.326	€/L
Biogas-derived electricity selling price	219	153.3	284.7	€/MWh
Digestate selling price	0.01	0.007	0.013	€/kg
Thermal energy price	0.059	0.0413	0.0767	€/kWh
Grid electricity price	0.10	0.07	0.13	€/kWh
Drying specific energy consumption	0.80	0.56	1.04	kWh/kg H_2O
Enzymes (cellulase + amylase)	1.00	0.70	1.30	€/L
Yeast cost	1.20	0.84	1.56	€/kg
Total capital investment	16.68	11.68	21.69	M€
Lipid content	11.2	7.84	14.56	% d.b.
Starch content	7.7	5.32	9.88	% d.b.
Cellulose content	14.6	10.15	18.85	% d.b.

Base values at the reference scenario. Gate fee and CAPEX subsidy appear here only for completeness.

3. Results and discussion

3.1. CAPEX and OPEX structure

Fig. 1 and Table 6 present the capital and operating cost structure of the commercial scale biorefinery at the reference scenario (150 t/d wet OFMSW, 49,500 t/yr). The bioconversion unit is the single largest contributor at 33.0%, reflecting the combined cost of the SSF bioreactor and the distillation column. The remaining three units each lie between 20% and 26%, meaning that the capital outlay is spread across the integrated chain rather than concentrated in any single piece of equipment. Total annual operating cost amounts to 4.17 M€/yr, with a markedly less balanced distribution than the CAPEX. The drying unit dominates at 39.6% (1.65 M€/yr), nearly double its 20.3% CAPEX share. General OPEX, comprising labor, overhead, supplies, and fixed charges unallocated to any specific unit, accounts for a further 27.5%.

The per-category view in Fig. 1c pinpoints the mechanism behind the drying unit's OPEX dominance: thermal energy is the single largest category at 41.7% of total OPEX, and approximately 84% of that thermal energy (1.46 M€/yr) is consumed by the drying unit alone. The concentration arises directly from the drying duty required to dewater the high moisture feedstock. The dominance of drying is a recurring structural pattern in wet feedstock biorefineries. Molina-Peñate et al. (2024) reported drying consuming 53-68% of total energy in a 100,000 t/yr OFMSW enzymatic-hydrolysis biorefinery, and Martynenko and Alves Vieira (2023) attribute this pattern to the fundamental thermodynamic cost of water evaporation, which scale-up cannot eliminate.

3.2. Break-even analysis and reference scenario selection

3.2.1. Break-even analysis

Given the 16.68 M€ capital investment and 4.17 M€/yr operating cost reported in Section 3.1, the biorefinery is unprofitable under purely market and policy-driven operation (Table 7, unsubsidized base case): without a gate fee from waste-management contracts and without a CAPEX subsidy from public support, the project loses 15.5 M€ over its 25-year lifetime. The break-even point (BEP), the locus of gate fee and CAPEX subsidy combinations yielding NPV = 0, is traced as the solid black contour in Fig. 2a, b. As the CAPEX subsidy increases, the gate fee required to reach this BEP drops from 25 €/t at zero subsidy to 17 €/t at 30%, and to 6 €/t at 70% (Fig. 2c).

All three break-even gate fees lie below the 55 €/t Greek landfill charge applicable from 2027, with the competitive margin widening as the CAPEX subsidy increases. Fig. 2b expresses the same parameter space through IRR. Profitability rises steeply once the BEP is crossed, but the highest returns, approaching more than 20%, occur only in the upper region of the map that combines a high gate fee with strong capital subsidy. These returns therefore reflect the level of policy support applied rather than market profitability alone.

