Pyrolysis is Not Circular by Conversion Alone

Six engineering checks for credible renewable-carbon value

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Pyrolysis can convert biomass residues, mixed organic wastes and difficult plastic streams into char, liquids and gases. That makes it an important technology family for bio-based production and chemical recycling. But conversion alone does not establish circularity, renewable-carbon content or climate benefit.

The carbon question starts before the reactor and ends after the product leaves it. What is the carbon source? How much carbon enters the useful product? Is that product returned to a material loop, used as fuel, stored in a solid or lost as gas? Does it actually replace virgin fossil carbon? What energy is used to run the process? And how is the claimed carbon share traced or certified?

These questions matter because the same reactor can support very different carbon outcomes. A pyrolysis oil used as cracker feedstock can serve a different carbon-management function from the same liquid burned as fuel. Biochar used in a durable application has a different carbon pathway from char that is immediately combusted. The process should therefore be evaluated as a carbon pathway, not only as a conversion unit.

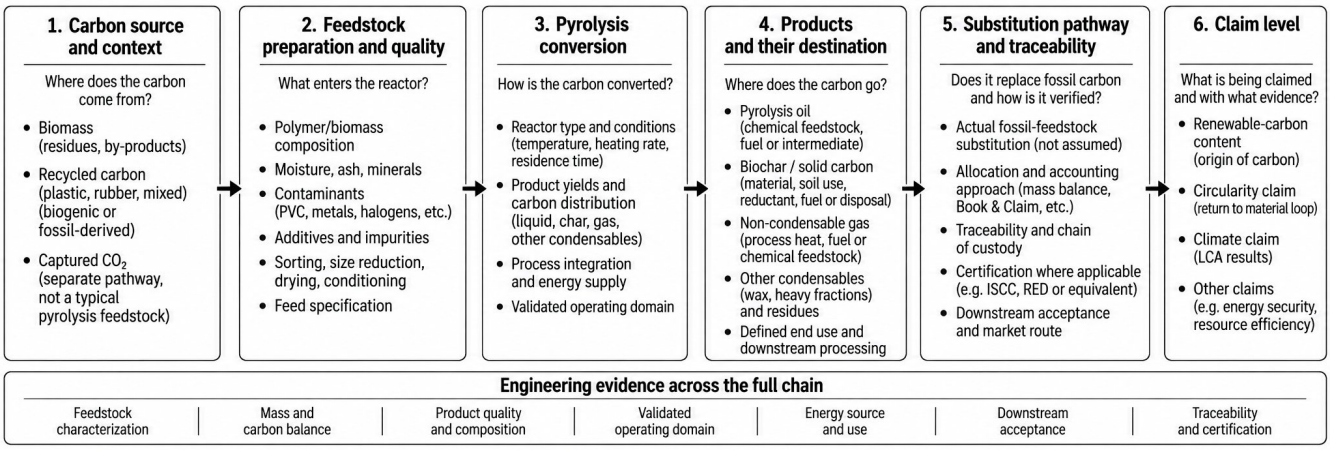


Figure 1. Pyrolysis is one step between carbon source and end-use claim. A credible claim needs evidence across the full chain.

1. Identify the carbon source correctly

The Renewable Carbon Initiative defines renewable carbon as carbon that avoids or substitutes additional fossil carbon from the geosphere. Under this umbrella, the three alternative sources are biomass, captured CO2 and recycling [1]. This definition is useful because it separates the origin of carbon from the conversion technology used to process it.

For pyrolysis, that means a biomass residue and a recycled plastic stream can both contribute to renewable-carbon strategies, but through different routes. Biomass brings carbon from the biosphere. Recycling can keep carbon circulating in the technosphere, but recycled fossil-derived carbon remains fossil-derived in origin. Its contribution to a renewable-carbon strategy comes from reusing existing carbon rather than extracting additional fossil carbon. These sources should not be merged into one feedstock category simply because both can enter a pyrolysis reactor.

Feedstock identity remains important inside each route. Moisture, ash, minerals, polymer family, additives and contamination affect both conversion and product quality. A renewable-carbon claim cannot repair a poorly defined feedstock.

2. Close the mass and carbon balance before discussing circularity

A high conversion percentage does not tell us where the carbon goes. For engineering decisions, mass yield should be separated from carbon yield. A process may produce a large liquid fraction, but the liquid may contain less of the feed carbon than expected because carbon is also distributed to gas, char or losses. The same issue appears when comparing wet or ash-rich biomass residues: part of the delivered mass is water or mineral matter and never becomes organic product.

This is why carbon recovery should be treated as an observable in its own right when the project is intended to replace fossil carbon. For solid products, retained carbon matters. For chemical-recycling liquids, the carbon content and usable fraction entering the next process matter. For gas, the destination matters: internal process fuel, exported energy or chemical feedstock are not the same carbon pathway.

Model validation should follow the same rule. A model that predicts the degradation temperature correctly has not automatically predicted char carbon recovery, liquid composition or gas carbon. These outputs need their own evidence.

