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.

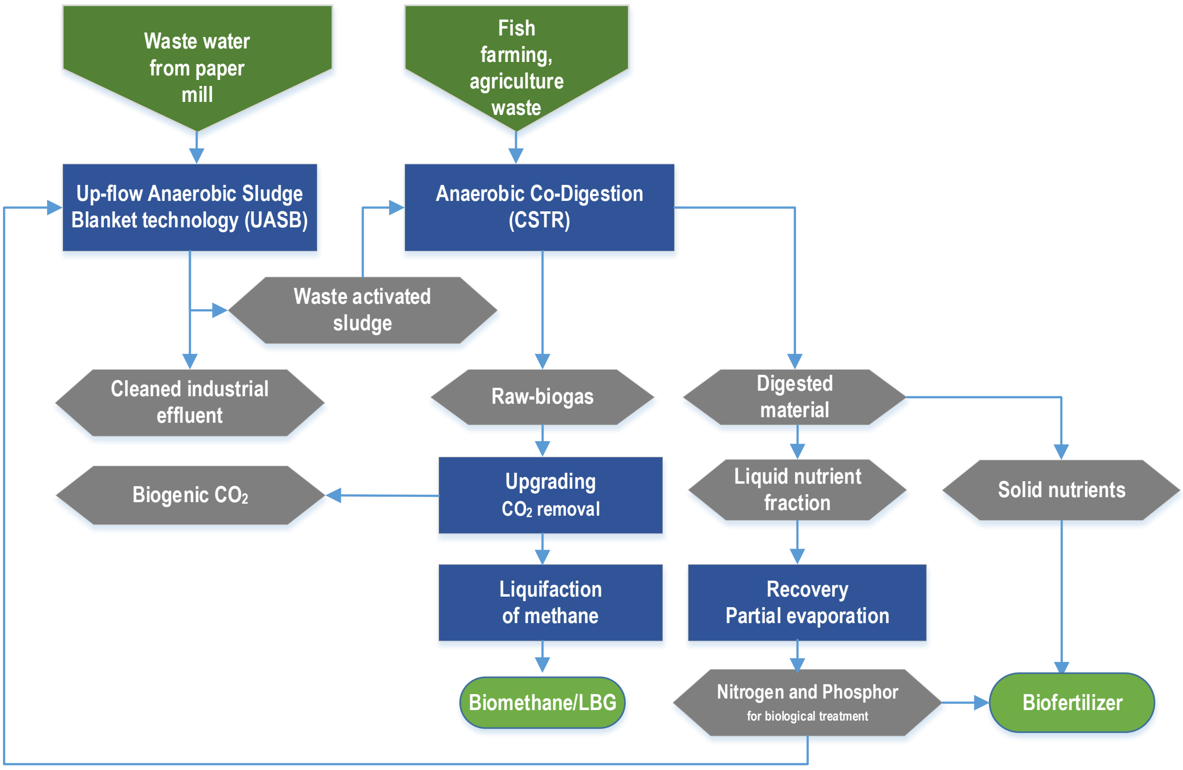


Figure 1: Basic flow chart of the biogas plant using paper mill wastewater, biosludge & regional fish/agri residues for the production of biomethane (LBG) and biofertilizer.

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.[1]

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**[2] 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.

