Waste biorefinery technologies for accelerating sustainable energy processes

D2.5 Roadmap for technologies to be integrated into biorefineries

CA 20127

Waste biorefinery technologies for accelerating sustainable energy processes (WIRE)
WG 2 | Biorefinery Technologies

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Thank you for your commitment to excellence and for advancing the shared goals of the WIRE COST Action.

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EXECUTIVE SUMMARY

This roadmap builds directly upon the findings of the **D2.4 Technical Report**, which provided a comprehensive SWOT analysis of selected biorefinery conversion technologies—biochemical, thermochemical, and physicochemical. This analysis was based on structured input from two primary stakeholder groups: Research and Technology Organizations and industrial technology providers. The insights were complemented by a targeted review of EU-funded project deliverables and relevant scientific literature.

Through the **TOWS framework**, the strengths, weaknesses, opportunities, and threats identified in D2.4 are systematically translated into **actionable strategies** that address both internal capabilities and external conditions affecting technology deployment. These strategies are designed to accelerate the integration of high-potential technologies into **biorefinery systems** while ensuring alignment with EU policy objectives, including the **European Green Deal**, **Fit for 55**, and the **Circular Economy Action Plan**.

A **GAP analysis** complements the TOWS results by identifying critical **regulatory**, **technological**, and **awareness gaps** that currently hinder large-scale deployment. These gaps are framed as **deployment barriers** and directly linked to the roadmap's recommended actions, ensuring a clear traceability from stakeholder observations to strategic interventions. Stakeholder insights not only shaped the analytical foundation but also inform the roadmap's implementation, ensuring that proposed actions reflect real needs and deployment conditions.

The roadmap defines **priority action areas** across four key domains:

1. **Policy and Regulatory Alignment** – Establishing harmonized standards, enhancing policy coherence, removing barriers, and aligning biorefinery deployment with renewable energy and circular economy frameworks.
2. **Investment and Financing Mechanisms** – Mobilizing targeted funding to bridge TRL gapl public–private partnerships and innovative finance to scale up demonstration and commercial plants.
3. **R&D and Innovation** – Advancing technology readiness, advancing hybrid and integrated systems, improving process efficiencies, and developing market-ready solutions.
4. **Market Development and Capacity Building** –Raising stakeholder awareness, strengthening cross-sector collaboration, and creating new value chains for bio-based products. *This area falls more directly under the scope of WG3 (D3.4 – Roadmap for Bio-based Fuels and Products and Circular Economy Viability Assessment); therefore, its analysis within D2.5 is limited to a high-level overview, with detailed examination deferred to WG3 outputs.*
5. **Timeline and milestones** are set across short-, medium-, and long-term horizons, supported by a **monitoring and evaluation framework** with measurable KPIs to track progress and impact.

By linking D2.4's analytical findings to D2.5's strategic vision, this roadmap provides a **clear, evidence-based pathway** for accelerating the uptake of sustainable biorefinery technologies.

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1. INTRODUCTION

Author: Marta Trninić

1.1. Purpose and Scope

This roadmap presents a strategic framework to guide the development and deployment of selected biorefinery conversion technologies, including biochemical, thermochemical, and physicochemical routes. Its primary objective is to translate the analytical insights gathered in the previous Technical Report (D2.4) into targeted strategies that address technical, regulatory, economic, and social factors influencing technology uptake.

The roadmap addresses barriers and opportunities at the intersection of technology development, policy, investment, market readiness, and capacity building. While all strategic areas are considered, the detailed analysis of market development and capacity building is limited, as this is the primary focus of WG3 (D3.4 – Roadmap for Bio-based Fuels and Products and Circular Economy Viability Assessment). Consequently, the present document concentrates on technology-oriented priorities and enabling conditions that fall within the remit of WG2.

1.2. Methodology Overview

The development of this roadmap employed a structured, multi-method approach designed to ensure strategic coherence and evidence-based prioritization of actions. Key elements of the methodology include:

1. **SWOT Analysis Foundation -** Building on the comprehensive SWOT analysis conducted in D2.4, which synthesized stakeholder insights on strengths, weaknesses, opportunities, and threats across biochemical, thermochemical, and physicochemical biorefinery technologies.
2. **TOWS Framework Application** – The SWOT findings were translated into actionable strategic options (SO, WO, ST, WT) through the TOWS framework, enabling the identification of strategies that leverage strengths and opportunities while addressing weaknesses and mitigating threats. This approach guided the formulation of tailored strategies for each technology pathway.

3. **GAP Analysis** – Complementing the TOWS results, a GAP analysis was conducted to identify critical regulatory, technological, and awareness gaps impeding technology deployment. These gaps were framed as deployment barriers and directly linked to proposed roadmap actions.
4. **Technology Readiness Level (TRL) Assessment:** Each technology pathway was positioned according to its TRL to inform realistic short-, medium-, and long-term targets and facilitate appropriate sequencing of actions.

This integrated methodology provided a robust foundation for identifying priority actions and ensuring that the roadmap's recommendations are both practical and aligned with stakeholder needs and policy objectives.

1.3. Link to D2.4 Findings

This roadmap is a direct continuation of the D2.4 Technical Report, which provided a comprehensive SWOT analysis for selected technologies. The TOWS analysis in this document transforms those findings into concrete strategic actions. By bridging the gap between assessment and implementation planning, the roadmap offers a structured pathway for decision-makers, investors, and innovators to accelerate the deployment of sustainable biorefinery solutions.

2. METHODOLOGICAL FRAMEWORK

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2.1.TSOW Analysis

The TOWS analysis builds directly upon the SWOT results, transforming them into actionable strategies that address both internal capabilities and external conditions influencing the deployment of biorefinery technologies. While the SWOT framework identifies the key strengths, weaknesses, opportunities, and threats, the TOWS methodology advances this by formulating targeted strategic responses—ensuring that technological potential is effectively aligned with prevailing policy frameworks and evolving market dynamics.

In essence, SWOT provides the *what*—a structured inventory of internal and external factors—whereas TOWS delivers the *how*, bridging the gap between analysis and action. By translating insights into concrete decision-making tools, TOWS enables stakeholders to prioritize investments, guide research and innovation, and define implementation pathways that are both market-relevant and policy-aligned.

In the context of biorefinery technology deployment, this approach is essential because:

1. SWOT identifies—TOWS acts:
   - SWOT tells us what the strengths, weaknesses, opportunities, and threats are.
   - TOWS tells us how to use strengths to capture opportunities, how to use strengths to mitigate threats, how to reduce weaknesses to exploit opportunities, and how to minimize weaknesses to defend against threats.
2. Deployment focus: The biorefinery sector faces unique implementation challenges—technical, regulatory, financial, and social. TOWS ensures that the analysis moves beyond diagnosis into solution-oriented strategy, enabling stakeholders to make informed choices about investment, policy advocacy, and collaboration.
3. Direct link to D2.5 (Roadmap): The TOWS output forms a key bridge between D2.4's stakeholder-driven assessment and D2.5's roadmap for technology integration. Each TOWS-derived strategy can be directly mapped to concrete roadmap actions, ensuring that the roadmap is evidence-based, stakeholder-informed, and action-ready.
4. EU Policy Alignment: By framing strategies in the context of the EU Green Deal, Fit for 55, and the Circular Economy Action Plan, TOWS helps align technological potential with

policy drivers, increasing the likelihood of funding, regulatory support, and market acceptance.

In summary, TOWS is not just an analytical tool—it is a strategic decision-making framework that ensures this report’s findings are directly usable for setting priorities, overcoming deployment barriers, and guiding the coordinated integration of biorefinery technologies into European markets.

The TOWS methodology applies a cross-combination approach, from SWOT analysis, to generate strategic options, Tabele 1.

Tabele 1 TOWS Matrix

SO (Strength–Opportunity) Use strengths to maximize opportunities	WO (Weakness–Opportunity) Overcome weaknesses using opportunities
ST (Strength–Threat) Use strengths to counter threats	WT (Weakness–Threat) Minimize weaknesses and avoid threats

2.2.GAP Analysis

GAP analysis is a strategic tool used to identify the key barriers and performance shortfalls between the current state of biorefinery technology development and the strategic objectives for effective deployment and market uptake. It focuses on three main categories:

1. Regulatory gaps – Lack of harmonized standards, unclear permitting procedures, and misalignment with EU directives (e.g., RED III, Circular Economy Action Plan).
2. Technological gaps – Limited scalability, low TRL levels for hybrid systems, and insufficient integration with existing infrastructure.
3. Awareness gaps – Low stakeholder knowledge, limited public visibility, and weak cross-sector collaboration.

These gaps illustrate the disconnect between current technology readiness and the conditions required for successful implementation.

The GAP analysis provides a bridge between D2.4 and D2.5:

1. In D2.4, gaps are identified through stakeholder input, SWOT synthesis, and a review of EU-funded project deliverables and relevant scientific literature.
2. In D2.5, these gaps are addressed through targeted roadmap measures, including:
    - Policy and regulatory recommendations
    - Investment and funding priorities

- Capacity-building initiatives
- Strategic partnerships and collaborations

By systematically mapping each gap to actionable solutions, the analysis ensures that roadmap development is grounded in real-world deployment challenges and fully aligned with EU`s and other countries sustainability targets.

3. TSOW ANALYSIS – RESULTS BY TECHNOLOGY PATHWAY

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This section presents the results of the TOWS analysis applied to selected biorefinery technology pathways. By systematically cross-referencing internal strengths and weaknesses with external opportunities and threats, the analysis identifies strategic directions tailored to each pathway. The aim is to support decision-making by highlighting how specific technologies can:

- Leverage their strengths to capitalize on emerging opportunities (SO),
- Address internal limitations through external enablers (WO),
- Use robust features to mitigate external risks (ST),
- Avoid or minimize vulnerabilities in challenging contexts (WT).

The following subsections provide a pathway-specific breakdown of TOWS strategies, offering actionable insights for roadmap development, stakeholder engagement, and policy alignment.