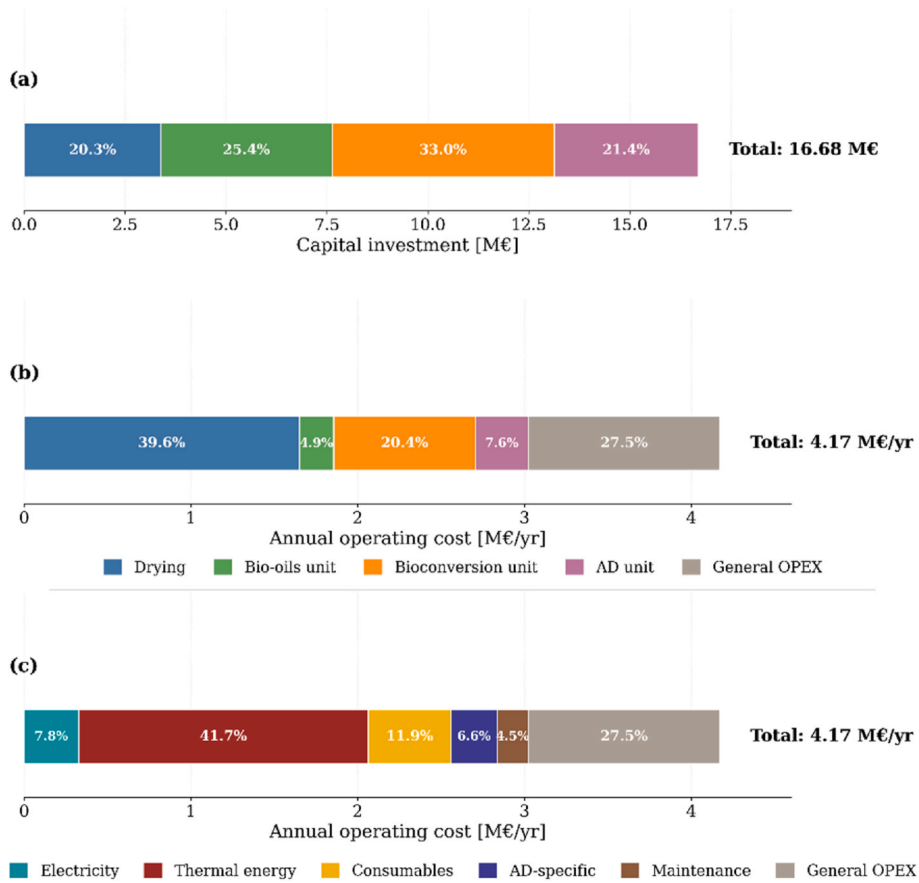

Fig. 1. CAPEX and OPEX structure of the commercial scale biorefinery at the reference scenario (150 t/d wet OFMSW; (a) CAPEX breakdown by process unit; (b) OPEX breakdown by process unit; (c) OPEX breakdown by cost category.

Table 6
Summary of capital and operating costs of the commercial scale biorefinery at the reference scenario (49,500 t/yr OFMSW).

Cost item	Value	Share
CAPEX (M€)		
Drying	3.39	20.3%
Extraction unit	4.23	25.4%
Bioconversion unit	5.50	33.0%
AD unit	3.56	21.4%
Total CAPEX	**16.68**	**100.0%**
OPEX (M€/yr)		
Drying	1.65	39.6%
Extraction unit	0.21	4.9%
Bioconversion unit	0.85	20.4%
AD unit	0.32	7.6%
General OPEX	1.14	27.5%
Total OPEX	**4.17**	**100.0%**

CAPEX and OPEX values are described in detail in supplementary file (§S4, §S5).

3.2.2. Reference scenario

On this basis, a reference scenario of 30 €/t gate fee and 30% CAPEX subsidy was adopted as the anchor for all subsequent analyses delivering an NPV of +8.42 M€ and an IRR of 11.74% (Table 7). Gate-fee income accounts for 26% of total annual revenue, underlining the dual role of the plant as both an energy producer and a waste-management service, consistent with Meng et al. (2021), who reported that gate fees contributed 64% of total revenues in their OFMSW-to-ethanol biorefinery. Whole-plant viability assessments of OFMSW biorefineries remain scarce and predominantly simulation-based: Molina-Peñate et al. (2024) report a positive NPV, an IRR below 12.8% and a six-year payback period for a process-modelled multi-product configuration producing biopesticides and biogas, while Anaya-Reza et al. (2022) obtain a negative NPV without subsidy for a simulated Mexican biomethane–cogeneration system, mirroring the structural dependence on policy support observed here. The present assessment extends both studies by anchoring the commercial-scale analysis in validated demonstration-plant data (Passadis et al., 2025). The 30 €/t gate fee is conservative against the 55 €/t Greek landfill benchmark, and the 30% subsidy lies well below the up to 85% EU co-financing rate available under Greek NSRF 2021-2027 PEKA programme (Hellenic Ministry of Environment and Energy, 2022).