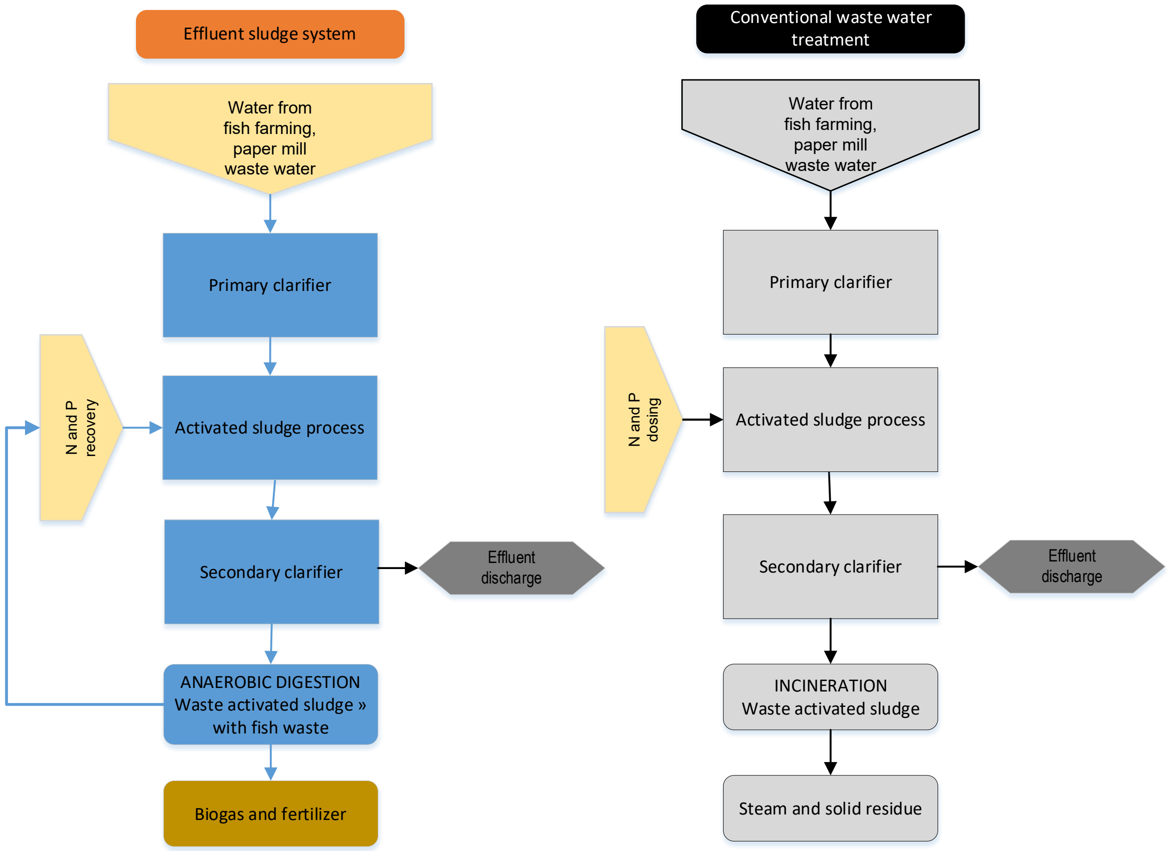
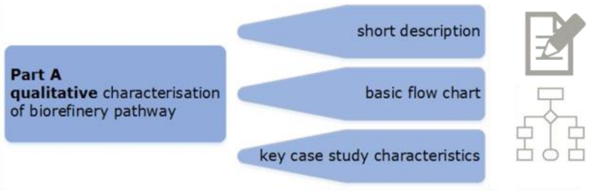


Figure 2: Simplified comparison of Effluent Sludge System and Conventional Wastewater Treatment Processes.

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.[3] 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.[4]

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}**).[5] 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 1: **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* [6],[7],[8],[9]

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[10]
- **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.[11]
- **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.[12]

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:

1. **Feedstock:** paper-mill biosludge and industrial/aquaculture residues; ~20,000 t d^{-1} wastewater plus ~112 t d^{-1} fish/agri wastes.
2. **Platforms: biogas/biomethane (energy) and digestate (material/nutrient platform).**
3. **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.
4. **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)[13]. 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)[14]. 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 2: Key technical characteristics of the biogas-based biorefinery (EffiSludge-type) based on[15],[16],[17]

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.