3.1. Thermochemical Conversion

3.1.1. Combustion Technologies

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Combustion is the most mature and commercially established biomass conversion pathway, widely deployed for heat and power generation across Europe. Its technological readiness, proven efficiency, and compatibility with existing energy infrastructure make it a key transitional technology in the bioenergy sector. However, challenges remain in meeting increasingly stringent air quality standards, ensuring sustainability certification, and addressing public perception regarding biomass sourcing and emissions.

Building on the SWOT analysis presented in the section *4.2.1.1.Direct Combustion SWOT Analysis* of the *D2.4 Technical Report*, which identified air quality performance, sustainability assurance, and efficiency as critical deployment barriers, this TOWS analysis translates those insights into targeted strategic actions. The strategies align internal strengths, such as technological maturity, proven efficiency, and feedstock flexibility, with external opportunities including EU policy incentives, modernization funding, and integration with bioenergy with carbon capture and storage or utilisation (BECCUS) for negative emissions. At the same time, these strategies address key weaknesses and mitigate external threats associated with regulatory tightening, competition from electrification, and public scepticism. The TSOW analytical framework provides a structured, evidence-based basis for translating SWOT findings into actionable strategies. It ensures that the proposed measures are both technically robust and policy-aligned, thereby offering a coherent pathway for advancing direct combustion technologies within the EU bioenergy transition. The TSOW Matrix for Combustion Technologies is presented in Table 2.

Table 2 TSOW Matrix for Combustion Technologies

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Leverage technological maturity (S1) and proven efficiency (S2) to accelerate modernization of combustion plants through EU funding streams (O4). (SO2) Utilize feedstock flexibility (S3) to support circular economy initiatives (O1), including ash valorization into fertilizers and construction materials. (SO3) Scaling deployment of low-emission boilers and CHP systems (S4), through incentives under RED III, REPowerEU, and national modernization programs. (SO4) Position direct combustion as a reliable platform for BECCUS integration (O2), building on its commercial readiness and infrastructure base.	(WO1) Address air quality concerns (W1) by investing in advanced emission control technologies, supported by EU modernization funding (O4). (WO2) Strengthen sustainability certification and traceability (W2, W4) in alignment with EU climate policies and circular economy goals (O3). (WO3) Improve combustion system efficiency (W3) via targeted R&D and integration with BECCUS pathways (O2). (WO4) Strengthening sustainability certification and traceability schemes (e.g. Sustainable Biomass PartnershipSBP) to mitigate concerns about sourcing, land-use change, and biodiversity.
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	**W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)**
(ST1) Emphasize environmental improvements and EU R&D outcomes (S2, S4) to counter tightening air quality regulations (T1). (ST2) Highlight local energy security and rural deployment benefits (S1, S3) to maintain relevance and competition from electrification and heat pumps (T2). (ST3) Promoting circular economy practices, such as ash valorization, to offset negative perceptions and mitigate the impact of tightening regulations.	(WT1) Mitigate regulatory risks (T1) by deploying real-time monitoring and control systems to meet MCPD and air quality directives (W1). (WT2) Reduce public skepticism (T4) by enhancing transparency in biomass supply chains and biodiversity safeguards (W2, W4). (WT3) Expanding R&D for advanced emission controls and piloting BECCUS integration (T3), in line with ongoing EU climate objectives and IEA Bioenergy recommendations (W3). (WT4) Counter market uncertainty (T4) by positioning direct combustion as a transitional technology with clear decarbonization potential (W2, W3).

Strategic Prioritization

To ensure coherent sequencing of actions and alignment with technology-readiness levels (TRLs), the identified strategies are prioritized across short-, medium-, and long-term horizons, as summarized in Table 3.

Table 3 Strategic Prioritization of Actions for Combustion Technologies

Time Horizon	Strategic Focus	Key Actions / Relevant Strategies
Short-term (1–3 years)	Immediate feasibility and regulatory compliance	• Emission-control and monitoring systems (WO1, WT1) • Supply-chain transparency and certification (WT2, WO2)
Medium-term (4–7 years)	Innovation, scaling, and integration	•BECCUS pathway integration (SO4, WO3, WT3) • Deployment of low-emission boilers and CHP systems (SO3) • Circular-economy valorisation of by-products (SO2, ST3)
Long-term (8–12 years)	System modernization and deep decarbonization	• Full modernization of combustion infrastructure (SO1) • Establishment of BECCUS-enabled biorefinery platforms (SO4) • Reinforcement of combustion's role in integrated carbon-neutral systems (ST2, WT4)

These combustion-specific strategies contribute to the overall implementation timeline and milestones presented in Section 7 of this roadmap.

Strategic Implications and Outlook

The integrated TSOW framework demonstrates that direct combustion, while a mature and transitional technology, remains a critical enabler within the EU's decarbonization pathway. Strategic actions should concentrate on tightening emission standards, improving sustainability verification, and accelerating integration with negative-emission technologies such as BECCUS. Coordinated collaboration among technology developers, policymakers, industry stakeholders, and funding bodies is essential to ensure that combustion technologies evolve toward cleaner, more efficient, and circular systems. By aligning technological improvements with EU policy instruments and capacity-building initiatives, direct combustion can continue to play a pivotal role in Europe's transition toward sustainable, secure, and climate-neutral bioenergy systems.

3.1.2. *Gasification Technologies*

This TOWS analysis explores how different gasification pathways can strategically position itself by leveraging its strengths, addressing internal limitations, and navigating external pressures.

A MOVING BED GASIFIERS

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As outlined earlier, the moving bed category includes updraft, downdraft, and cross-draft configurations.

Updraft Gasification

Updraft gasification is a mature and robust technology primarily used for heat generation from biomass. Its counter-current flow design enables high thermal efficiency and tolerance to moist feedstocks, making it suitable for continuous operation in district heating and industrial thermal systems. However, its limitations in syngas quality and tar production restrict its applicability in advanced biorefinery contexts. This TOWS analysis explores how updraft gasification can strategically position itself by leveraging its strengths, addressing internal limitations, and navigating external pressures.

The TSOW Matrix for updraft gasification is presented in Table 4.

Table 4 TSOW Matrix for Updraft gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Deploy in district heating systems (O1) using moist agricultural residues (O2) to capitalize on high thermal efficiency (S1) and moisture tolerance (S3). (SO2) Retrofit legacy biomass systems (O3) with low-maintenance updraft units (S4, S5) to extend operational life and align with renewable heat incentives (O4). (SO3) Integrate with drying systems (O5) to enhance feedstock compatibility and optimize continuous operation (S6).	(WO1) Use policy incentives (O4) to support investment in tar mitigation technologies (W1). (WO2) Combine with pre-treatment systems (O5) to improve syngas quality (W4) and expand application scope. (WO3) Retrofit older systems (O3) to improve modularity and integration potential (W3).
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	**W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)**
(ST1) Emphasize proven reliability (S4) and simplicity (S2) to mitigate competition from emerging technologies (T3). (ST2) Highlight moisture tolerance (S3) to reduce vulnerability to seasonal feedstock variability (T5). (ST3) Promote durability and low maintenance (S5) to counter declining interest in heat-only systems (T2).	(WT1) Avoid deployment in regions with strict emission standards (T1) unless advanced cleaning is feasible (W1). (WT2) Limit use in chemical synthesis markets (T4) due to low syngas quality (W2, W4). (WT3) Implement feedstock storage strategies to reduce exposure to seasonal fluctuations (T5).

Updraft gasification remains a viable solution for heat-dominant applications, particularly in legacy infrastructure and decentralized thermal networks. Its operational simplicity and feedstock tolerance offer strategic advantages in specific contexts. However, to remain relevant in evolving energy systems, targeted retrofits, integration with pre-treatment technologies, and alignment with policy incentives are essential. Strategic deployment must focus on leveraging its strengths while mitigating its limited syngas quality and tar-related challenges.

Downdraft Gasification

Downdraft gasification is a well-established technology known for producing low-tar syngas suitable for small-scale energy systems. Its modularity, fast response, and relatively low capital cost make it ideal for decentralized applications, particularly in rural or remote areas. However, its feedstock sensitivity and limited scalability pose challenges for broader industrial integration. This TOWS analysis outlines strategic pathways to enhance its role in clean energy transitions.

The TSOW Matrix for downdraft gasification is presented in Table 5.

Table 5 TSOW Matrix for Downdraft gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Deploy in rural and off-grid areas (O1) using modular systems (S4) and clean syngas production (S1) to meet local energy needs. (SO2) Leverage low CAPEX (S6) and policy support (O2) to accelerate adoption in small-scale biorefineries. (SO3) Integrate with hybrid systems (O3) to enhance flexibility and resilience	(WO1) Invest in drying and feedstock preparation infrastructure (O5) to overcome moisture sensitivity (W1, W2). (WO2) Apply syngas upgrading technologies (O5) to expand into fuel and chemical markets (W3). (WO3) Use policy frameworks (O2) to support ash and char valorisation (W5).
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)
(ST1) Promote low-tar syngas (S1) to ease regulatory compliance (T4) and improve public perception (T3). (ST2) Emphasize modularity and fast startup (S4) to counter biomass market volatility (T6). (ST3) Position as a resilient solution for decentralized energy systems facing feedstock supply challenges (T5).	(WT1) Avoid deployment in large-scale industrial settings (T1) due to throughput limitations (W4). (WT2) Strengthen supply chain partnerships to reduce vulnerability to biomass price shifts (T5, T6). (WT3) Maintain high syngas cleanliness standards to navigate permitting challenges (T4).

Downdraft gasification offers a compelling pathway for decentralized bioenergy, especially in rural and modular contexts. Its clean syngas and operational simplicity align well with emerging demands for small-scale renewable systems. To expand its impact, strategic efforts should focus on improving feedstock logistics, enabling syngas upgrading, and leveraging policy support. While scalability remains a constraint, downdraft systems can play a vital role in localized energy transitions.