3.3. Deterministic sensitivity analysis

The deterministic sensitivity analysis translates the cost-structure observation of Section 3.1, that drying dominates the operating cost through its thermal-energy demand, into a quantified ranking of the parameters governing profitability. Fig. 3 presents the NPV response of the biorefinery to a flat ±30% perturbation of each of the fifteen

Table 7
Comparison of the commercial scale biorefinery under an unsubsidized base case and the reference scenario.

	Unsubsidized base case (0 €/t, 0% subsidy)	Reference scenario (30 €/t, 30% subsidy)
Lipids		
Annual production (t yr^{-1})	1140	
LCOF (€ kg^{-1})	2.34	
Selling price (€ kg^{-1})	1.18	
Bioethanol		
Annual production (m^3 yr^{-1})	1672	
LCOF (€ L^{-1})	1.26	
Selling price (€ L^{-1})	1.02	
Biogas-CHP		
Annual net electricity (MWh yr^{-1})	5184	
LCOE (€ MWh^{-1})	110	
Selling price (€ MWh^{-1})	219	
Plant-level		
Annual product revenue (M€ yr^{-1})	4.24	
Annual gate fee revenue (M€ yr^{-1})	0	1.49
Total annual revenue (M€ yr^{-1})	4.24	5.73
Annual OPEX (M€ yr^{-1})	4.17	
Total CAPEX, gross (M€)	16.68	
Net investment after subsidy (M€)	16.68	11.68
EBITDA (M€ yr^{-1})	0.08	1.56
NPV, 25-year (M€)	−15.50	+8.42
IRR (%)	N.A.	11.74
Payback period (yr)	N.A.	10

LCOF and LCOE values are reported on a full-cost basis, including allocated general plant OPEX. A year-by-year cash-flow breakdown at the reference scenario is provided in the Supplementary Material (S6).

parameters listed in Table 4, ranked from largest to smallest swing around the reference scenario. The vertical red dashed line marks the NPV = 0 threshold at a deviation of −8.42 M€ from the reference point; any parameter whose unfavourable bar reaches this line is capable of pushing the project into loss territory under an isolated perturbation.

Two thermal-energy parameters dominate the ranking. The thermal energy price generates the largest swing (17.3 M€) and the drying SEC is nearly identical (17.0 M€). Both bars extend past the NPV = 0 line on their unfavourable side: at a thermal price of 0.077 €/kWh or a drying SEC of 1.04 kWh/kg H_2O, the reference scenario shifts into marginal loss (NPV ≈ −0.7 M€). The dominance of thermal energy price and drying specific energy consumption identified here contrasts with Molina-Peñate et al. (2024), whose equivalent sensitivity analysis for an OFMSW biopesticide biorefinery identified enzyme cost as the dominant driver. The same pattern is observed in Bastidas-Oyanedel and Schmidt (2018), whose sensitivity ranking for a 50 t/d food waste biorefinery operating under multiple AD-based scenarios identified capital cost and methane-related parameters as the dominant drivers, with no thermal energy or drying parameter appearing in the ranking. Both observations illustrate that sensitivity drivers map onto the product slate and the resulting process route rather than onto the feedstock itself. The dominance of these two thermal parameters underlines the value of reducing the drying thermal demand and its exposure to energy prices; the waste-heat-symbiosis pathway that addresses this directly is quantified in Section 3.6.

A second cluster of parameters captures market and policy revenue. Bioethanol price (11.8 M€), gate fee (10.2 M€), lipids price (9.2 M€), and the biogas-derived electricity price (7.7 M€) form a band of comparable sensitivity. These lie substantially below the two thermal-energy drivers but well above the remaining parameters and together they define the project's exposure to external market and policy conditions. Although gate fee and CAPEX subsidy appear here as local sensitivities, their full response across the policy and market relevant range is characterised in Fig. 2 (Section 3.2); the tornado represents only a local perturbation around the reference point.

Feedstock composition shows a marked asymmetry. Lipid content ranks sixth with a swing of 8.5 M€, comparable to the CAPEX multiplier (8.0 M€), whereas starch (2.0 M€) and cellulose (2.6 M€) contents have considerably smaller effects.

The remaining nine parameters each displace NPV by less than 4 M€ over the ±30% window. The smallest swings come from the enzyme bundle (1.0 M€) and the digestate price (0.5 M€).

