Call: Sustainable, secure and competitive energy supply (HORIZON-CL5-2021-D3-03)
Project number: 101084405
Duration: 45 months
Starting date: 01/12/2022
End date: 31/08/2026
Budget (EU contribution): 4,390,894.50 €

Funded by the European Union

CRONUS

CAPTURE AND REUSE OF BIOGENIC GASES FOR NEGATIVE-EMISSION - SUSTAINABLE BIOFUELS

2ND POLICY BRIEF

Five validated pathways for biogenic carbon - and Policy Related Analysis

Why CRONUS matters

CRONUS (Capture and Reuse Of biogenic gases for Negative-emission sustainable biofUelS) addresses a major untapped opportunity in the European bioeconomy: the capture and utilization of biogenic CO_2 and other carbon-containing gas streams, generated across biofuel and organic-waste value chains.

The project developed and validated five Functional Prototypes (FPs) at Technology Readiness Level (TRL) 5. These demonstrate different pathways for converting biogenic carbon into valuable products or storing it durably: algae cultivation using captured CO_2, biological upgrading of biogas to biomethane, syngas biomethanation, biochar production and carbon storage, and anaerobic digestion enhanced by a microbial electrolysis cell.

Beyond technical validation, CRONUS assessed the environmental, economic, circularity and social performance of each pathway. It also examined stakeholder perspectives, standardisation and certification needs, and the policy conditions required for responsible scale-up. The project therefore provides an evidence base for moving emerging biogenic-carbon technologies towards commercially viable, low-carbon and, under appropriate deployment conditions, net-negative biofuel systems.

5
Functional Prototypes
validated at TRL 5 in five European locations

~99%
CO_2 capture efficiency
reached in FP1 with the digestate–K_2CO_3 medium

>95%
CH_4 in biomethane
sustained by FP2 under variable operating conditions

93–100%
Material reuse
circularity indicators across the five pathways

0.66–0.87
kg CO_2e per kg biomass
maximum sequestration potential of FP4 biochar

FIVE PATHWAYS FOR BIOGENIC CARBON

	Location	Feedstock	Core conversion	Main output	Carbon outcome
FP1	Athens, GR	Biogenic flue gas & liquid digestate from a food-waste biorefinery	Chemical/enzymatic CO_2 absorption + outdoor algae cultivation	**Algal biomass → biofuel**	**CO_2 utilisation**
FP2	Thessaloniki, GR	Cattle manure and wastewater-rich brine	Anaerobic digestion + PEM electrolysis + trickle-bed biological methanation	**Biomethane >95% CH_4**	**CO_2 utilisation**
FP3	Copenhagen, DK	Organic waste, via digestate pyrolysis syngas	Thermochemical pyrolysis + biological syngas methanation	**Renewable methane (+ biochar)**	**CO_2 utilisation + storage**
FP4	Montpellier, FR	Rice straw, rice husk, oak wood, digestate	Pilot-scale pyrolysis at 800 °C	**Biochar, pyrolysis gas, bio-oil**	**Durable carbon storage**
FP5	Boecillo, ES	Pig manure and animal fats	Two-phase anaerobic digestion with an integrated microbial electrolysis cell	**Methane-enriched biogas**	**In-situ CO_2 utilisation**

How much biogenic carbon was actually handled

Across the operational campaigns, the prototypes treated real feedstocks and, depending on the pathway, real or process-representative gas streams. This provides evidence of performance under conditions extending beyond laboratory-only testing.

~3,920 m^3
Biogenic gas treated in FP1
≈ 429 kg of CO_2-equivalent captured

62 m^3
CO_2 converted in FP2
from ~126 m^3 of biogenic gas treated

36 kg
CO_2 converted in FP3
cumulative, at 2 h residence time

>85%
Feedstock valorised in FP4
converted into useful fuels and materials

31–46%
In-situ CO_2 use in FP5
depending on feedstock composition

The evidence base behind this brief

Prototype design, construction and operation - monitoring data from all five prototypes under real feedstock and gas-stream conditions.

Integrated sustainability assessment - life-cycle assessment, techno-economic assessment, circularity indicators aligned with ISO 59020 and a social impact assessment.

Quantitative storytelling – examination of the societal implications of full-scale biomethane deployment with Communities of Practice.

Standardisation and certification review - mapping of the existing standards applicable to each prototype output.