Cross draft Gasification

Cross-draft gasification is a compact, low-cost technology suited for niche and small-scale applications. Its rapid startup and minimal automation requirements make it attractive for off-grid scenarios, emergency energy kits, and educational use. However, its low efficiency, poor tar cracking, and limited scalability restrict its industrial relevance. This TOWS analysis identifies strategic opportunities to deploy cross-draft systems in targeted contexts while mitigating their inherent limitations.

The TSOW Matrix for cross draft gasification is presented in Table 6.

Table 6 TSOW Matrix for Cross draft gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Deploy in remote areas (O2, O3) using compact, low-cost systems (S1, S3). (SO2) Utilize rapid startup (S2) and simple controls (S4) for portable biomass energy kits (O5). (SO3) Promote as educational tools (S6) in demonstration projects (O4).	(WO1) Integrate with hybrid systems (O6) to compensate for low efficiency (W5) and poor tar cracking (W1). (WO2) Tailor feedstock selection and pre-treatment (O1) to reduce slagging and temperature issues (W3, W4). (WO3) Use niche deployment models (O2, O3) to offset limited scalability (W6)
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)
(ST1) Emphasize affordability and simplicity (S3, S4) to maintain relevance in low-investment contexts (T3). (ST2) Promote adaptability (S2) to counter operational inconsistencies (T4). (ST3) Leverage compact design (S1) to differentiate from larger, more complex systems (T1).	(WT1) Avoid deployment in regulated markets lacking certification pathways (T2) due to design limitations (W6). (WT2) Focus on controlled environments to reduce sensitivity to feedstock variability (W2, T4). (WT3) Limit expectations for industrial integration and instead target niche or temporary use cases (T3, T1).

Cross-draft gasification holds strategic value in specialized contexts where simplicity, portability, and rapid deployment are prioritized. While its technical limitations preclude large-scale adoption, it can serve as a useful tool in emergency response, education, and off-grid energy access. Future development should focus on hybrid integration, feedstock adaptation, and targeted niche applications to maximize its utility.

B FLUIDIZED BED GASIFIERS

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As outlined earlier, the fluidised bed gasification can be performed in bubbling fluidised beds or circulating fluidised beds which vary in the applied gas velocities (Alperen Tozlu et al., 2024). A special form of fluidised bed gasifiers are dual fluidised beds (DFBs).

Bubbling Fluidised Bed gasification

Bubbling Fluidized Bed Gasification (BFBG) is a versatile and scalable biomass conversion technology known for its high syngas yields and excellent heat and mass transfer characteristics. It accommodates a wide range of feedstocks and offers integration potential with CO_2 absorption and hydrogen production pathways. However, its operational complexity, tar management challenges, and capital intensity require strategic planning. This TOWS analysis identifies how BFBG can be positioned to maximize its strengths and mitigate its vulnerabilities in evolving energy systems.

The TSOW Matrix for Bubbling Fluidised Bed gasification is presented in Table 7.

Table 7 TSOW Matrix for Bubbling Fluidised Bed gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Leverage feedstock versatility (S1) and high hydrogen yield (S6) to support renewable energy initiatives (O1) and biomass valorisation (O4). (SO2) Promote syngas flexibility (S4) and CO_2 integration (S8) to align with green energy incentives (O3). (SO3) Deploy scalable systems (S3) in decentralized energy contexts (O5) to enhance local energy resilience.	(WO1) Use policy support (O3) to offset high investment costs (W1) and enable advanced cleaning systems (W3). (WO2) Integrate with other renewables (O2) to simplify operations and reduce energy consumption from steam requirements (W6). (WO3) Apply pre-treatment and feedstock conditioning to reduce agglomeration risks (W4) and optimize bed material use (W5).
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	**W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)**
(ST1) Emphasize robust mixing and heat transfer (S5, S7) to maintain performance despite feedstock volatility (T3). (ST2) Highlight syngas upgrade potential (S4) to counter competition from alternative technologies (T2, T6). (ST3) Promote environmental benefits of CO_2 absorption (S8) to navigate regulatory pressures (T1).	(WT1) Avoid deployment in regions with high tar removal costs (T4) unless advanced purification is feasible (W3). (WT2) Monitor biomass markets and implement flexible sourcing strategies to reduce exposure to feedstock volatility (T3, T5). (WT3) Engage stakeholders to improve public perception and acceptance (T7), especially in waste-to-energy contexts.

BFBG offers a technically mature and adaptable platform for biomass conversion, with strong potential in hydrogen production and syngas upgrading. Its strengths in feedstock flexibility and energy efficiency make it suitable for both centralized and decentralized applications. To ensure long-term viability, strategic integration with policy incentives, hybrid systems, and advanced cleaning technologies is essential. Addressing operational complexity and public perception will further enhance its role in sustainable energy transitions.

Circulating Fluidised Bed gasification

Circulating Fluidized Bed Gasification (CFBG) is a high-efficiency biomass conversion technology characterized by superior gas-solid contact and fuel flexibility. Its scalability and syngas versatility make it attractive for industrial applications and integrated energy systems. However, erosion risks, capital intensity, and tar management remain key challenges. This TOWS analysis outlines strategic directions to enhance CFBG's competitiveness and resilience in dynamic energy markets.

The TSOW Matrix for Circulating Fluidised Bed gasification is presented in Table 8.

Table 8 TSOW Matrix for Circulating Fluidised Bed gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Utilize high conversion efficiency (S1) and fuel flexibility (S2) to meet rising demand for renewable energy (O1) and sustainable waste management (O2). (SO2) Promote syngas versatility (S4) and heat recovery potential (O4) to align with policy incentives and carbon credit schemes (O3). (SO3) Deploy scalable systems (S3) in industrial zones with access to diverse biomass streams.	(WO1) Apply heat integration strategies (O4) to reduce operational complexity (W2) and improve energy efficiency. (WO2) Use policy support (O3) to offset capital costs (W1) and invest in erosion-resistant materials (W4). (WO3) Implement advanced gas cleaning systems to manage tar and ash residues (W3) and meet environmental standards.
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)
(ST1) Emphasize system configurability and fuel flexibility (S2, S3) to mitigate feedstock variability (T2). (ST2) Promote high syngas quality and conversion rates (S1, S4) to counter competition from alternative technologies (T1). (ST3) Highlight environmental benefits and energy recovery features to address public perception concerns (T6).	(WT1) Avoid deployment in volatile biomass markets (T4) unless long-term feedstock contracts are secured (W1, W2). (WT2) Monitor operational disruptions (T5) and implement predictive maintenance to reduce downtime. (WT3) Engage with regulators early to ensure compliance and reduce risk of costly upgrades (T3)..

CFBG stands out as a high-performance solution for biomass gasification, particularly in large-scale and industrial contexts. Its strengths in conversion efficiency and fuel flexibility position well for integration into net-zero energy systems. To fully realize its potential, strategic investment in erosion mitigation, gas cleaning, and heat recovery is essential. Proactive engagement with policy frameworks and public stakeholders will further support its deployment.

Dual Fluidised Bed gasification

Dual Fluidized Bed Gasification (DFBG) is an advanced biomass conversion technology that separates combustion and gasification zones to optimize reaction conditions. It produces low-tar syngas and supports integration with carbon capture systems, making it highly relevant for decarbonization strategies. However, its complexity, capital intensity, and heat integration challenges require careful planning. This TOWS analysis identifies strategic pathways to enhance DFBG's role in future biorefinery systems.

The TSOW Matrix for Dual Fluidised Bed gasification is presented in Table 9.

Table 9 TSOW Matrix for Dual Fluidised Bed gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Leverage high efficiency (S1) and low-tar syngas (S2) to meet global demand for clean energy (O1) and sustainable waste management (O2). (SO2) Promote compatibility with CCS (O3) and syngas versatility (S5) to align with carbon-neutral energy goals. (SO3) Highlight reduced emissions (S4) to support regulatory compliance and policy incentives (O3).	(WO1) Use R&D advancements (O4) to simplify reactor design and reduce operational complexity (W2). (WO2) Apply CCS integration (O3) to enhance environmental performance and justify capital investment (W1). (WO3) Improve heat exchange systems to address integration challenges (W3) and boost overall efficiency
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	**W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)**
(ST1) Emphasize staged conversion and emission control (S2, S4) to mitigate regulatory risks (T3). (ST2) Promote feedstock flexibility (S3) to reduce vulnerability to biomass variability (T2). (ST3) Position as a premium solution for high-value syngas applications to counter emerging alternatives (T1, T5).	(WT1) Avoid deployment in volatile energy markets (T4) unless supported by long-term contracts or subsidies. (WT2) Engage with stakeholders to improve public perception and acceptance (T5). (WT3) Limit deployment in regions with weak infrastructure for skilled operation and maintenance (W2, T5).

DFBG offers a technically advanced and environmentally aligned pathway for biomass gasification, particularly in contexts requiring low-emission, high-quality syngas. Its strengths in conversion efficiency and CCS compatibility make it a strategic asset in decarbonization efforts. To ensure successful deployment, investments in reactor simplification, heat integration, and stakeholder engagement are essential. With the right support, DFBG can play a pivotal role in next generation of biorefinery systems.

C PLASMA GASIFICATION

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Plasma-assisted gasification represents a high-potential, though still maturing, thermochemical pathway for converting biomass and biowaste into clean syngas and value-added products. Its core strengths—such as high conversion efficiency, environmental performance, and feedstock versatility—position it as a promising candidate for integration into decarbonization strategies, circular economy models, and modular plant development. To support strategic deployment, the TSOW analysis identifies actionable leverage points that align technological advantages with emerging opportunities in EU climate and energy frameworks.

Building on this foundation, the SWOT analysis informs roadmap development through its integration into the TOWS framework, ensuring that plasma-assisted gasification is recognized as a viable option within EU waste-to-energy pathways. The results underscore how key strengths—particularly syngas quality and feedstock flexibility—can be matched with opportunities in renewable fuels and circular economy markets. At the same time, identified weaknesses and external threats reveal priority areas for research, innovation, and policy support, guiding targeted interventions across commercialization, regulatory alignment, and public engagement.