The eight parameters selected for stochastic analysis (Section 3.5) are, in descending order of swing: thermal energy price, drying SEC, bioethanol price, gate fee, lipids price, biogas feed-in tariff, lipid content, and the CAPEX multiplier.

3.4. Levelised cost of fuels and electricity

This section reframes the cost information on a per-unit-of-output basis through the LCOF for lipids and bioethanol, and LCOE for biogas-derived electricity (Equation (4)). Two LCOF values are reported in Fig. 4: (a) the full LCOF including the general OPEX, and (b) the process-only LCOF excluding it. The sensitivity of the lipid and bioethanol LCOF to the drying-allocation ratio is examined in Supplementary §S8.

3.4.1. Levelised cost of lipids

The full LCOF of lipids is 2.34 €/kg, almost twice the European reference price for used cooking oil (UCO) at 1.18 €/kg (Prykhodko, 2025). The UCO price used here is a December 2024 spot reference and is subject to market variability; UCO prices have risen in recent years (Prykhodko, 2025), and a higher benchmark would narrow the gap to the lipid LCOF. Excluding the general OPEX (Fig. 4b) reduces the lipids LCOF to 1.77 €/kg, halving the gap to UCO but leaving the product uncompetitive on a process-only basis. Direct benchmarking against published commercial-scale TEAs is constrained: no study isolates lipid-extraction cost from OFMSW (Musharavati et al., 2024), and recent OFMSW lipid-extraction studies (Sini et al., 2025) remain at laboratory scale and report extraction yields and product chemistry without economic analysis. UCO market price is therefore adopted as the functional benchmark, given the shared triglyceride and FFA composition and identical downstream conversion pathways.

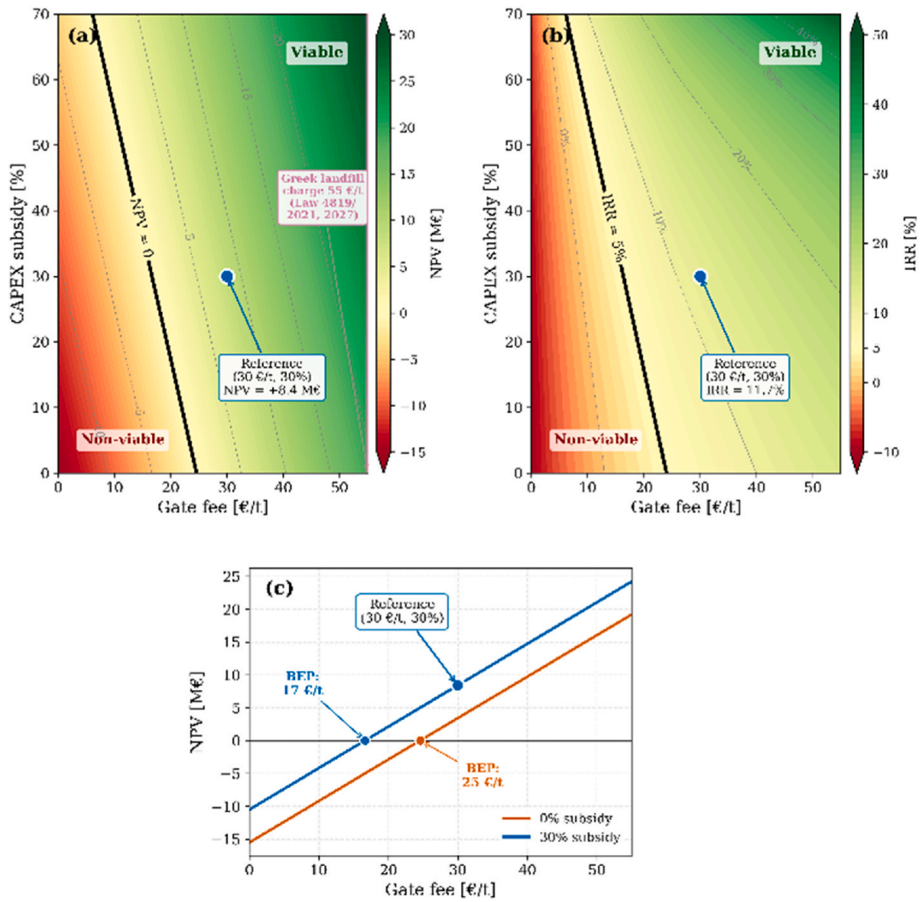

Fig. 2. Financial viability of the OFMSW biorefinery as a function of gate fee and CAPEX subsidy: (a) impact on NPV, with the NPV = 0 frontier marking the viability threshold; (b) impact on IRR, with the IRR = 5% contour matching the discount rate; and (c) NPV versus gate fee at 0% and 30% CAPEX subsidy.