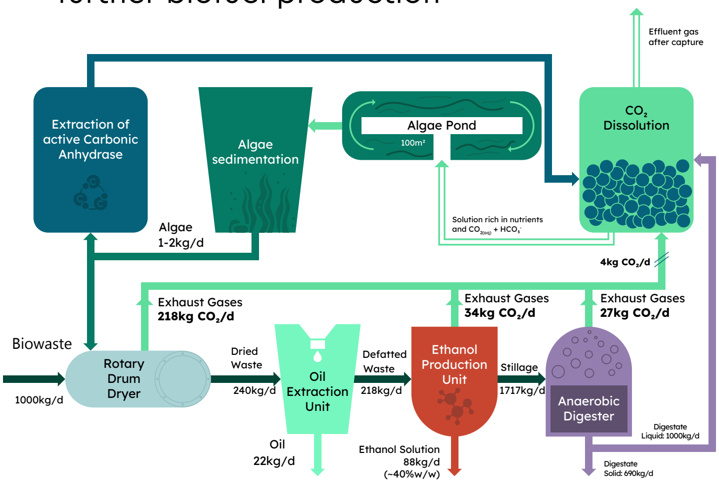
The five prototypes process different feedstocks, perform different functions and were assessed using different system boundaries and functional units. The figures that follow describe each pathway against **its own reference system**. They are not a league table, and the prototypes should not be ranked against one another.

KEY OPERATIONAL RESULTS FROM THE FUNCTIONAL PROTOTYPES

FP1

CO_2 capture and valorisation through algae cultivation

Athens, Greece
Main output: Algal biomass for further biofuel production



Carbonic anhydrase accelerated absorption but did not increase the final amount of CO_2 captured under the tested conditions.

Integrated into a food-waste biorefinery, FP1 captured biogenic CO_2 from process gas streams, including flue gas from biomass combustion, into liquid media containing potassium carbonate, digestate or a combination of the two, with carbonic anhydrase tested as an absorption accelerator. The carbon-rich streams fed outdoor raceway ponds, and the harvested algal biomass returned to the biorefinery as a co-substrate for anaerobic digestion.

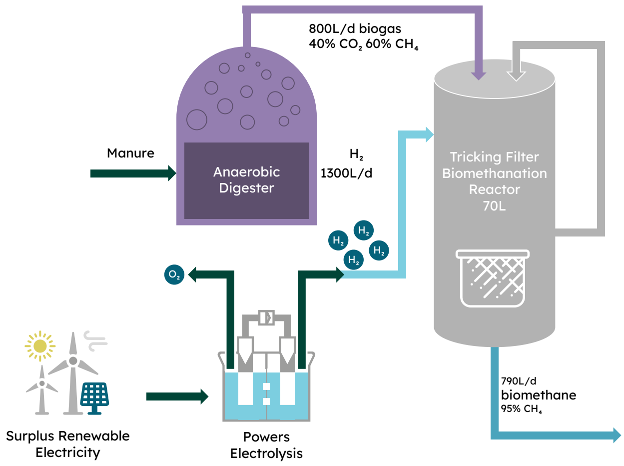
KEY RESULTS

- CO_2 capture efficiency above **85%** under optimised conditions and approximately **99%** with the combined digestate–K_2CO_3 medium.
- ~**3,920 m³** of biogenic gas treated, corresponding to **~429 kg** of captured CO_2-equivalent.
- Highest biomass productivity with the digestate–K_2CO_3 medium: **7.18 ± 0.53 g/m²/day**, above the synthetic-nutrient control.
- Versus the reference biorefinery: **−88.8%** CO_2 per unit of biofuel, **+51.5%** bioenergy efficiency, **+28.1%** biomass resource utilisation.

FP2

Biological upgrading of biogas to biomethane

Thessaloniki, Greece
Main output: Biomethane with more than 95% CH_4



FP2 combined anaerobic digestion, renewable hydrogen production through a proton-exchange membrane electrolyser and biological methanation in a thermophilic trickle-bed reactor. Green hydrogen reacted biologically with the CO_2 contained in real agricultural biogas, converting it into additional methane instead of separating and releasing it.