At the same time, these strengths offer a buffer against threats like high capital costs, limited public awareness, and regulatory uncertainty. By aligning plasma gasification with EU Green Deal and RED III objectives, stakeholders can position it as a key enabler of sustainable waste-to-energy systems.

Addressing weaknesses, notably high energy demand, electrode erosion, and limited commercial deployment—requires targeted R&I, policy support, and public engagement. Opportunities such as expanding into emerging markets and integrating with renewable fuel pathways offer a clear route to overcoming these internal limitations.

The TSOW Matrix for Plasma gasification is presented in Table 10.

Table 10 TSOW Matrix for Plasma gasification

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Utilize high conversion efficiency (S1) to support EU Green Deal, RED III decarbonization goals (O1) and EU waste valorization targets, through clean hydrogen and synthetic fuel production. (SO2) Leverage cleaner syngas production (S2) to enable integration into circular economy pathways (O2), including methanol and ammonia synthesis. (SO3) Promote environmental performance (S3) to attract investment in modular plant development (O3) and sustainability certification schemes. (SO4) Exploit feedstock versatility (S4) to expand into emerging markets (O4) dealing with complex waste streams like medical and plastic waste.	(ST1) Highlight environmental benefits (S3) such as low emissions and vitrified slag reuse to mitigate high CAPEX and public skepticism. (T2). (ST2) Emphasize syngas purity and feedstock flexibility (S2, S4) to differentiate plasma gasification from competing low-carbon technologies (T5). (ST3) Use high conversion rates (S1) and slag recovery (S3) to justify higher capital investment (T1) through long-term value and reduced landfill costs

S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)
(WO1) Address high energy demand (W1) by investing in R&I for energy efficiency and electrode durability, supported by policy incentives (O5). (WO2) Accelerate commercialization (W2) through EU-funded demonstration projects and modular reactor deployment (O3). (WO3) Improve public awareness (W5) via outreach campaigns that emphasize circular economy benefits (O2) and environmental performance. (WO4) Standardize feedstock preparation (W4) to enable smoother integration into decentralized waste valorization systems (O3, O4).	(WT1) Mitigate commercialization risks (W2, T3) by strengthening regulatory frameworks and developing clear policy support for plasma technologies. (WT2) Reduce technology risk (W3, T4) through improved process control, monitoring systems, and operator training. (WT3) Address public skepticism (W5, T2) by demonstrating environmental safety and showcasing successful pilot projects. (WT4) Develop cost-reduction strategies (W1, T1) including energy recovery, optimized plasma generation, and scalable modular designs.

Plasma-assisted gasification stands at a strategic inflection point. Its technical advantages and environmental benefits make it a compelling candidate for future energy systems, especially in contexts demanding high syngas purity and feedstock flexibility. However, to unlock its full potential, coordinated efforts are needed across research, policy, and industry.

The TSOW framework highlights actionable strategies that can guide roadmap development, investment prioritization, and stakeholder alignment. By focusing on cost reduction, demonstration projects, and integration with climate-aligned fuel pathways, plasma gasification can evolve from a promising innovation to a scalable solution for sustainable energy and waste valorization.

3.1.3. Pyrolysis Technologies

This TOWS analysis explores how different pyrolysis pathways can strategically position itself by leveraging its strengths, addressing internal limitations, and navigating external pressures.

A SLOW PYROLYSIS

Author: Marta Trninić

Slow pyrolysis offers a robust platform for biochar-centric innovation, especially as global attention shifts toward carbon-negative solutions and regenerative land use. The following strategic pathways illustrate how its core strengths can be leveraged, and its limitations addressed, in alignment with emerging opportunities and external pressures.

The TSOW Matrix for slow pyrolysis is presented in Table 11.

Slow pyrolysis is uniquely positioned to meet the rising demand for carbon-negative soil amendments by capitalizing on its high biochar yield (SO1). As climate policies and agricultural practices increasingly favor long-term carbon storage (O1, O2), this strength becomes a cornerstone of sustainable land management.

Table 11 TSOW Matrix for Slow pyrolysis

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Use high biochar yield (S1) to meet growing demand for carbon-negative soil amendments (O1, O2) (SO2) Promote low-energy, mature technology (S2, S4) within circular economy and agroecological programs (O4) (SO3) Leverage feedstock versatility (S3) to support waste valorization under EU climate policies (O3). (SO4): Align biochar benefits (S5) with certification schemes and voluntary carbon markets (O2, O3).	(WO1) Apply AI and machine learning (O5) to optimize emissions control and reactor performance (W3, W5). (WO2) Use certification and public outreach (O2, O8) to improve awareness and trust in biochar applications (W4). (WO3) Develop feedstock screening protocols to ensure consistent biochar quality (W5) and meet regulatory standards (O3).
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS) (ST1) Emphasize soil and climate benefits (S1, S5) to overcome public skepticism and regulatory inertia (T1, T2, T3). (ST2) Use mature TRL and simplicity (S2, S4) to differentiate from more complex competitors (T1, T5).	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS) (WT1) Improve emissions monitoring (W3) to meet environmental compliance and avoid reputational risks (T3, T4). (WT2) Address feedstock contamination risks (W5) through pre-treatment and certification alignment (T4, T5)

Its low-energy, mature technology (S2, S4) aligns naturally with circular economy and agroecological programs (SO2), offering a reliable and accessible solution for regions seeking low-tech, high-impact interventions. The process’s feedstock versatility (S3) enables the valorization of diverse biomass streams, supporting EU climate goals and waste reduction mandates (SO3).

By emphasizing the soil and climate benefits of biochar (S5) and aligning with certification schemes and voluntary carbon markets (O2, O3), slow pyrolysis can build trust, unlock incentives, and scale responsibly (SO4).

To overcome emissions challenges and variability in biochar quality, AI and machine learning can be deployed to optimize reactor performance and emissions control (WO1). These digital tools offer precision and adaptability, especially in decentralized or variable feedstock contexts.

Certification schemes and public outreach (O2, O8) are essential to improve awareness and trust in biochar applications (WO2), helping to counteract limited public familiarity and build a stronger social license to operate. Meanwhile, feedstock screening protocols can ensure consistent biochar quality and support compliance with emerging regulatory standards (WO3).

Slow pyrolysis can directly counter public skepticism and regulatory inertia by foregrounding its soil and climate benefits (ST1). These outcomes resonate with both environmental and agricultural stakeholders, positioning biochar as a tangible climate solution.

Its mature TRL and operational simplicity (S2, S4) offer a strategic advantage over more complex or capital-intensive competitors (ST2), especially in regions where infrastructure and investment are constrained.

To maintain credibility and compliance, emissions monitoring systems must be strengthened (WT1), ensuring that industrial setups meet environmental standards and avoid reputational risks. Additionally, feedstock contamination risks—particularly airborne metal(loid) particles—can be mitigated through pre-treatment and certification alignment (WT2), safeguarding both product integrity and public health.

Slow pyrolysis excels in biochar production and soil applications, offering strong environmental benefits. Its success depends on overcoming scale-up complexity and emissions challenges through innovation and certification. With proper positioning, it can thrive in carbon-negative and circular economy frameworks.

B INTERMEDIATE PYROLYSIS

Intermediate pyrolysis offers a flexible and integrative approach to biomass conversion, producing a balanced mix of bio-oil, biochar, and syngas. Its versatility makes it well-suited for multi-sector applications, especially as policy frameworks and market demands increasingly favor circularity, resource efficiency, and low-carbon innovation.

The TSOW Matrix for intermediate pyrolysis is presented in Table 12.

The balanced product output of intermediate pyrolysis (S1) enables it to serve diverse markets—from renewable fuels and soil amendments to industrial heat—meeting the multi-sector demand driven by climate goals and energy diversification (SO1). Its feedstock flexibility (S3) supports waste valorization under EU RED III and circular economy mandates (SO2), making it a strategic fit for regions with heterogeneous biomass streams.

By integrating into biorefineries (S5), intermediate pyrolysis can maximize resource efficiency and align with policy incentives for multi-output systems (SO3). Its co-product benefits—including energy recovery and soil enhancement (S4)—can be promoted to attract climate-focused investment and build public support for emerging bio-based technologies (SO4).

Table 12 TSOW Matrix for Intermediate pyrolysis

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Use balanced product output (S1) to meet multi-sector demand for fuels, soil amendments, and heat (O1, O4). (SO2) Leverage feedstock flexibility (S3) to support waste valorization under RED III and circular economy goals (O3). (SO39 Integrate into biorefineries (S5) to maximize resource efficiency and policy alignment (O4, O3). (SO4) Promote co-product benefits (S4) to attract climate-focused investment and public support (O2, O8).	(WO1) Improve bio-oil quality (W2) through catalytic innovations and microwave pyrolysis (O2). (WO2) Use AI and CFD (O5) to stabilize reactor performance and reduce sensitivity (W3, W4). (WO3) Enhance public visibility through demonstration projects and stakeholder engagement (W5, O8).
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	**W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)**
(ST1) Use product control and flexibility (S2, S5) to compete with specialized technologies (T1). (ST2) Highlight feedstock adaptability (S3) to mitigate supply chain risks (T2). (ST3) Promote TRL advancement and integration potential (S5) to attract funding and policy support (T3, T4).	(WT1) Streamline reactor design and control systems (W3, W4) to reduce capital costs and scale-up barriers (T4, T5). (WT2) Address regulatory gaps by aligning outputs with emerging standards and certification (W2, T3)

To overcome the challenge of raw bio-oil quality (W2), catalytic innovations and microwave-assisted pyrolysis (O2) offer promising solutions that enhance stability and reduce upgrading costs (WO1). Meanwhile, AI and CFD tools (O5) can be deployed to stabilize reactor performance and mitigate sensitivity issues (W3, W4), improving reliability and scalability.

Public visibility remains limited (W5), but this can be addressed through demonstration projects and stakeholder engagement (WO3), helping to build trust, attract funding, and position intermediate pyrolysis as a viable contributor to the bioeconomy (O8).