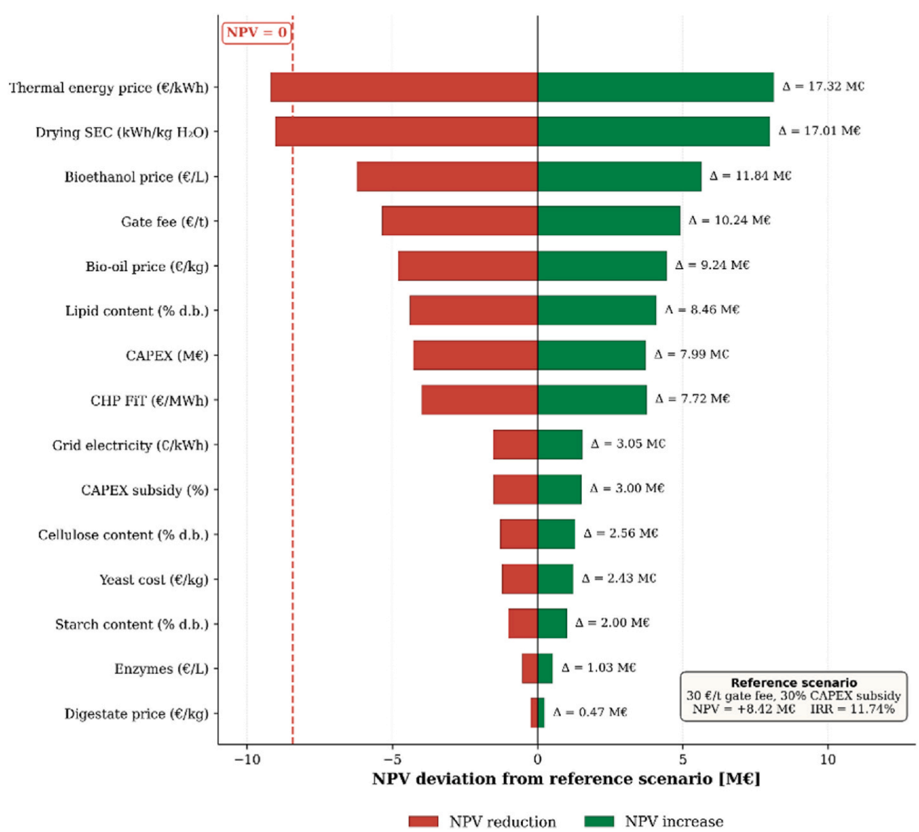

Fig. 3. Tornado diagram of NPV sensitivity to a flat ±30% perturbation of each of the fifteen parameters listed in Table 4, ranked by swing magnitude.