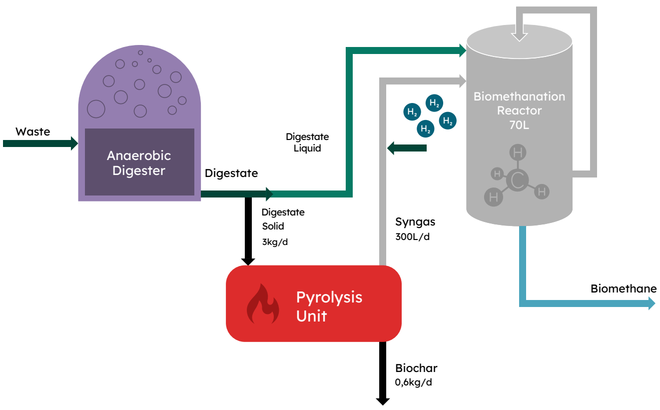
KEY RESULTS

- Consistent production of biomethane containing more than **95% CH_4**, even under variable feedstock and gas-flow conditions.
- **~126 m³** of biogenic gas treated and **62 m³** of CO_2 biologically converted into methane.
- CO_2 emissions reduced from **1.83 to 0.049 kg** CO_2 per kg of biomethane.
- Carbon utilisation of **0.078 kg C** per kg of feedstock volatile solids.
- Bioenergy efficiency and biomass resource utilisation both improved by approximately **51%** compared with the reference system.

FP3

Biomethanation of pyrolysis-derived syngas

Copenhagen, Denmark
Main output: Renewable methane



Hydrogen addition substantially improved carbon utilisation, bioenergy efficiency and biomass resource utilisation.

FP3 demonstrated the biological conversion of a gas mixture representative of syngas from digestate pyrolysis – containing carbon monoxide, carbon dioxide and hydrogen, into methane in a thermophilic trickle-bed reactor. Supplementary hydrogen was added to improve the conversion of the carbon-containing gases.

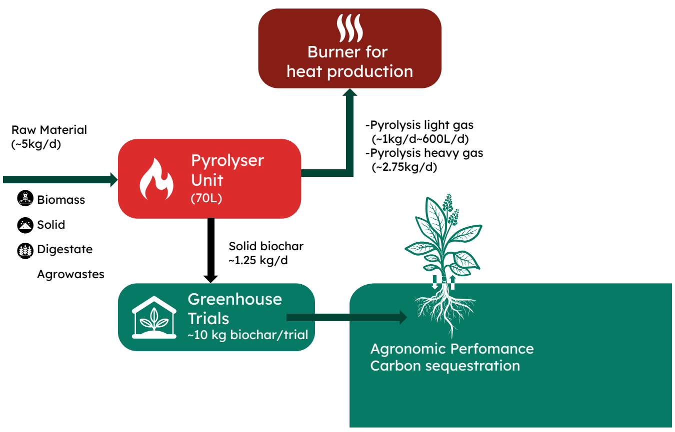
KEY RESULTS

- Stable biomethanation at a gas residence time of only **2 h**, with a maximum methane productivity of **176 L CH_4/day**.
- An estimated cumulative **36 kg** of CO_2 converted into methane over the operational campaign.
- Carbon conversion efficiency of **93%** with supplementary hydrogen addition.
- CO_2 emissions of **0.615 kg** per kg of biomethane, against **32.27 kg** in the reference syngas-combustion scenario.

FP4

Biochar production and biogenic carbon storage

Montpellier, France
Main output: Biochar, pyrolysis gas and bio-oil



Bioenergy efficiency above **50%**, reaching approximately **60%** for rice husks. Agronomic performance depends strongly on biochar type, soil pH and application rate.

FP4 validated a flexible pilot-scale pyrolysis process using rice straw, rice husks, oak wood and digestate as feedstocks. The process converts biomass into stable biochar while generating energy-rich gas and bio-oil as co-products, combining material and energy recovery with the potential for long-term storage of biogenic carbon.