3. Product destination determines the carbon function

Pyrolysis products can serve different material, energy or treatment purposes. Their contribution to renewable-carbon objectives depends not only on how much is produced, but also on product quality, downstream acceptance and final use. The table summarizes the main product pathways and the evidence needed to assess them.

Pyrolysis product	Possible carbon role	Engineering evidence needed
Bio-oil / pyrolysis oil	Chemical or cracker feedstock; fuel; upgrading intermediate	Usable carbon fraction, product quality, contaminants, downstream acceptance and actual substitution route.
Biochar / solid carbon	Material, soil-related use, reductant, fuel or disposal	Carbon content/retention, stability or end-use specification, ash/minerals, contaminants and final destination.
Non-condensable gas	Internal heat, exported fuel or chemical intermediate	Composition, energy value, treatment needs and whether carbon is combusted or retained in products.
Wax / heavy condensables	Recycled feedstock or intermediate	Product specification, compatibility with upgrading and material-loop destination.
Mixed/aqueous fractions	Recovery, treatment or energy route	Carbon concentration, treatment burden and realistic recovery pathway.

4. Do not confuse five different carbon claims

Mass yield, carbon yield, renewable-carbon share, circularity and climate performance answer different questions. They should not be collapsed into one percentage.

A product can have a high recycled-carbon share and still carry a poor process energy balance. A process can have a favorable energy balance while sending most carbon to fuel rather than material recycling. A high char yield does not by itself prove durable carbon storage. And a strong mass-balance-and-attribution claim requires a certification and accounting framework; it is not created by a reactor model.

This separation makes communication more credible. It also helps engineering teams collect the right data instead of trying to make one metric serve several purposes.

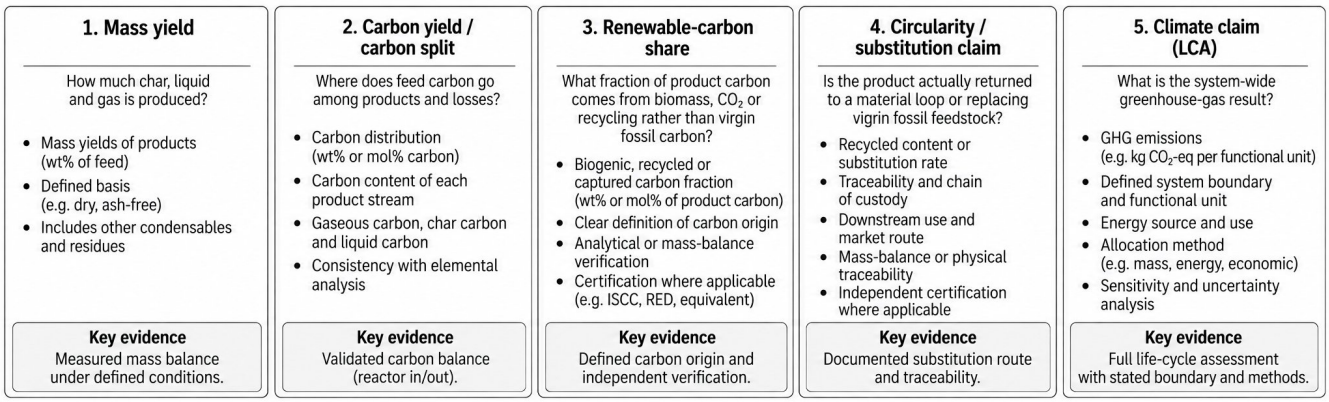


Figure 2. Five distinct carbon-performance and environmental claims. Each addresses a different question and requires corresponding evidence; none can be established from product yield alone.

5. Energy source and process severity belong in the claim boundary

Pyrolysis requires heat. The amount and quality of that heat depend on feed moisture, solids heating, reaction duty, reactor losses and the selected operating condition. Hot gas, char, flue gas or non-condensable products may provide internal heat, but using a carbon-containing gas as fuel changes where that carbon ends up.

This creates a practical trade-off. Burning process gas can reduce imported energy and improve process self-sufficiency, but that carbon is then converted to CO2 rather than returned to a material product. Keeping more carbon in liquids or solids may support a different renewable-carbon objective but require more external energy. The right answer depends on the product route and system boundary.

For this reason, process optimization should not maximize product yield alone. It should state the carbon objective together with heat supply, product quality and downstream use. A universal 'best pyrolysis temperature' is not a defensible renewable-carbon concept.

6. Three examples show why destination changes the claim

Consider a biomass residue converted mainly to biochar and gas. If the gas is burned internally to supply process heat, that can reduce imported energy, while the char retains a fraction of the feed carbon in a solid product. The carbon value of the route then depends on char carbon content, stability and final use, together with the fossil energy actually displaced. A char-yield number alone does not answer those questions.

Now consider mixed plastic waste converted to pyrolysis oil for a steam cracker. The important quantity is not only the liquid mass yield. The oil must meet the downstream unit's quality limits, the usable carbon fraction must enter the chemical-material value chain, and traceability or mass-balance-and-attribution rules must be handled through the relevant certification system. If much of the liquid needs disposal, fuel use or severe upgrading, the circular-carbon result changes [2, 3].