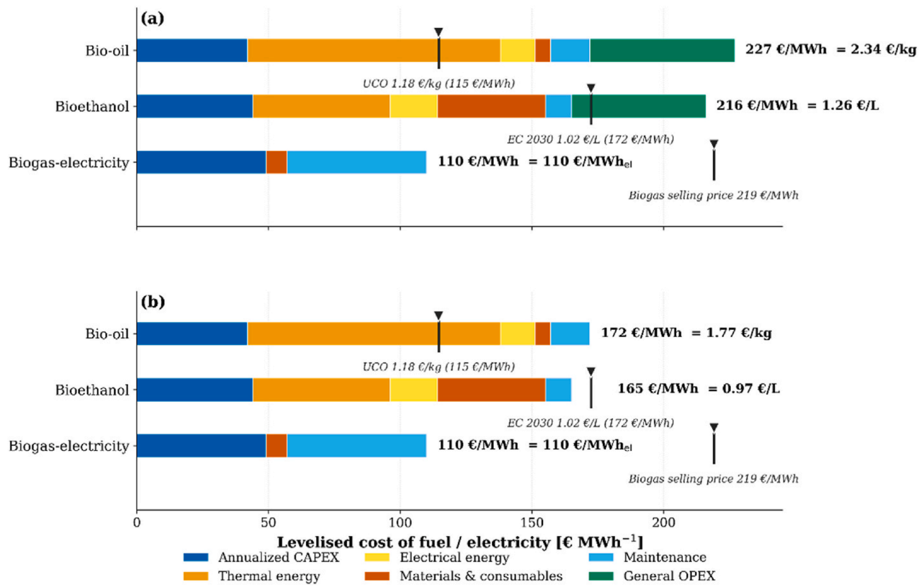

Fig. 4. LCOF and LCOE for the three biorefinery products. (a) Full LCOF includes the general OPEX; (b) process-only LCOF excludes it.

3.4.2. *Levelised cost of ethanol*

The full LCOF of bioethanol is 1.26 €/L, approximately 24% above the European Commission projected average selling price for advanced bioethanol of 1.02 €/L by 2030 (European Commission, 2024). Unlike lipids, its cost composition is balanced: thermal energy (52 €/MWh), materials and consumables (41 €/MWh, dominated by enzymes and yeast), general OPEX (51 €/MWh), and annualised CAPEX (45 €/MWh) all contribute comparable shares. The process-only LCOF (Fig. 4b) drops to 0.97 €/L (165 €/MWh), placing bioethanol approximately 5% below the EC 2030 projection. Two simulation-based food-waste TEAs report lower MESPs: 0.64 €/L for a 2000 t/d SuperPro model (Muhammad and Rosentrater, 2020) and 0.43 €/L for a 10 t/d enzymatic-hydrolysis plant (Chen et al., 2022), but both rely on process simulation rather than scale-up from operating data and treat homogeneous food-waste streams rather than heterogeneous OFMSW. The gap to these simulated MESPs reflects real-world feedstock heterogeneity and operational reality (Imtiaz, 2024; Peters et al., 2003). In the broader 2G bioethanol context, the present full LCOF of 1.26 €/L falls below the commercial-scale MESPs of 2.19 and 2.45 €/L reported by Correia et al. (2024), confirming competitiveness with alternative lignocellulosic pathways.

3.4.3. *Levelised cost of electricity*

The LCOE of biogas-derived electricity is 110 €/MWh, approximately half the 219 €/MWh selling price applied for the reference scenario. This value sits inside the 101.4-147.4 €/MWh range that Banja et al. (2019) reported for German biogas plants. It is also below the value of approximately 175 €/MWh reported by Thi et al. (2016) which is a representative value from a review rather than a plant-specific estimate. These figures are indicative rather than strictly comparable, since the system boundaries of the reference studies differ from the integrated configuration assessed here, where the AD unit shares feedstock and infrastructure with the upstream units. Such boundary differences are an important determinant of reported AD economics, alongside feedstock composition and plant scale (Prasanna Kumar et al., 2024; Bhatt and Tao, 2020), and the position of the present LCOE within the reported values should be read in that light.

3.5. *Stochastic risk analysis*

Stochastic treatment remains uncommon for OFMSW multi-product biorefineries, where assessments typically rely on deterministic sensitivity and scenario analysis (Anaya-Reza et al., 2022; Molina-Peñate et al., 2024). Fig. 5 presents the NPV distribution obtained from Monte Carlo iterations in which the eight dominant parameters identified in Section 3.3 were sampled jointly from independent triangular distributions (mode equal to the reference value, bounds at ±30%). The median NPV is +8.6 M€, closely matching the deterministic reference (+8.4 M€), with the 5th and 95th percentiles at −2.5 and + 17.6 M€, respectively, defining a 90% confidence interval of 20.0 M€. The probability of a positive NPV across the 10,000 iterations is P(NPV > 0) = 90.4%, confirming that the reference scenario remains in viable territory under the joint variation of the eight dominant parameters. Two caveats apply to the interpretation of this result. First, the eight parameters were sampled independently. In practice, energy prices, commodity-linked product prices, and policy instruments are mutually correlated. Depending on the sign of these corelations, the true confidence interval may be narrower (where energy costs and energy-linked revenues co-vary and partially offset) or wider (where variability is concentrated on the revenue side), depending on the sign of these correlations. Second, broader or asymmetric distributions, particularly on the revenue side, would lower P(NPV > 0). The reported probability of 90.4% should accordingly be regarded as a first-order estimate, conditional on the assumption of parameter independence.