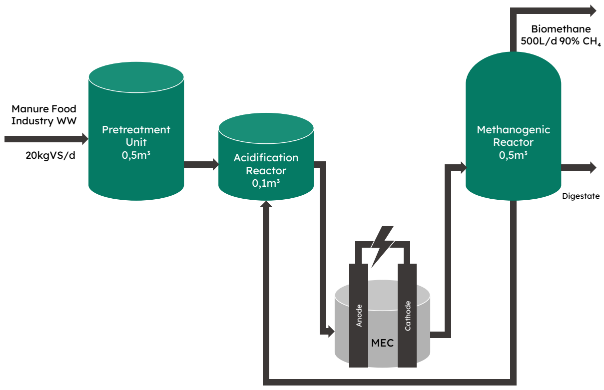
KEY RESULTS

- Pilot-scale pyrolysis at **800 °C** validated across four contrasting feedstocks.
- All analysed biochars showed **H/C molar ratios below 0.4**, indicating highly stable carbon structures.
- Estimated maximum sequestration potential of **0.66–0.87 kg** CO_2-equivalent per kg of raw biomass processed, highest for oak wood.
- More than **85%** of the feedstock converted into useful fuels and materials; carbon retained in biochar equal to **18–23%** of initial feedstock mass.

FP5

Anaerobic digestion coupled with a microbial electrolysis cell

Boecillo, Spain
Main output: Methane-enriched biogas



Biomass resource utilisation of approximately 52–55%, exceeding the FP5 target of 35%.

FP5 integrated a microbial electrolysis cell directly into an anaerobic digester. The system produces hydrogen in situ and supports its biological reaction with CO_2 to form additional methane, avoiding the need for an external hydrogen supply. It was evaluated against a conventional anaerobic digestion system using different organic feedstocks.

KEY RESULTS

- **Two to three times** more biogas than conventional anaerobic digestion, with methane concentrations of **63–64%**.
- In-situ CO_2 utilisation efficiencies of **31–46%**, depending strongly on feedstock composition.
- CO_2 per kg of methane down from **2.91 to 1.52 kg** (COD ≈10.7 g/L) and from **5.83 to 1.61 kg** (COD 27.55 g/L).

Key lessons for scale-up

FP1

Outdoor algae systems require weather-resistant infrastructure, buffer capacity and effective coordination between CO_2 capture, algae cultivation, harvesting and anaerobic digestion.

FP2

Stable gas supply, precise control of hydrogen addition and robust monitoring and restart strategies are essential for maintaining biological methanation performance.

FP3

As for FP2, plus tar removal and gas conditioning are required before real pyrolysis gas enters the biological reactor.

FP4

Feedstock properties strongly affect reactor operability, biochar quality, carbon sequestration and agronomic performance. Scale-up requires appropriate reactor design, heat integration and feedstock-specific biochar applications.

FP5

Feedstock composition, foaming, temperature control and mixing must be carefully managed. Heat recovery and energy-efficient industrial equipment are essential for improving overall energy performance.

The prototypes are stronger in combination than in isolation

The clearest example is FP3 with FP4: syngas biomethanation increases energy recovery from the same feedstock, while pyrolysis produces biochar that stores carbon durably. One pathway converts biogenic CO_2 into a fuel that will be burned again; the other removes carbon from the cycle. Deployed together they cover both halves of the carbon-management problem, which is also why monitoring and certification rules need to distinguish clearly between the two.

THE EU POLICY LANDSCAPE RELATED TO THE FUNCTIONAL PROTOTYPES

Carbon Removals and Carbon Farming Regulation - (EU) 2024/3012. The CRCF, adopted on 27 November 2024, establishes the first EU-wide voluntary certification framework for permanent carbon removals, carbon farming and carbon storage in products.

Enabling: Provides a clear and legally grounded certification pathway for biochar carbon removal through the Biochar Carbon Removal Delegated Act adopted in February 2026. Directly supports FP3 and FP4. Introduces standardised MRV requirements and an additionality principle that reduces administrative burden for small-scale operators.

Renewable Energy Directive – RED III (EU) 2023/2413. Sets binding renewable energy targets and GHG savings crediting rules for biofuels and bioenergy, including the eccr (CO_2 captured and replaced in commercial products) and eccs (CO_2 captured and geologically stored) mechanisms.

Enabling: Algae listed in Annex IX as advanced biofuel feedstock, supporting FP1. REPowerEU biomethane target of 35 bcm by 2030 creates market demand for FP2, FP3 and FP5 outputs. Digestate-derived products listed as advanced feedstocks, benefiting FP3.