Intermediate pyrolysis can compete with specialized technologies by emphasizing its product control and operational flexibility (S2, S5)—a key differentiator in dynamic policy and market environments (ST1). Its feedstock adaptability (S3) helps mitigate supply chain risks and biomass cost fluctuations (ST2), while its integration potential and advancing TRL (S5) can be leveraged to attract funding and policy support, especially in the face of regulatory ambiguity and scale-up challenges (ST3).

To reduce capital costs and scale-up barriers (W3, W4), intermediate pyrolysis must streamline reactor design and control systems (WT1), making deployment more feasible in diverse contexts. Addressing regulatory gaps around bio-oil classification and emissions (T3) requires aligning outputs with emerging standards and certification schemes—a critical step in improving market access and investor confidence (WT2).

C FAST PYROLYSIS

Fast pyrolysis is a high-yield, commercially advancing technology that converts biomass into bio-oil, syngas, and biochar within seconds. Its rapid conversion and scalability make it a strong candidate for liquid biofuel production, especially as global markets and climate policies increasingly prioritize renewable alternatives.

The TSOW Matrix for fast pyrolysis is presented in Table 13.

Table 13 TSOW Matrix for Fast pyrolysis

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Use high bio-oil yield (S1) to meet global demand for renewable fuels and chemicals (O1, O6) (SO2) Promote co-products (S6) to align with climate mitigation and soil health goals (O4) (SO3) Leverage feedstock versatility (S4) to support biorefinery integration and waste valorization (O3) (SO4) Apply machine learning and CFD (O5) to optimize reactor performance and reduce operational costs (S3, S5)	(WO1) Improve bio-oil quality (W1) using catalytic pyrolysis and novel upgrading pathways (O2) (WO2) Offset upgrading costs (W2) through co-location in biorefineries and shared infrastructure (O3) (WO3) Reduce pre-treatment burden (W3) via feedstock standardization and AI-driven control (O5) (WO4) Enhance public perception of bio-oil through certification and policy inclusion (W5, O6, O8).
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS) (ST1) Use high throughput and energy density (S1, S5) to compete with gasification and hydrogen systems (T1, T4) (ST2) Promote TRL maturity and commercial demonstrations (S7) to attract investment and policy support (T3, T6). (ST3) Emphasize co-product value (S6) to justify capital investment and meet emissions targets (T4, T5).	**W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)** (WT1) Streamline upgrading and reactor design (W2, W4) to reduce capital costs and improve scalability (T4, T6) (WT2) Implement emissions control systems to ensure compliance and public trust (W1, T5, T3) (WT3) Stabilize biomass supply through partnerships and logistics planning (W5, T2)

Fast pyrolysis can directly address the global demand for renewable fuels and chemicals by leveraging its high bio-oil yield (S1) and aligning with advanced biofuel incentives under frameworks like EU RED III (SO1). Its co-products—syngas and biochar—offer additional environmental and economic value, supporting climate mitigation and soil health goals (SO2).

The technology's feedstock versatility (S4) enables integration into biorefineries and supports waste valorization across agricultural, municipal, and industrial sectors (SO3). Meanwhile, machine learning and CFD tools (O5) can be applied to optimize reactor performance and reduce operational costs, especially in managing heating rates and feedstock variability (SO4).

To overcome the challenge of poor raw bio-oil quality (W1), catalytic pyrolysis and novel upgrading pathways (O2) offer promising solutions that enhance stability, reduce oxygen content, and improve marketability (WO1). Co-location in biorefineries (O3) can help offset upgrading costs (W2) by sharing infrastructure and utilities (WO2).

The burden of stringent feedstock pre-treatment (W3) can be reduced through standardization protocols and AI-driven control systems (O5), improving efficiency and consistency (WO3). To address limited public perception of bio-oil (W5), targeted certification and policy inclusion efforts (O6, O8) can help build trust and visibility (WO4).

Fast pyrolysis can compete with gasification and hydrogen systems by emphasizing its high throughput and energy-dense bio-oil (S1, S5), which supports efficient storage, transport, and end-use applications (ST1). Its TRL maturity and commercial demonstrations (S7) provide credibility and attract investment and policy support, especially in uncertain regulatory environments (ST2).

By highlighting the value of co-products (S6), fast pyrolysis can justify capital investment and meet emissions targets, reinforcing its role in integrated climate strategies (ST3).

To reduce capital costs and improve scalability, fast pyrolysis must streamline upgrading and reactor design (W2, W4), making deployment more feasible across diverse contexts (WT1). Emissions control systems are essential to ensure compliance and public trust, particularly in managing VOCs and regulatory scrutiny (WT2).

Finally, stabilizing biomass supply chains through strategic partnerships and logistics planning (WT3) will help mitigate feedstock cost fluctuations and ensure consistent operation, especially in competitive or resource-constrained environments (W5, T2).

D FLASH PYROLYSIS

Flash pyrolysis is an emerging, high-speed biomass conversion technology that offers modularity, mobility, and rapid throughput. Its strengths position it as a compelling solution for decentralized energy systems, especially in contexts where infrastructure is limited, waste streams are diverse, and responsiveness is key.

The TSOW Matrix for flash pyrolysis is presented in Table 14.

Table 14 TSOW Matrix for Flash pyrolysis

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Deploy ultra-fast conversion and modular reactors (S1, S3) to meet demand for decentralized energy (O1, O2) (SO2) Use co-produced syngas (S6) to enhance energy efficiency in renewable-powered setups (O3) (SO3) Apply feedstock versatility (S5) to broaden market reach and support local waste valorization (O6)	(WO1) Improve bio-oil quality (W1) using advanced catalytic pyrolysis techniques (O4) (WO2) Offset upgrading complexity and cost (W2) by integrating flash pyrolysis into biorefineries (O3) (WO3) Reduce energy-intensive pre-treatment (W3) through process optimization with CFD and AI (O5)

(SO4) Integrate machine learning and CFD (O5) to optimize reactor control and throughput (S1, S4) (SO5) Position flash pyrolysis as a mobile solution for remote or off-grid applications (S4, O3, O7)	(WO4) Mitigate reactor sensitivity (W4) using predictive control systems and modular design innovations (O2, O5) (WO5) Address biomass variability (W5) by developing adaptive feedstock protocols and catalyst systems (O4)
S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS) (ST1) Highlight rapid conversion and throughput (S1, S2) to compete with slower pyrolysis technologies (T1) (ST2) Use feedstock adaptability (S5) to buffer against supply chain instability (T3) (ST3) Promote compact reactor design and decentralized deployment (S3, S4) to attract policy support and reduce regulatory exposure (T2, T7) (ST4) Emphasize co-product benefits (S6) to differentiate from single-output technologies and justify capital investment (T1, T4)	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS) (WT1) Streamline upgrading processes (W2) to reduce capital costs and improve competitiveness (T4, T6). (WT2) Standardize reactor modules and control systems (W4) to simplify scale-up and reduce investment risk (T4, T6). (WT3) Implement emissions monitoring and mitigation strategies to ensure environmental compliance (W1, T5, T7). (WT4) Establish biomass sourcing partnerships and flexible logistics to stabilize feedstock supply (W5, T3).

Flash pyrolysis can directly address the demand for decentralized energy by deploying its ultra-fast conversion capabilities and modular reactor designs (S1, S3) in urban, rural, and off-grid settings (SO1). The co-produced syngas (S6) enhances energy efficiency, particularly when coupled with renewable-powered setups or microgrids (SO2).

Its feedstock versatility (S5) allows it to tap into local waste valorization initiatives and broaden its market reach across sectors and geographies (SO3). By integrating machine learning and CFD tools (O5), flash pyrolysis can optimize reactor control and throughput, improving reliability and performance in dynamic operating environments (SO4).

Finally, its compact and mobile design (S4) makes it ideal for remote or off-grid applications, offering a flexible solution for distributed bioenergy deployment and future regulatory inclusion (SO5).

To overcome the challenge of poor bio-oil quality (W1), advanced catalytic pyrolysis techniques (O4) can be applied to improve stability, reduce oxygen content, and enhance usability (WO1). Integrating flash pyrolysis into biorefineries (O3) helps offset upgrading complexity and cost (W2) by leveraging shared infrastructure and co-processing opportunities (WO2).

The burden of energy-intensive feedstock pre-treatment (W3) can be reduced through process optimization using CFD and AI (O5), improving efficiency and lowering operational costs (WO3). Predictive control systems and modular design innovations (O2, O5) can help mitigate reactor sensitivity and improve scalability (WO4), while adaptive feedstock protocols and catalyst systems (O4) address biomass variability and ensure consistent output (WO5).

Flash pyrolysis can compete with slower pyrolysis technologies by emphasizing its rapid conversion and high throughput (S1, S2), offering speed and responsiveness in dynamic energy markets (ST1). Its feedstock adaptability (S5) provides resilience against supply chain instability, making it suitable for regions with fluctuating biomass availability (ST2).

By promoting its compact reactor design and decentralized deployment potential (S3, S4), flash pyrolysis can attract policy support and reduce exposure to regulatory gaps and public skepticism (ST3). Its co-product benefits (S6) offer a strategic edge over single-output technologies, helping to justify capital investment and meet emissions targets (ST4).

To reduce capital costs and improve competitiveness, flash pyrolysis must streamline upgrading processes (W2) and explore modular, scalable reactor configurations (WT1). Standardizing reactor modules and control systems (W4) will simplify scale-up and reduce investment risk, especially in early-stage deployments (WT2).

Emissions monitoring and mitigation strategies are essential to ensure environmental compliance and build public trust, particularly in managing VOCs and thermal residues (WT3). Finally, biomass sourcing partnerships and flexible logistics can help stabilize feedstock supply and buffer against market volatility (WT4), ensuring consistent operation and output quality.

The pyrolysis landscape offers a spectrum of technologies, each with distinct strategic profiles shaped by their outputs, technical maturity, scalability, and alignment with environmental and policy goals. A comparative synthesis reveals how each process leverages its strengths, addresses its weaknesses, and navigates opportunities and threats in a rapidly evolving bioeconomy.