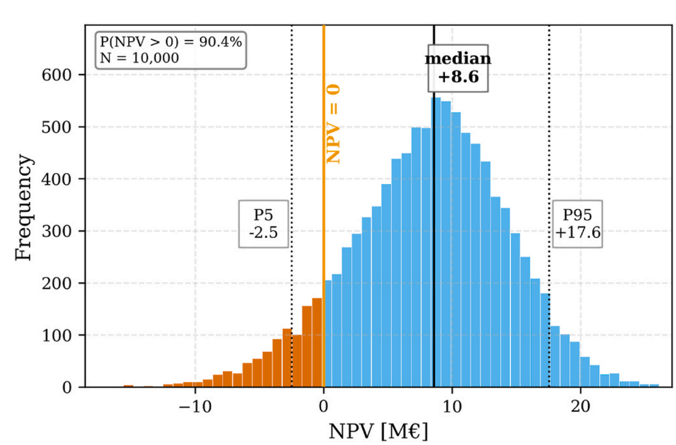

Fig. 5. Monte Carlo NPV distribution of the OFMSW biorefinery at the reference scenario (10,000 iterations, eight dominant parameters sampled from triangular distributions at ±30%).

3.6. Circular-economy and environmental implications

Although a full environmental assessment lies beyond the scope of this study, the proposed biorefinery carries several circular-economy and cleaner-production benefits. The system diverts 49,500 t/yr of source-separated organic waste from landfill. It also follows a cascading logic, converting this feedstock into several value-added products rather than disposing of it, and so advances the OFMSW up the EU waste hierarchy. The three products, lipids, bioethanol and biogas-derived electricity, replace fossil-derived counterparts. The system therefore mitigates greenhouse-gas (GHG) emissions in two ways: by avoiding landfill methane and by displacing fossil fuels. In addition, when the dryer is biomass-fuelled, the exhausted CO_2 is biogenic and is treated as carbon-neutral under standard accounting conventions. The climate burden of the plant's largest energy demand is thus much lower than its size alone would indicate.

Several of these benefits can be quantified for the plant as modelled. Drying dominates both cost and energy demand (Section 3.1), so it is the main target. The dryer operates at a system-level SEC of 0.80 kWh per kg of evaporated water. On the material side, the extraction unit recovers about 99.4% of its hexane in a closed loop (0.6% loss per cycle, 47.8 t/yr make-up; Supplementary §S1.2, Table S2), which limits both consumption and fugitive emissions. The digestion stage valorises 5576 t/yr of solid digestate and recirculates 28,800 t/yr of liquid effluent, reducing fresh-water demand and discharge. The solid digestate is treated as a low-value fertiliser product; its use on land may require further upgrading which lies outside the present scope and is reflected in its conservative valuation.

Several potential improvements could further enhance the sustainability of the biorefinery. The first concerns the drying vapour, which carries both water and heat. Condensing this vapour would recover the 36,190 t/yr of water currently evaporated; after treatment, this could offset much of the 47,300 t/yr of fresh process water used downstream, reducing both water import and discharge. The latent heat released on condensation is recovered at a low temperature, set by the dewpoint of the exhaust. It is therefore not suited to reheating the dryer itself, but it is appropriately graded for low temperature demands such as digester or feedstock preheating. This measure is thus best regarded as combined water and low-grade heat recovery. The second improvement is co-digestion: replacing the fresh-water dilution used to reach 10% TS with a dilute waste stream such as livestock slurry would avoid about 14,800 t/yr of fresh water and add biogas substrate. The third is solvent substitution: replacing the fossil-derived hexane with a bio-based green solvent would remove a fossil consumable and reduce the hazard of its residual emissions. A particularly significant option follows from the biogenic nature of the drying CO_2: capturing it with durable storage or utilisation would make the drying step a net carbon sink rather than merely carbon-neutral. This is one of the few ways to achieve genuinely negative emissions in waste valorisation, though capturing the CO_2 has its own energy and cost penalties. The largest energy opportunity, however, lies in industrial symbiosis: because high-grade external waste heat can be supplied directly to the dryer, valorising about 1 MW of such heat would meet roughly 24 MWh/d of the drying demand and lower the system-level SEC from 0.80 to 0.61 kWh/kg, directly easing the main cost and energy bottleneck.