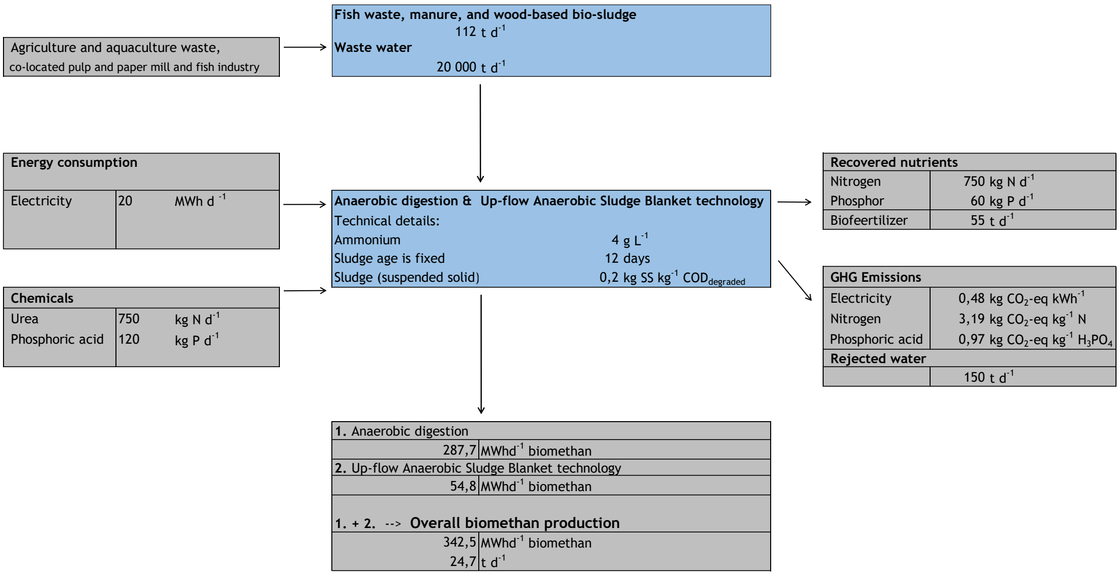


Figure 3: Overview of TEE assessment — Process pathway for biomethane (LBG) and biofertilizer from mill biosludge and fish/agri residues (EffiSludge industrial symbiosis: UASB + CSTR → upgrading → liquefaction; digestate solids to fertilizer, liquid to WWTP nutrient recirculation). Based on own calculations 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 3 summarizes the key characteristics of the considered case study.