Constraining: Under RED III's lifecycle GHG methodology, the $e_{(ccr)}$ emission-saving term may be counted only where captured biogenic CO_2 demonstrably replaces fossil-derived CO_2 in the production of commercial products or services. The use and origin of both the captured and replaced CO_2 must be supported by auditable evidence; a written declaration by the operator using the captured CO_2 may serve as such evidence. FP2 and FP5 convert biogenic CO_2 into additional methane and therefore do not, on that basis alone, qualify for $e_{(ccr)}$, since they do not replace fossil-derived CO_2 used in a commercial product or service. Under the current RED III text, $e_{(ccr)}$ applies only to replacement occurring before 1 January 2036, limiting long-term regulatory certainty.

Net-Zero Industry Act – (EU) 2024/1735. Establishes a framework for strengthening Europe's net-zero technology manufacturing ecosystem, designating strategic technologies and streamlining permitting under Article 4.

Enabling: The inclusion of these technologies within the scope of the NZIA may make related manufacturing projects eligible to apply for net-zero strategic project status, subject to the criteria established in Article 13. Once recognised, such projects benefit from priority treatment and shortened permit-granting timelines of 9–12 months. Article 33 also allows Member States to establish regulatory sandboxes that could support the further testing and scale-up of relevant CRONUS technologies, subject to national implementation and project acceptance.

EU Emissions Trading System – Directive 2003/87/EC

Enabling: The Innovation Fund supports breakthrough technologies including BECCS and DAC. Receiving Innovation Fund support triggers automatic net-zero strategic project recognition under the NZIA. The existing MRV infrastructure could be extended to biogenic carbon capture installations in the future.

Constraining: The EU ETS does not currently recognise negative emissions or carbon removals as compliance instruments. Biogenic CO_2 is treated as carbon-neutral, capturing it earns no credits. The Industrial Carbon Management Strategy commits the Commission to assess ETS integration of carbon removals by 2026. The outcome of this assessment is the single most consequential pending policy decision for the commercial viability of all five CRONUS pathways.

Industrial Carbon Management Strategy – COM/2024/62

Enabling: Explicitly recognises that by 2040 close to half of all CO_2 captured annually in the EU must come from biogenic sources or the atmosphere. Endorses CCS, CDR and CCU as three equally valid pathways, directly covering all five CRONUS FPs. Commits to EU-wide CO_2 transport infrastructure planning and ETS integration assessment by 2026.

Constraining: Remains a strategy document, no binding obligations and no new instruments. All commitments are subject to further legislative proposals not yet tabled.

THE STANDARDISATION RELATED TO THE FUNCTIONAL PROTOTYPES

Standards, certification and market uptake

No critical standardisation gaps were identified that would prevent the quality assessment of the main outputs produced by the CRONUS prototypes. The priority is therefore not the development of entirely new product standards, but the **consistent application of existing ones,** accredited testing, clear classification according to intended end use, and harmonised monitoring and certification of climate benefits.

Biogas and methane-enriched biogas – FP1, FP5

Characterisation is covered by ISO 20675 and ISO 24252 for terminology and system requirements, together with the ISO 6974 series, ISO 6976, ISO 19739 and ISO 2613-1 for composition, energy properties, sulphur compounds and silicon-related contaminants. As no single harmonised standard sets universal acceptance limits for raw biogas used in CHP or heat production, final gas-quality requirements should additionally follow the specifications of the relevant engine or boiler manufacturer.

Biomethane — FP2, FP3

Covered by EN 16723-1 for grid injection, EN 16723-2 where transport use is intended, and EN 16726 for compatibility with Group H gas infrastructure, supplemented by applicable national network-operator requirements.

Biochar — FP3, FP4

Assessable under the EU Fertilising Products Regulation and CMC 14, the European Biochar Certificate and the IBI Biochar Standards, supported by established EN and ISO analytical methods for moisture, pH, electrical conductivity, organic matter, sulphur and chlorine, surface area and plant response

Recognising the climate benefit

The Biochar Carbon Removal (BCR) Delegated Act, adopted under the EU Carbon Removals and Carbon Farming (CRCF) Regulation (EU) 2024/3012, provides the operative basis for recognising verified biochar carbon storage from FP3 and FP4. What remains missing is a consistent rulebook that distinguishes the conversion of CO_2 into fuels (FP1, FP2, FP5) from durable carbon storage (FP3, FP4 via biochar), and that prevents the same climate benefit from being counted twice.