4. Conclusion

This study delivered a techno-economic assessment of an integrated commercial-scale OFMSW biorefinery co-producing lipids, advanced bioethanol and biogas-derived electricity, anchored on demonstration-plant data. At 49,500 t/yr the biorefinery requires 16.68 M€ of capital and 4.17 M€/yr of operating expenditure. Through market-only operation without gate fee or capital support, the biorefinery is not viable, returning an NPV of −15.50 M€. Under a reference scenario of 30 €/t gate fee and 30% CAPEX subsidy, the project delivers an NPV of +8.42 M€, an IRR of 11.74% and a 10-year payback period. Break-even gate fees of 6–25 €/t sit well below the 55 €/t Greek landfill charge applicable from 2027 and remain competitive with those typically required by more mature waste-treatment technologies, positioning OFMSW biorefineries as a credible component of future municipal waste-management portfolios. OFMSW biorefineries therefore emerge as an economically attractive pathway for advanced biofuel production, conditional on a moderate policy-support package.

Three concrete insights emerge. First, drying accounts for 39.6% of total OPEX and 84% of plant thermal energy, identifying drying-thermal-demand reduction, through high-efficiency dryers or industrial waste-heat symbiosis, as the dominant lever for OFMSW biorefinery competitiveness and a pathway to move lipids from a structurally uncompetitive by-product into a marketable co-product. Second, gate-fee revenue contributes 26% of total annual income, confirming the dual role of the system as energy producer and waste-management service and explaining why subsidy-and-gate-fee combinations, rather than market revenues alone, determine commercial viability. Third, general plant OPEX raises the lipid LCOF from 1.77 to 2.34 €/kg and the bioethanol LCOF from 0.97 to 1.26 €/L, enough to reverse the competitiveness verdict against EU benchmarks and underline the importance of full cost accounting.

Limitations and future work. The present assessment is anchored on the measured composition of source-separated household food waste from a single Greek municipality, characterised across 23 batches over a 12-month period. While this captures the seasonal variability of the feedstock, the absolute economic results are most representative of Mediterranean settings with broadly comparable food-waste profiles; the analytical framework is fully transferable, but the composition and product yields should be re-evaluated against local characterisation data before application to regions with materially different OFMSW streams. The framework also transfers across policy settings. Public support ultimately acts through only two channels: it either lowers the capital cost or raises the annual cash flow. These are the two axes of the break-even map (Fig. 2), represented here by the CAPEX subsidy and the gate fee. Other instruments enter through the same channels. Investment grants act on the capital axis, while feed-in premiums, tax credits, or renewable fuel credits add to annual revenue alongside the gate fee. Viability is correspondingly stronger where landfill taxes or carbon prices are high and weaker where waste management charges are low or absent. The analysis also adopts constant real values for gate fees, capital subsidies, and product prices over the project lifetime; their long-term variation and volatility are not modelled, as the required forecast data are not available and this should be borne in mind when interpreting the long-run results. A further limitation concerns the cost boundary. Several items specific to the site and jurisdiction are excluded at this screening level. These include permitting, treatment of the non-recycled liquid effluent of AD, odour control, and environmental compliance monitoring. All of them raise costs but are small relative to the dominant drying energy cost and the capital range already tested. Their omission therefore makes the reported economics slightly optimistic without altering the qualitative conclusions. Finally, the commercial-scale performance is extrapolated from the operation of a single demonstration plant: the assumed commercial drying energy, the shift from a plug-flow to a CSTR digester, and the six-tenths capital scaling across a 150-fold size increase are all engineering assumptions whose bases and uncertainty bounds are set out in Section 2.1 and propagated through the ±30% deterministic and Monte Carlo analyses. Vendor-quoted equipment costs, together with validation of the assumed biogas yield against operating data from existing CSTR digesters treating comparable OFMSW-derived substrates, would tighten these estimates and are needed before a final investment decision. A complementary environmental life-cycle assessment, benchmarked against landfill, incineration and AD-only counterfactuals, is the natural next step and the subject of ongoing work, to deliver the comprehensive economic-environmental picture required to position OFMSW biorefineries within EU cleaner-production strategy.

CRediT authorship contribution statement

K. Passadis: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **G. Pachakis:** Data curation, Investigation, Methodology, Writing – original draft. **D. Malamis:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.149181.

Data availability

Data will be made available on request.

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