Table 3: 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

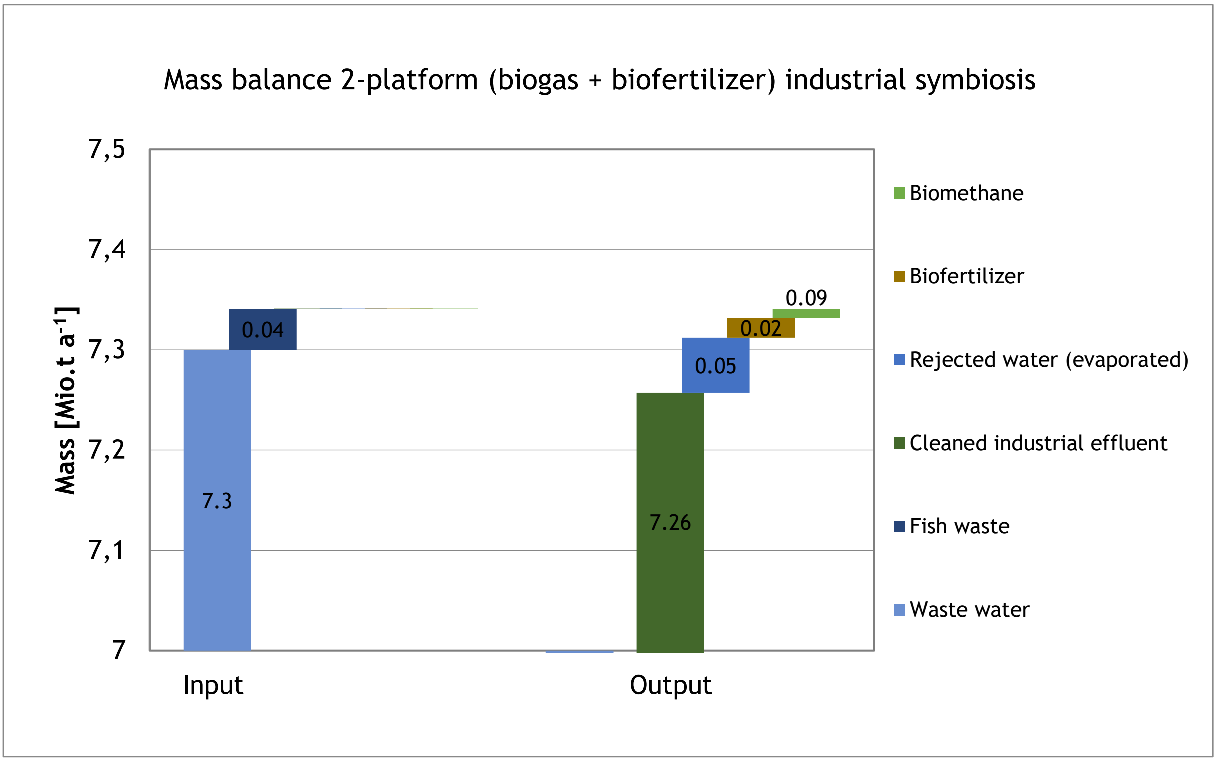


Figure 4: Simplified balance of mass of input and output stream.

PART B: VALUE CHAIN ASSESSMENT

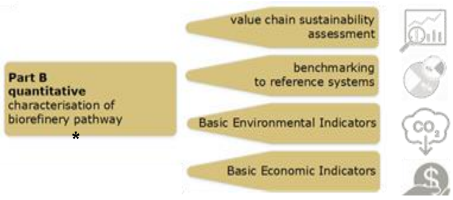


Figure 5 shows the annual revenue and cost structure for the biogas-based biorefinery. Revenues