KEY TAKEAWAY

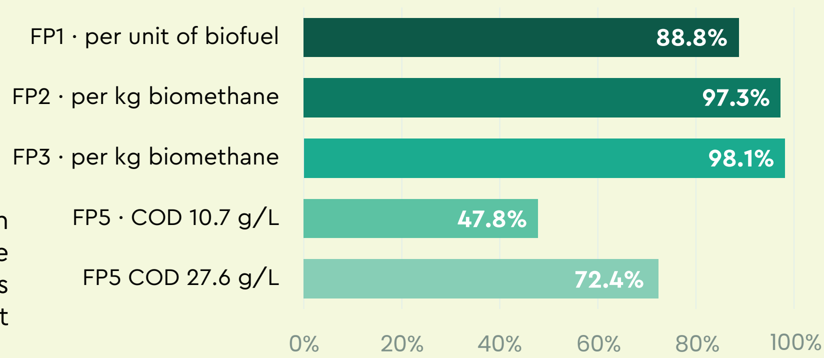
The most significant cross-cutting gap is the absence of a single harmonised EU methodology applied consistently across relevant policy and certification frameworks for verifying that a CO_2 stream is genuinely biogenic rather than fossil-derived.

KEY FINDINGS ACROSS THE FIVE PROTOTYPES

Every prototype reduced the carbon intensity of its product compared with the conventional system it was benchmarked against, and one – FP4 – moved from emission reduction to durable carbon removal. Circularity was consistently high across all five pathways, although high circularity alone did not guarantee favourable environmental or economic performance.

Reduction in CO_2 emissions per unit of product

FP3 is benchmarked against syngas combustion (32.27 kg CO_2 per kg), which explains the magnitude of its reduction. Each prototype is compared with its own reference system, not with the others.



Material reuse and circularity

99% FP1 resource efficiency

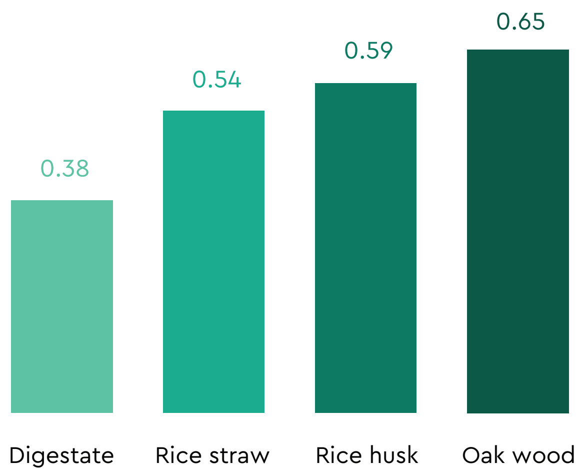
93% FP2 reused fraction

99% FP3 reused fraction

100% FP4 reused fraction

100% FP5 reused fraction

From reduction to removal: FP4 carbon storage



Why this matters

FP4 was the only pathway to deliver net-negative climate-change results across **all** assessed feedstocks. Every analysed biochar had an H/C molar ratio below 0.4, the threshold conventionally associated with highly stable carbon structures — which is what makes the stored carbon defensible as a durable removal rather than a temporary delay of emissions.

The technical assessment estimated a maximum sequestration potential of **0.66–0.87 kg CO_2e per kg of raw biomass**. The life-cycle assessment, which nets out drying, electricity and process emissions, reports the lower figures shown here – and that difference is precisely what a credible certification methodology has to capture.

ECONOMIC AND SOCIAL VIABILITY AT COMMERCIAL SCALE

The integrated sustainability assessment indicates that all five pathways could contribute to low-carbon - and under appropriate conditions, potentially net-negative – biofuel systems. Under one modelled commercial-scale scenario, assuming a 12% target internal rate of return and a carbon credit of €60/t CO_2, potentially viable configurations were identified for every prototype. **These represent modelled scale-up scenarios, not demonstrated pilot-scale profitability.**

	Modelled design scale	CAPEX	NPV (20 y, 5%)	P(NPV>0)	Main hotspot
FP1	145 t/d biowaste	€14.5 M	**€9.7 M**	99.6%	Process electricity demand
FP2	277 m^3/d manure	€9.7 M	**€6.5 M**	99.6%	PEM electricity (~73% of OPEX)
FP3	107 t/d biomass	€8.6 M	**€5.7 M**	94.7%	Renewable hydrogen production
FP4	1.62 t/h dry oak	€5.13 M	**€3.4 M**	86.4%	Digestate drying and dewatering
FP5	364 m^3/d feed	€15.4 M	**€10.3 M**	97.6%	MEC electrode replacement (~75% of OPEX)

All configurations modelled at a 12% target IRR with a €60/t CO_2 credit. Figures are scenario outputs conditioned on feedstock supply, offtake agreements and access to competitively priced renewable electricity.