A third example is a process that maximizes non-condensable gas and uses it for internal heat. This may be an excellent energy-integration decision, but it sends more feed carbon toward combustion. That can still support an efficient process, yet it should not be described in the same way as a route designed to retain carbon in new materials. The engineering optimum and the carbon-circularity optimum can therefore be different.

7. Use the lowest model fidelity that resolves the carbon decision

The modelling requirement follows the claim. A simple empirical or global model may be enough to screen bulk conversion. A product-yield model can support phase-split decisions inside a bounded domain. Elemental ledgers become useful when carbon, nitrogen or other elements must be tracked between char,

gas and condensable phases. Detailed chemistry is justified when molecular product quality affects downstream acceptance. Particle and reactor models become necessary when heat transfer, residence time and hydrodynamics change the product split.

More detail is not automatically more credible. Detailed chemistry cannot compensate for a poorly characterized feed, and reactor CFD cannot create evidence for a product composition that was never measured. The strongest model is the least complex one that resolves the decision with adequate validation.

The same principle applies to circularity claims. If the decision is whether pyrolysis oil can enter a chemical-material loop, then conversion timing is secondary to usable liquid yield, contaminant control, downstream qualification and traceability. The model should resolve those quantities or remain a screening tool [6].

8. Measure the carbon pathway, not only reactor performance

At project-development stage, the minimum data package should follow the carbon pathway. For the feed, measure the carbon-bearing fraction and the properties that control conversion. For the reactor, close product mass and, where the claim requires it, carbon across solid, condensable and gas phases. For the product, measure the properties that determine whether the next user will actually accept it.

The downstream step is equally important. A material-loop claim needs evidence that the product enters a material process and substitutes an equivalent virgin fossil input under a defined accounting approach. A climate claim needs an appropriate life-cycle boundary, energy mix and allocation method [4, 5]. These are not jobs for the kinetic model, but the kinetic/process model can supply some of the material and energy quantities needed by those later assessments.

This separation is useful operationally. The modelling team does not need to become the certification or LCA team. It does need to deliver transparent mass, carbon, product-quality and energy information at the resolution those teams require.

9. A six-check gate for pyrolysis in renewable-carbon projects

The six checks below provide a practical screening framework for assessing whether a pyrolysis pathway can support a specific renewable-carbon objective. Each check identifies a question that must be answered and the minimum evidence needed to proceed. A GO decision means that the proposed pathway is sufficiently supported for the stated engineering decision; it does not automatically establish certified circularity, fossil-carbon substitution or climate benefit. Where evidence is incomplete, the appropriate decision is REFINE or HOLD until the limiting issue is resolved.

Check	Question	GO condition
1 - Source	Where does the carbon come from?	Biomass, recycled carbon or captured CO2 route is explicit; feedstock is characterized.
2 - Carbon closure	Where does feed carbon go?	Product carbon split is known at the resolution needed by the project.
3 - Product destination	What happens to each carbon-containing product?	Material, fuel, storage or treatment route is explicit.
4 - Substitution	What virgin fossil carbon is actually avoided or replaced?	Downstream use and substitution logic are technically credible.
5 - Energy / process	What heat and utilities are required?	Energy source, process severity and internal-use trade-offs are inside the boundary.
6 - Evidence / claim	What can be claimed and verified?	Model validation, product data, traceability/certification and LCA are separated correctly.
Decision	GO / REFINE / HOLD	Proceed within the verified scope. REFINE: Address specific evidence or process gaps. HOLD: Do not advance the proposed claim until critical evidence is available.

10. Why this matters now

Pyrolysis and advanced recycling are moving from laboratory work to pilot and commercial projects. That progress makes claim discipline more important, not less. At larger scale, feed variability, reactor reliability, product specification, financing and integration with existing chemical infrastructure become decisive.

A project should therefore be able to answer a simple sequence: what carbon enters, where it leaves, what useful product it becomes, what fossil feed it replaces, how much energy is required, and what evidence supports each statement. If one link is missing, the correct status may be REFINE or HOLD rather than a broader circularity claim.

This does not reduce the value of pyrolysis. It makes its value easier to defend. Pyrolysis can be an important route for renewable and circular carbon when it is connected to the right feedstock, product, energy system and downstream market. The strongest projects will be those that show that connection quantitatively and transparently.

11. References and further reading

[1] Renewable Carbon Initiative (RCI). Definition of Renewable Carbon. https://renewable-carbon-initiative.com/about-us/

[2] Garcia-Gutierrez, P., et al. (2025). Environmental and economic assessment of plastic waste recycling and energy recovery pathways in the EU. Resources, Conservation and Recycling. https://doi.org/10.1016/j.resconrec.2024.108099

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[4] ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework. https://www.iso.org/standard/37456.html

[5] ISO 14044:2006. Environmental management — Life cycle assessment — Requirements and guidelines. https://www.iso.org/standard/38498.html

[6] Saylam, A. (2026). Pyrolysis Modelling for Process Optimization across Feedstocks and Scales: Principles, Development, Quantitative Validation, and Open Python Tools. Zenodo. https://doi.org/10.5281/zenodo.22708031