remain dominated by biomethane/LBG sales. On a **representative 2025 basis** of **€70/MWh** (LHV basis), total biomethane income is **~€8.75 million yr^{-1}** (for ~125 GWh yr^{-1}). Additional value arises 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.

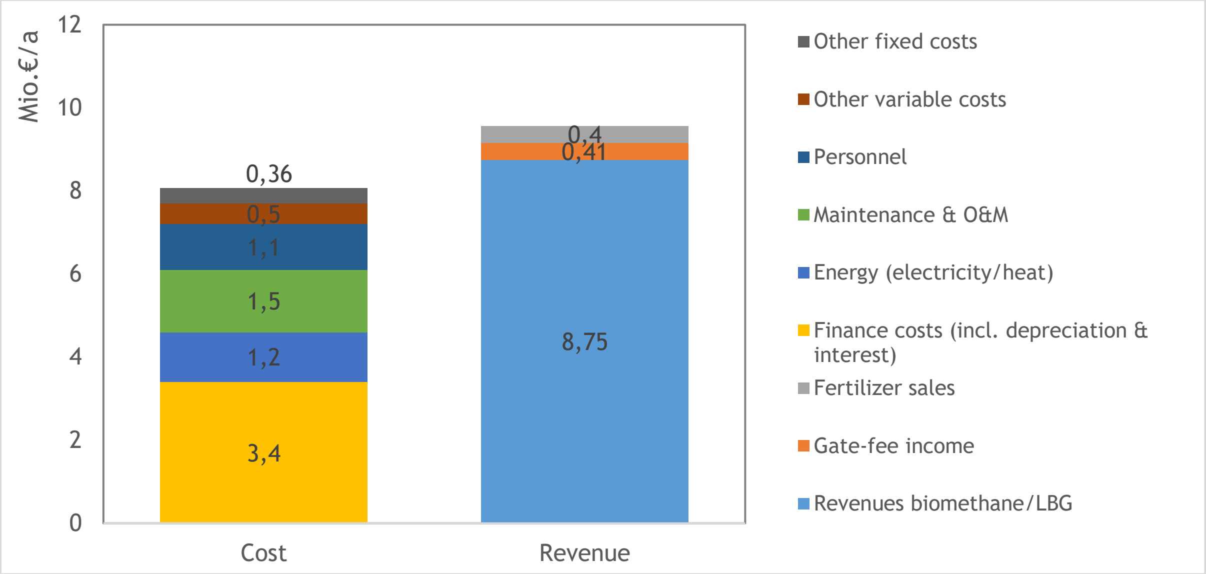
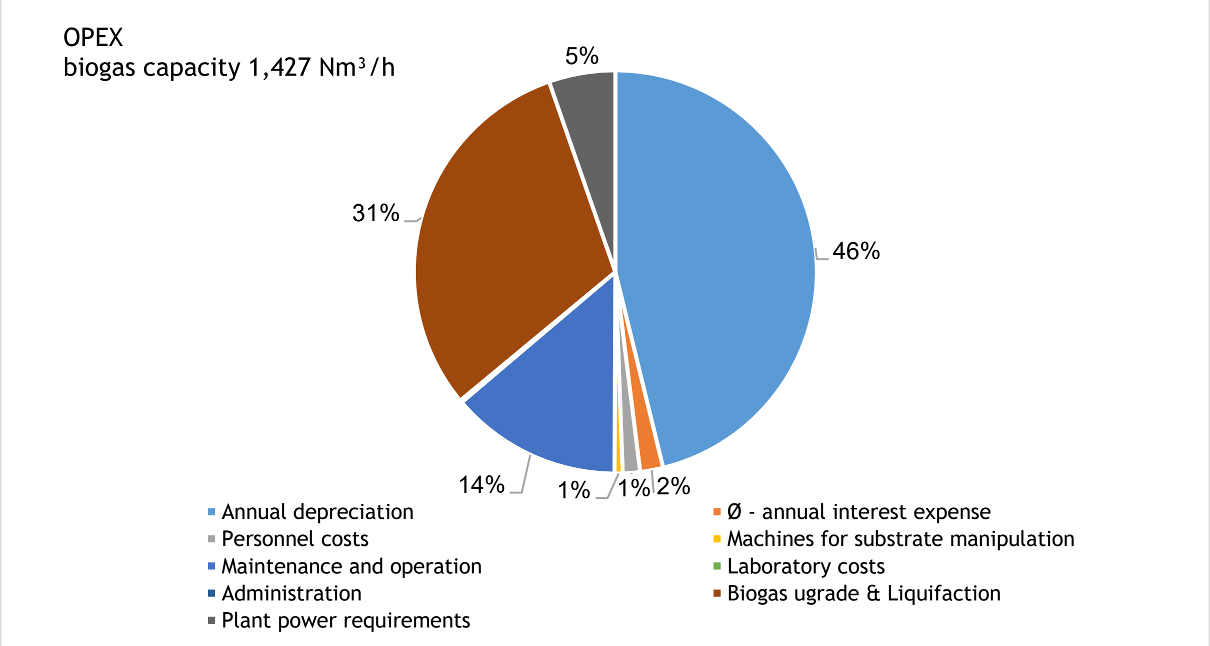