Slow pyrolysis is the most mature and biochar-focused pathway, ideally suited for carbon sequestration and regenerative agriculture. Its strengths—high biochar yield, low energy input, and feedstock versatility—align well with rising demand for carbon-negative soil amendments and circular farming practices. Strategic opportunities include certification schemes (e.g., EBC), voluntary carbon markets, and EU climate policies recognizing biochar as a carbon sink.

However, slow pyrolysis faces throughput limitations, emissions challenges, and low public awareness. These are addressed through AI-driven emissions control, feedstock screening protocols, and public outreach. Its simplicity and TRL maturity allow it to counter regulatory inertia and compete with more complex technologies. Scaling requires careful attention to environmental compliance and feedstock quality, especially in contaminated biomass streams.

Intermediate pyrolysis offers a balanced output of bio-oil, biochar, and syngas, making it a flexible candidate for integrated biorefineries. Its moderate residence times and feedstock tolerance support waste valorization and circular economy goals. Strategic strengths include co-product synergy, biorefinery compatibility, and adaptability to policy frameworks like RED III.

Weaknesses—such as bio-oil upgrading complexity, reactor sensitivity, and limited public visibility—are mitigated through catalytic innovations, AI-based control systems, and demonstration projects. Intermediate pyrolysis competes by emphasizing product flexibility and integration potential, while addressing threats like regulatory ambiguity and scale-up costs through standardization and certification alignment.

Fast pyrolysis is the most commercially advanced liquid-fuel pathway, delivering high bio-oil yields with rapid conversion. Its strengths—versatile feedstock processing, co-product value, and TRL maturity—position it well for decarbonizing transport and chemicals. Opportunities include catalytic upgrading, biorefinery integration, and advanced biofuel incentives.

Challenges include poor raw bio-oil quality, costly upgrading, and complex reactor design. These are addressed through catalytic innovations, co-location strategies, and AI-driven optimization. Fast pyrolysis competes with gasification and hydrogen systems by emphasizing throughput and energy density, while managing emissions and biomass variability through control systems and logistics planning.

Flash pyrolysis is the most agile and modular technology, offering ultra-fast conversion and high throughput in compact reactor systems. It excels in decentralized and mobile deployment, making it ideal for on-site waste-to-energy applications. Strategic strengths include syngas co-production, feedstock flexibility, and alignment with circular economy and local energy autonomy.

Its early-stage TRL, poor bio-oil quality, and reactor sensitivity pose challenges, addressed through catalytic enhancements, CFD-based control, and integration into biorefineries. Flash pyrolysis competes by highlighting speed, modularity, and responsiveness, while mitigating threats through emissions monitoring, standardization, and adaptive feedstock protocols.

Strategic Positioning Summary

1. Slow Pyrolysis: Best suited for biochar-centric applications, carbon sequestration, and low-tech rural deployment. Mature, reliable, and policy-aligned.
2. Intermediate Pyrolysis: Ideal for multi-output systems and biorefinery integration. Flexible but requires technical refinement and regulatory clarity.
3. Fast Pyrolysis: Strong candidate for renewable liquid fuels and industrial energy. Commercially viable with targeted innovation in upgrading and control.
4. Flash Pyrolysis: Emerging solution for decentralized, mobile energy systems. High potential if TRL, emissions, and public trust are actively developed.

Together, these technologies form a complementary toolkit for advancing the bioeconomy—each suited to different contexts, feedstocks, and strategic goals. Deployment decisions should consider not only technical performance but also policy alignment, public perception, and integration potential.

3.1.4. Torrefaction

Author: Marta Trninić

This TOWS analysis explores how torrefaction pathways can strategically position itself by leveraging its strengths, addressing internal limitations, and navigating external pressures.

The TSOW Matrix for torrefaction is presented in Table 15.

Torrefaction's enhanced fuel properties (S1) and compatibility with coal-fired infrastructure (S3) position it as a strong candidate for integration into EU climate initiatives such as the Green Deal, Fit for 55, and REPowerEU (O1). These policies promote biomass as a transitional energy source, and torrefaction's technical advantages make it well-suited to meet these goals. Improved grindability and storage stability (S2, S4) also support international trade and certification efforts (O3), helping torrefied biomass gain recognition as a standardized, exportable commodity. Furthermore, the ability to process diverse waste biomass streams (S1–S4) aligns with circular bioeconomy objectives (O4), reinforcing torrefaction's role in sustainable resource valorization.

The high capital and operational costs of torrefaction (W1), along with its limited commercial deployment (W4), can be mitigated by tapping into EU funding and regulatory support (O1). These frameworks offer financial incentives and policy alignment that can accelerate market entry. Product inconsistency (W2) can be addressed through the development of ISO standards and safety certifications (O3), ensuring quality control across diverse feedstocks. Additionally, integrating torrefaction with other thermochemical processes such as pyrolysis or gasification (O2) may help resolve pelletization challenges (W3) by optimizing energy use and improving material handling.

Torrefaction's compatibility with existing infrastructure (S3) and its stable, hydrophobic fuel output (S4) can help reduce operational risks associated with dust explosions (T1), especially when paired with appropriate safety protocols. These strengths also support efforts to counter public skepticism (T4), as torrefied biomass offers a cleaner, more stable alternative to raw biomass with lower risks of spoilage and emissions. Moreover, its adaptability to various feedstocks (S1–S2) provides resilience against seasonal and geographic variability (T3), helping maintain consistent performance across supply chains.

To reduce exposure to regulatory uncertainty (T2), torrefaction developers should align their practices with emerging standards and ensure compliance with REACH and IMO protocols — addressing both limited deployment (W4) and product inconsistency (W2). Safety risks (T1) can be managed through investment in dust mitigation systems and improved pelletization techniques (W3). Finally, transparent sustainability frameworks and traceability systems are essential to address public concerns (T4), especially those related to land-use change and biodiversity, helping build trust and secure long-term policy and market support.

Table 15 TSOW Matrix for Torrefaction

S-O STRATEGIES (LEVERAGE STRENGTHS WITH OPPORTUNITIES)	W-O STRATEGIES (ADDRESS WEAKNESSES BY CAPITALIZING ON OPPORTUNITIES)
(SO1) Leverage enhanced fuel properties (S1) and compatibility with coal infrastructure (S3) to align with EU decarbonization goals and co-firing incentives under Fit for 55 and REPowerEU (O1). (SO2) Use improved grindability and storage stability (S2, S4) to support international trade and certification efforts (O3), positioning torrefied biomass as a reliable global commodity. (SO3) Promote torrefaction's ability to process waste biomass (S1–S4) as a solution for circular bioeconomy initiatives (O4), reinforcing its role in sustainable energy systems.	(WO1) Address high operational costs (W1) and limited deployment (W4) by tapping into EU funding and policy support (O1), accelerating commercialization. (WO2) Mitigate product inconsistency (W2) through standardization efforts (O3), ensuring quality control across diverse feedstocks. (WO3) Improve pelletization efficiency (W3) by integrating torrefaction with complementary processes (O2), optimizing energy use and material handling.

S-T STRATEGIES (USE STRENGTHS TO COUNTER THREATS)	W-T STRATEGIES (MINIMIZE WEAKNESSES TO AVOID THREATS)
(ST1) Use torrefaction's compatibility with existing infrastructure (S3) and improved fuel stability (S4) to reduce operational risks and justify safety investments (T1). (ST2) Highlight hydrophobicity and reduced biological degradation (S4) to counter public skepticism (T4), emphasizing environmental benefits and reduced land-use pressure (ST3) Promote torrefaction's adaptability to various feedstocks (S1–S2) to manage variability risks (T3) and support flexible sourcing strategies	(WT1) Reduce regulatory exposure (T2) by aligning torrefaction practices with emerging ISO standards and REACH-compliant protocols, addressing W2 and W4. (WT2) Invest in safety engineering and dust mitigation systems to manage explosion risks (T1), while improving pelletization and handling (W3). (WT3) Develop transparent sustainability frameworks to address public concerns (T4) and build trust, especially in regions with sensitive land-use dynamics.

Torrefaction stands out as a technically robust and strategically aligned biomass upgrading technology, offering enhanced fuel properties, improved handling, and compatibility with existing coal infrastructure. These strengths position it well within the EU's climate and energy frameworks, particularly the Green Deal, Fit for 55, and REPowerEU, which actively support biomass as part of the renewable transition.

However, successful deployment depends on overcoming key weaknesses — notably high operational costs, product variability, and limited commercial scale. These challenges can be addressed through targeted integration with complementary technologies, standardization efforts, and policy-backed investment.

At the same time, torrefaction must proactively manage external threats such as safety risks, regulatory ambiguity, and public skepticism. Transparent sustainability practices, robust safety protocols, and alignment with international standards will be essential to build trust and secure market access.

By strategically leveraging its strengths and opportunities while mitigating weaknesses and threats, torrefaction can evolve from a promising innovation into a scalable, sustainable pillar of the low-carbon energy landscape.

3. GAP ANALYSIS AND PROPOSED STRATEGIC ACTIONS

This section identifies key barriers hindering the large-scale deployment of biorefinery technologies. The gaps are organized into regulatory, technological, investment, and awareness/market categories, each linked to potential roadmap actions.

3.2. Thermochemical Conversion

3.2.3. Regulatory Gaps

Author: Marta Trninić

Despite growing interest in thermochemical conversion technologies, several regulatory barriers continue to hinder their deployment across EU Member States and associated regions:

1. Lack of harmonized standards and permitting frameworks for emerging technologies such as plasma gasification, catalytic pyrolysis and hydrothermal liquefaction (HTL),. These systems often fall outside existing regulatory categories, creating uncertainty for developers and permitting authorities (European Commission, 2023b).
2. Inconsistent regional policies regarding biomass sustainability, waste-to-energy classification, and lifecycle emissions accounting. This fragmentation complicates cross-border collaboration and technology transfer and may result in unequal access to incentives or recognition under EU climate and energy targets (EEA, 2023, European Union, 2018).
3. Lengthy and opaque permitting procedures, including unclear requirements for environmental impact assessments (EIAs) and risk evaluations for novel conversion processes (European Union, 2011, European Commission, 2023a). These delays discourage investment and slow down pilot-to-commercial transitions.