Social Dimension

Technical and economic viability are necessary but not su fficient conditions for the responsible scale-up of CRONUD technologies. The CRONUS project's social research – conducted through stakeholder interviews, Communities of Practice and engagement with local actors across the five prototype sites – reveals that public and community acceptance is shaped by a consistent set of concerns that policy frameworks must address.

Proximity and Local Impact

Odour, noise, increased truck movements and visual impact on local landscapes were cited repeatedly by residents and local stakeholders. These concerns were strongest where facilities were sited in or near residential areas and where local communities had not been consulted before key decisions were taken.

Ownership and Benefit Distribution

Communities that perceived a facility as externally owned – bringing jobs and revenue out of the area while leaving local residents with the negative externalities – showed significantly lower acceptance than those with cooperative or community-participation ownership models. Transparent benefit-sharing arrangements, including local employment, affordable energy tariffs and shared revenues, consistently increased legitimacy.

Trust in Institutions and Operators

Where regulatory authorities were perceived as independent and effective, and where operators communicated proactively and accessibly, acceptance was higher. Where communities felt decisions had been imposed rather than negotiated, opposition was more persistent and more difficult to address after the fact.

Justice and Distributional Concerns

Stakeholders raised questions about who benefits from the green transition and who bears its costs - concerns that are particularly acute in rural and agricultural communities, where biomethane feedstock sourcing can compete with food production, soil health and existing land uses.

POLICY PRIORITIES FOR RESPONSIBLE SCALE-UP

CRONUS shows that biogenic carbon can be captured, converted into additional biomethane or algal biomass, and stored more durably in biochar. Policy support should reward verified outcomes and remain conditional on responsible deployment—not production volume alone.

Align connected policies

Biomethane and biogenic-carbon strategies should be developed in coordination with agricultural, food-system, waste, water and spatial-planning policies. Assessments of biomethane potential should consider feed imports, food and livestock production, land availability, nutrient balances and competing uses of agricultural residues, rather than aggregated national feedstock estimates alone. Support should prioritise genuine wastes and residues, while ensuring that their use for energy does not undermine soil health. Incentives must not inadvertently encourage intensive livestock expansion solely to secure feedstock.

Reward verified climate performance

Financial support and market recognition should be based on life-cycle climate performance rather than on renewable gas production alone, accounting for upstream feedstock impacts, methane leakage, transport, digestate management and the energy intensity of the electricity and hydrogen used. Harmonised monitoring, reporting and verification rules are needed to distinguish the conversion of CO_2 into fuels from durable carbon storage and to prevent double counting.

Plan deployment territorially

The scale and location of facilities should reflect local resource availability, infrastructure capacity and environmental limits. Regional assessments should examine feedstock collection distances, truck movements, grid access, opportunities for local energy use, water and energy requirements, and the capacity of surrounding land to absorb recovered nutrients. Decentralised production and local use should be considered where grid injection or long-distance transport would reduce environmental and economic performance.

Share decisions and benefits

Local participation should begin before decisions on plant location, capacity and ownership have effectively been finalised. Transparent benefit-sharing arrangements increase legitimacy by ensuring host communities receive tangible value through employment, local investment, affordable energy or shared revenues. Cooperative and community-participation models should be encouraged, together with accessible grievance and monitoring mechanisms throughout plant operation.

Close nutrient loops responsibly

Increased biomethane production must be accompanied by credible plans for managing the resulting digestate. Regional strategies should match digestate production with the capacity of local soils and crops to absorb nutrients, with particular attention to Nitrate Vulnerable Zones and water-stressed areas. A system is not circular merely because nutrients are recovered, if their production exceeds local demand or creates additional transport and pollution pressures.

POLICY TAKEAWAY

Policy support should reward verified climate and resource benefits – not production volume alone - and remain conditional on territorial suitability, responsible nutrient management and meaningful local participation.

CRONUS

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