Figure 5: Costs and revenues for the biogas-based biorefinery (EffiSludge industrial symbiosis: biomethane/LBG and biofertilizer).

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).



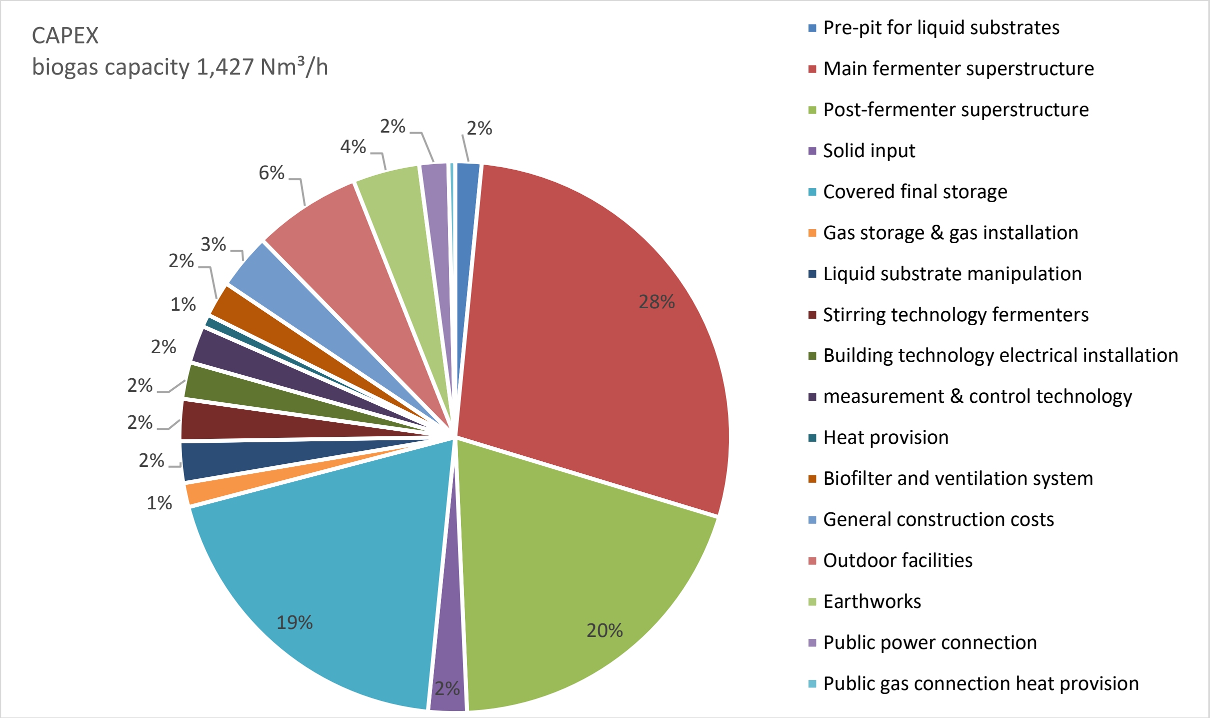


Figure 6 & 7: Share breakdown of costs for the biogas-based biorefinery case study. (see Table 3)[18],[19],[20],

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 4: 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**)[21],[22] the plant achieves a **positive margin (~15.7 % with interest; ~24.7 % without)**; policy tools (renewable gas certificates, transport fuel credits) and **CO₂/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.

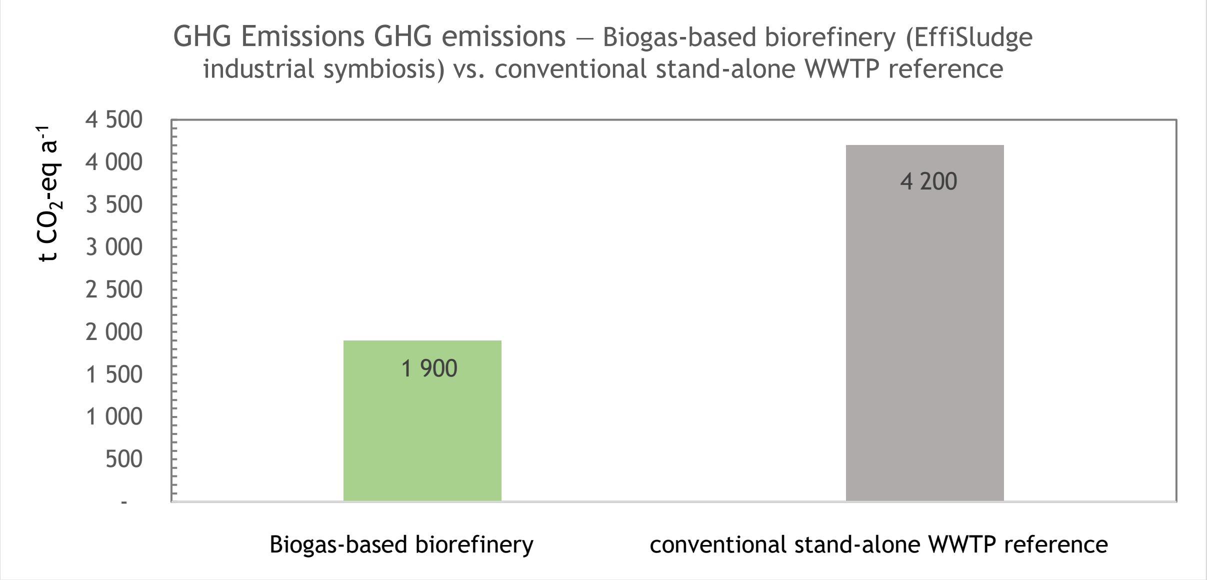


Figure 8: simplified comparison of annual GHG emissions — Biogas-based biorefinery (EffiSludge industrial symbiosis) vs. conventional stand-alone WWTP reference.

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·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 5: 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·d^{-1}** solid digestate; integrated-plant **aeration demand** ~**20 MWh·d^{-1}** (vs. ~**39 MWh·d^{-1}** in the reference).
- **Feedstocks:** pulp and paper **biosludge** plus regional fish/agri residues; **internal nutrient recycling** of ~**750 kg N·d^{-1}** and ~**120 kg P·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 6: 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/

Appendix A: 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.

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