To address the identified regulatory gaps and accelerate the deployment of thermochemical conversion technologies, the following **strategic actions** are proposed:

1. Develop and implement harmonized international and EU-level standards and certification schemes for bio-based fuels and thermochemical products, ensuring interoperability and market acceptance across Europe.

- Promote adoption of recognized schemes such as ISCC EU[1], RSB Global Fuels Certification[2], and 2BSvs[3], which ensure sustainability and traceability of bio-based fuels across the full value chain (European Union, 2018, Commission, 2021, ISCC System GmbH, 2024).
- Align certification practices with the EU Renewable Energy Directive II (RED II), which sets sustainability and GHG savings criteria for biofuels, bioliquids, and biomass fuels (Roundtable on Sustainable Biomaterials (RSB), 2024).

2. Streamline and standardize permitting procedures by introducing dedicated technical guidelines tailored to thermochemical conversion plants, including emerging technologies such as hydrothermal liquefaction and plasma gasification.
   - Apply best practices from the European Commission's Recommendation on speeding up permit-granting procedures for renewable energy projects (Commission, 2022, Directorate-General for Energy, 2024).
   - Tailor permitting guidelines to thermochemical technologies such as pyrolysis, gasification, drawing from insights in IRENA's permitting framework and CAN Europe's checklist for fairer permitting (Thorson M et al., 2024, IRENA, 2025, Veerle Dossche et al., 2023, Szabo John, 2023).
3. Align biomass sustainability criteria with established frameworks such as the EU Renewable Energy Directive II (RED II) or equivalent national schemes, ensuring consistency in lifecycle emissions accounting and eligibility for renewable energy incentives (European Union, 2018, Commission, 2024, ISCC, 2025).

3.2.4. Technological Gaps

Author: Marta Trninić, Leonarda F. Liotta, Carla Calabrese, Laura Valentino

Thermochemical conversion technologies exhibit a wide range of maturity and deployment readiness, with several critical technical barriers limiting their scalability and integration into advanced biorefinery systems:

1. Technology Readiness Disparity: Mature technologies such as combustion and gasification operate at TRL 8–9, while emerging systems like hydrothermal liquefaction (HTL), catalytic

[1] ISCC EU - International Sustainability and Carbon Certification – EU version
[2] RSB Global Fuels Certification - Roundtable on Sustainable Biomaterials – Global Fuels Scheme
[3] 2BSvs - Biomass Biofuel Sustainability Voluntary Scheme

upgrading, and plasma gasification remain at TRL 4–6, requiring further demonstration and validation (Motola V et al., 2023, BEIS and AECOM, 2021, Alperen Tozlu et al., 2024).

2. Feedstock Flexibility Constraints: Most systems are optimized for dry, homogeneous biomass, limiting their capacity to process wet, mixed, or contaminated feedstocks (Motola V et al., 2023, DOE, 2016, Adapa et al., 2011, Alperen Tozlu et al., 2024). This restricts deployment in sectors with diverse waste streams and necessitates robust pre-treatment technologies. Furthermore, the instability of the raw material supply chain (e.g., seasonality) exacerbates this challenge.
3. Product Quality Limitations: Bio-oil derived from pyrolysis and HTL suffers from chemical instability, high oxygen content, and corrosiveness, requiring catalytic upgrading to meet fuel standards. Similarly, syngas cleaning technologies must be improved to remove tars, particulates, and trace contaminants for engine or synthesis use (Panwar and Paul, 2021, Alperen Tozlu et al., 2024, Gea et al., 2023).
4. Underdeveloped CCUS Integration: The integration of carbon capture, utilization, and storage (CCUS) with thermochemical plants is still in its infancy (Acampora et al., 2025). While technically feasible, it faces challenges in energy efficiency, cost, and system compatibility.
5. Process Control and Automation Gaps: Modular and decentralized thermochemical systems lack advanced control architectures, real-time optimization, and interoperability. This limits scalability and responsiveness to dynamic feedstock and energy demands.

To address the identified regulatory gaps and accelerate the deployment of thermochemical conversion technologies, the **following strategic** actions are proposed:

1. Accelerate Technology Maturation for Emerging Systems
    - Emerging systems such as hydrothermal liquefaction, catalytic upgrading, and plasma gasification should be prioritized for pilot-scale demonstration to raise their technology readiness levels. This will help bridge disparity with more mature systems like combustion and gasification.
    - Launch targeted demonstration projects under relevant support instruments (e.g., Horizon Europe Cluster 5, Innovation Fund – Large-scale Projects, ERA-NET Bioenergy) to advance TRL from 4–6 to ≥7 through multi-stakeholder pilots and industrial validation.

   - Scalable, cost-effective BECCUS solutions compatible with direct combustion should be piloted to enhance the climate performance of mature systems and support negative emissions strategies.
2. Enhance Feedstock Flexibility and Pre-treatment Innovation
   - To overcome feedstock flexibility constraints in thermochemical systems, strategic actions should focus on developing modular pre-treatment technologies capable of handling wet, mixed, and contaminated biomass, while promoting reactor designs that accommodate variable feedstock properties.
   - Integrating digital tools for feedstock monitoring and forecasting can help mitigate supply chain instability caused by seasonality. Establishing regional biomass hubs would stabilize input quality and logistics, and hybrid conversion pathways—such as combining anaerobic digestion with gasification—can enhance valorization of diverse waste streams.
   - These efforts should be supported by EU circular economy policies and funding instruments (e.g. Circular Bio-based Europe Joint Undertaking (CBE JU), LIFE Programme – Waste Valorization).
   - Improved ash management and valorization technologies should also be prioritized to reduce waste volumes and environmental impact, especially in systems relying on direct combustion.
3. Improve Product Quality and Upgrading Technologies
   - Product quality issues—such as the instability and corrosiveness of bio-oils and the impurity of syngas—require targeted investment in catalytic upgrading and advanced cleaning systems to meet fuel standards and enable downstream use.
   - These efforts should be supported by funding instruments (e.g. European Partnerships on Clean Hydrogen, Processes4Planet, EIC Pathfinder).
   - Integration with hydrogen, methanol, and Bioenergy with Carbon Capture and Utilization (BECCU) pathways should be prioritized to enhance climate alignment and unlock cross-sector synergies.
4. Integrate CCUS into Thermochemical Platforms

- Carbon capture, utilization, and storage (CCUS) should be integrated into thermochemical platforms through retrofit demonstrations and co-designed systems, including biochar-based carbon storage, to enhance climate performance.
- These efforts should be supported by funding instruments (e.g. Innovation Fund, Modernisation Fund, Net Zero Industry Act).
- For energy-intensive plasma processes, cost-reduction strategies—such as energy recovery, optimized plasma generation, and modular system design—should be developed to improve economic viability and support broader adoption.

5. Deploy Advanced Process Control and Automation
   - Modular and decentralized systems need advanced process control and automation. Deploying digital twins and interoperable control architectures will enable real-time optimization and scalability.
   - These efforts should be supported by funding instruments (e.g. Digital Europe Programme, Horizon Europe Cluster 4, AI-on-Demand Platform).
   - Enhanced real-time monitoring and control systems are essential to meet increasingly strict emission requirements under the MCPD and air quality directives, ensuring regulatory compliance and public trust.
6. Foster Cross-sector Integration and Hybrid Systems
   - Hybrid biorefinery models that combine thermochemical and biochemical routes ((e.g. HTL + anaerobic digestion, gasification + syngas fermentation).) should be promoted to improve resource efficiency and circularity, especially in multi-feedstock environments.
   - These efforts should be supported by funding instruments (e.g. CBE JU, EU Bioeconomy Strategy).

3.2.5. Investment and Financing Gaps

Author: Marta Trninić

The successful deployment of thermochemical biorefinery technologies hinges not only on technical readiness but also on the availability of robust and targeted financial support mechanisms. Despite their potential to contribute to the EU's climate neutrality and circular economy goals, these technologies face persistent investment and financing barriers that slow down market uptake and scale-up.

Thermochemical technologies face persistent financing barriers due to their perceived technical complexity, long payback periods, and limited commercial track record. Public funding mechanisms often prioritize more mature renewable solutions, while private investors remain cautious due to unclear risk profiles and regulatory uncertainties. Additionally, fragmented support across EU Member States and the absence of dedicated financial instruments for waste-based thermochemical valorization hinder large-scale deployment. Bridging these gaps requires:

1. Policy-backed de-risking tools (e.g. guarantees, blended finance),
2. Targeted EU and national funding calls aligned with TRL advancement,
3. Clear techno-economic benchmarks to support investor confidence,
4. Public-private partnerships to accelerate demonstration and scale-up.

Some of identified barriers are:

1. High CAPEX (Capital Expenditure) Requirements: First-of-a-kind thermochemical conversion facilities demand substantial capital investment, which discourages private sector participation and increases dependency on public funding sources (Bioenergy, 2023, US Department of Energy, 2017, Alperen Tozlu et al., 2024).
2. High OPEX (Operating Expenditure): These costs are critical to assessing the long-term viability and competitiveness of technologies such as gasification, pyrolysis, and liquefaction (Alperen Tozlu et al., 2024, Bioenergy, 2023).
3. Limited Financial Incentives: Compared to other renewable energy pathways (e.g. solar, wind, anaerobic digestion), thermochemical biofuels receive disproportionately low support through grants, subsidies, or feed-in tariffs, undermining their competitiveness (Govindji Al-Karim, 2013).
4. Absence of Dedicated Funding Mechanisms: There is a lack of targeted financial instruments for demonstration-scale and scale-up projects, which impedes the transition from TRL 5–6 to full commercial deployment (EUROPEAN COURT OF AUDITORS, 2023).

To overcome the persistent investment and financing barriers hindering the deployment of thermochemical biorefinery technologies, a set of targeted strategic actions is proposed.

1. First, addressing high capital expenditure (CAPEX) requires the establishment of blended financing models that combine EU grants, national co-funding, and private equity. Risk-sharing mechanisms such as loan guarantees and green bonds should be promoted to

attract private sector participation, while CAPEX-intensive projects should be prioritized under Horizon Europe and the Innovation Fund.

2. To mitigate high operating expenditure (OPEX), operational benchmarking across EU regions is essential to identify efficiency gaps and inform cost-reduction strategies. Early-stage facilities would benefit from targeted operational subsidies, and the adoption of automation and digitalization should be encouraged to reduce labor and maintenance costs.
3. To counter limited financial incentives, thermochemical pathways should be included in feed-in tariff schemes and renewable energy auctions. EU taxonomy and state aid frameworks must be aligned to recognize these technologies as strategic low-carbon investments, and dedicated incentive programs should be launched under instruments such as the Circular Bio-based Europe Joint Undertaking (CBE JU) and the LIFE Programme.
4. The absence of dedicated funding mechanisms for demonstration and scale-up projects must be addressed through the creation of a targeted EU funding window for TRL 5–7 initiatives. Regional innovation clusters should be supported to pool resources and infrastructure, and thermochemical scale-up should be explicitly integrated into the Strategic Energy Technology (SET) Plan to ensure long-term policy coherence and funding continuity

3.2.6. Awareness & Market Gaps

Author: Marta Trninić

Despite their potential to contribute to climate neutrality and circular bioeconomy goals, thermochemical technologies remain underrepresented in public discourse, policy frameworks, and investment portfolios. Limited awareness among stakeholders—including policymakers, investors, and end-users—hampers market confidence and slows adoption. In addition, the absence of clear market signals, standardized product specifications, and targeted outreach campaigns restricts demand creation and technology visibility. Bridging these gaps requires coordinated communication strategies, inclusion in national energy plans, and stronger engagement with industry platforms and certification bodies.

4. STRATEGIC PRIORITIES AND ACTION AREAS

Author: Marta Trninić

This roadmap outlines a set of strategic priorities aimed at accelerating the integration of promising biorefinery technologies into sustainable European value chains. These priorities are grounded in stakeholder input, policy alignment, and deployment readiness, and are organized into four interconnected action areas:

1. Policy and Regulatory Alignment
   - Develop harmonized standards and certification schemes to support technology deployment across EU Member States.
   - Clarify regulatory pathways for emerging technologies, including hybrid systems and BECCUS, to reduce uncertainty and facilitate investment.
   - Ensure coherence between biorefinery development and broader EU strategies such as RED III, REPowerEU, and the Circular Economy Action Plan.
2. Investment and Financing Mechanisms
   - Mobilize targeted funding to bridge the gap between research and market deployment, particularly for demonstration and first-of-a-kind commercial plants.
   - Promote public–private partnerships and innovative financing models to attract private capital and reduce risk.
   - Support regional investment platforms, especially in Inclusiveness Target Countries, to foster balanced development across Europe.
3. Research, Development & Innovation
   - Advance hybrid and integrated systems that combine biochemical, thermochemical, and physicochemical routes.
   - Improve process efficiency and feedstock flexibility through targeted R&D and pilot-scale validation.
   - Support open-access data platforms and harmonized life-cycle methodologies to improve transparency and comparability.
4. Market Development and Capacity Building
   - Raise awareness among stakeholders through outreach, training, and demonstration activities.

- Strengthen collaboration between academia, industry, and policymakers to co-create viable business models.
- Develop new value chains for bio-based products, with a focus on rural regions and industrial transition areas.
- Foster skills development through training schools, mentoring programs, and knowledge exchange platforms, with particular support for young researchers and innovators.
- These priorities are designed to work in concert, creating the conditions needed for large-scale deployment of sustainable biorefinery technologies across Europe.

5. TIMELINE AND MILESTONES

Author: Marta Trninić

The roadmap's implementation is structured into three phases—short-term (1–3 years), medium-term (4–7 years), and long-term (8–12 years)—to ensure a realistic, coordinated progression from pilot demonstrations to full-scale deployment. Milestones are sequenced based on Technology Readiness Levels (TRLs), regulatory evolution, and market dynamics, while recognizing critical interdependencies between R&D, policy, financing, and stakeholder engagement.

This phased approach aligns with EU strategic frameworks including the European Green Deal, Fit for 55 package, and the Circular Economy Action Plan, and supports objectives under Horizon Europe, LIFE Program, and Innovation Fund (Platt Richard et al., 2021).

Short-term (1–3 years):

1. Launch targeted pilot and demonstration projects for emerging biochemical, thermochemical, and physicochemical processes (TRL 5–6) (Calvo-Flores and Martin-Martinez, 2022).
2. Establish harmonized sustainability criteria for biomass waste feedstocks, aligned with RED II and EU Taxonomy (European Union, 2018, Commission, 2025, Platt Richard et al., 2021).
3. Initiate policy dialogues to streamline permitting and certification procedures across Europe (Platt Richard et al., 2021).
4. Develop regional biomass waste hubs to improve feedstock logistics, traceability, and quality control (Calvo-Flores and Martin-Martinez, 2022).
5. Publish technical guidelines and best practices for biorefinery configurations, hybrid biorefinery configurations (e.g., coupling biochemical and thermochemical routes), supporting replication and scale-up (Valdez-Vazquez et al., 2024).

Medium-term (4–7 years):

6. Advance TRL of priority processes to TRL ≥7 through large-scale demonstration and validation under Horizon Europe clusters (Calvo-Flores and Martin-Martinez, 2022).

1. Integrate Carbon Capture, Utilization, and Storage (CCUS) into selected thermochemical platforms to support Fit for 55 targets (Platt Richard et al., 2021).

2. Deploy advanced automation and process control systems for modular and decentralized biorefinery plants (Valdez-Vazquez et al., 2024).
7. Launch dedicated funding instruments (e.g. Innovation Fund, InvestEU) to support scale-up and commercialization (Calvo-Flores and Martin-Martinez, 2022).
3. Foster cross-sector hybridization, coupling biochemical and thermochemical routes to enhance resource efficiency (Platt Richard et al., 2021).

Long-term (8–12 years):

1. Achieve full commercial-scale deployment across multiple EU regions, supported by stable policy frameworks (Calvo-Flores and Martin-Martinez, 2022).
2. Establish standardized product specifications for bio-based intermediates and fuels, aligned with CEN standards (Calvo-Flores and Martin-Martinez, 2022).
3. Implement integrated biorefinery networks to optimize resource use, circularity, and regional synergies (Valdez-Vazquez et al., 2024).
4. Realize sustained market uptake through mature value chains and long-term policy support (Calvo-Flores and Martin-Martinez, 2022).
5. Monitor and document climate and socio-economic impacts, contributing to EU climate neutrality goals (Valdez-Vazquez et al., 2024).

6. MONITORING AND EVALUATION FRAMEWORK

Author: Marta Trninić

A robust Monitoring & Evaluation (M&E) framework will track progress, measure impact, and inform adaptive management. It is anchored in quantifiable Key Performance Indicators (KPIs), transparent review cycles, and active stakeholder involvement. This framework supports compliance with EU reporting standards and ensures alignment with evolving policy landscapes.

This approach builds methodologies from the IEA Bioenergy Task 42 and integrated techno-economic and environmental assessment (ETEA) frameworks (Pérez-Almada et al., 2023, Lindorfer Johannes et al., 2019).

Key Performance Indicators (examples):

1. Technology deployment: Number of operational pilot, demonstration, and commercial facilities (TRL 6–9).
2. TRL advancement: Increase in technology readiness levels for priority processes.
3. Environmental performance: Reduction in lifecycle GHG emissions; percentage of waste diverted from landfill/incineration.
4. Economic impact: Amount of private and public investment mobilized; number of jobs created in biorefinery value chains.
5. Regulatory alignment: Number of countries adopting harmonized sustainability standards and permitting procedures.
6. Market development: Volume of certified bio-based products entering EU markets.

Review cycles:

1. Annual reviews to assess KPI achievement and update short-term actions.
2. Mid-term evaluations (every 3–4 years) to reassess priorities, funding needs, and policy alignment.
3. End-of-phase reviews to consolidate lessons learned, validate outcomes, and adjust long-term vision.

Stakeholder engagement:

1. Establish a Biorefinery Roadmap Implementation Forum involving RTOs, industry, policymakers, and investors.
2. Use workshops, digital platforms, and surveys to collect feedback and disseminate results.

3. Integrate multi-actor input into annual and mid-term reviews to ensure relevance and legitimacy.

Adaptive management mechanisms:

1. Flexibly adjust strategies in response to technological breakthroughs, regulatory changes, or market shifts.
2. Maintain a living roadmap document, updated annually, to integrate new evidence and stakeholder priorities.

CONCLUSION

Author: Marta Trninić

This roadmap offers a strategic framework for advancing the deployment of sustainable biorefinery technologies in Europe. Building on the analytical foundation of the D2.4 Technical Report, it translates stakeholder insights into concrete actions that address technical, regulatory, and market challenges.

By aligning technological development with EU policy goals—including the European Green Deal, Fit for 55, and the Circular Economy Action Plan—the roadmap supports the creation of coherent pathways for renewable carbon integration. It identifies key barriers and proposes targeted measures to overcome them through coordinated investment, policy reform, and innovation.

The document emphasizes the importance of inclusive participation, regional balance, and capacity building, particularly in underrepresented regions and among early-career professionals. It also highlights the need for harmonized methodologies, transparent data systems, and collaborative governance to ensure that biorefinery deployment is both effective and equitable.

Ultimately, this roadmap serves as a practical guide for policymakers, researchers, industry leaders, and civil society. Through shared knowledge, strategic investment, and coordinated action, Europe can transform its biomass and waste resources into sustainable fuels, chemicals, and materials—delivering on its climate and circular economy ambitions with resilience, innovation, and inclusivity.

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Weblink: https://wire-cost-eu.ipportalegre.pt/

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