



PREPARED FOR RENEWABLE HYDROGEN ALLIANCE

MAY 2026

# Hidden Hydrogen

Clean Fuel Opportunities in the Pacific Northwest from Organic and Waste Feedstocks

## Disclaimer

This document was prepared as an account of work conducted as an independent study in partial fulfillment of the requirements for the Master in Public Policy degree in the Department of Public Policy at the University of California, Los Angeles. It was prepared at the direction of the Renewable Hydrogen Alliance. The views expressed herein are those of the authors and not necessarily those of the Department, the UCLA Luskin School of Public Affairs, or UCLA as a whole.

## Acknowledgements

This research and its findings would not be possible without the support of Renewable Hydrogen Alliance and its members and industry technical advisors. The author would like to acknowledge the contributions of technical advisors, industry participants, and partner organizations who provided insight and feedback during the development of this study. Their perspectives helped ground the analysis in real-world conditions and practical considerations.

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# Executive Summary

The Pacific Northwest (PNW) – defined as Montana, Oregon, Washington, and Idaho – is entering a period of heightened constraint on both its electric and gas systems, driven by electrification, load growth, infrastructure limits, and climate commitments. While electrolytic hydrogen has emerged as a prominent clean fuel pathway in regional planning discussions, other clean fuel production pathways – particularly those utilizing organic and waste feedstocks – remain underexplored despite their potential to deliver near-term energy, carbon, and environmental benefits.

This white paper assesses the opportunity to expand clean hydrogen production in the PNW using organic and waste feedstocks paired with commercially ready or near-commercial technologies. It synthesizes findings from four technical working sessions convened with regional experts and stakeholders to evaluate production pathways, feedstock availability, economics and carbon impacts, and broader environmental and community considerations.

Several key findings emerged from this effort:

- **Commercially ready pathways exist now.** Several non-electrolytic clean fuel technologies are mature and deployable today. They can convert regionally abundant waste and organic feedstocks into clean hydrogen without waiting for next-generation breakthroughs.
- **There is an abundance of diverse and unused organic feedstocks.** Under a near-term outlook, the region holds an estimated 288 trillion BTU of unused organic feedstock across seven categories – from agricultural residues and forestry biomass to landfill gas and municipal waste.
- **The climate case is real, but economics are policy-sensitive.** Many pathways deliver meaningful lifecycle greenhouse gas reductions – particularly where they displace unmanaged waste emissions or reduce wildfire fuel loads. However, project economics hinge on carbon value and incentive design, making policy clarity a prerequisite for investment.
- **Non-carbon benefits are often what make or break a project.** Methane mitigation, waste diversion, and local economic development frequently drive public acceptance more than emissions metrics alone.
- **Strategic state action is needed.** Legislative action can accelerate responsible deployment by clarifying credit eligibility for organic fuel pathways, aligning clean fuel incentives with waste and land management goals, and establishing guardrails that prioritize high-benefit, low-risk projects.

# Introduction & Approach

The purpose of this assessment is to understand the breadth and key characteristics of new or maturing hydrogen production pathways that use organic or waste-based hydrocarbon feedstocks. This assessment is not intended to serve as a technology maturity or commercial viability evaluation, nor is it intending to proscribe specific solutions for use. The primary objective is to identify which production pathways are sufficiently mature and compatible with feedstocks that are realistically available in the Pacific Northwest.

Accordingly, this study aims to establish a consistent framework for understanding:

- The types of feedstocks that could be used for hydrogen production in the region;
- The inputs required by different production pathways; and
- The hydrogen outputs and associated co-products or byproducts generated by each pathway.

By narrowing the scope to commercially relevant pathways, this assessment seeks to support near-term decision-making and provide a shared technical baseline for stakeholders.

To ensure analytical clarity and relevance, the scope of this assessment is bounded by several key criteria. This study focuses exclusively on hydrogen production pathways that meet all of the following conditions:

- Hydrogen is a primary end product or a recoverable co-product of the process.
- Feedstocks are realistically available in the Pacific Northwest and are not already committed to higher-priority or planned uses. A more detailed assessment of feedstock availability will be addressed in subsequent work.
- Technologies have a Technology Readiness Level (TRL) of 7 or higher, meaning they are commercially deployed or have been demonstrated in an operational environment.

By applying a TRL threshold, the assessment intentionally excludes purely theoretical or early-stage concepts and focuses on pathways that could plausibly be deployed within the near-term.

This assessment is not intended to serve as a feasibility study. Specifically, it does not evaluate:

- Feedstock logistics, including transportation, aggregation, or preprocessing constraints or costs;
- Site availability or siting feasibility for specific technologies;
- Project-level economics or detailed lifecycle emissions performance.

Instead, the analysis is intended as a level-setting exercise to characterize available technologies and their theoretical hydrogen production potential given high-level assumptions.

# Organic Hydrogen Production Pathways

A range of clean fuel production pathways can convert organic and waste feedstocks into usable fuels, including clean hydrogen. Hydrogen production pathways can be broadly grouped into three categories based on the fundamental mechanism by which hydrogen is produced: thermochemical, biological, and photochemical. These categories are defined by process characteristics rather than end-use applications or color-based classifications. These pathways are distinct from electrolytic hydrogen in that they rely primarily on organic or waste feedstocks rather than electricity as the primary input.

**Thermochemical pathways** rely on heat-driven chemical reactions to convert carbon-containing feedstocks into hydrogen-rich gases. These pathways are the most mature of the three categories, with multiple technologies that are commercially deployed or have been demonstrated at operational scale.

**Biological pathways** use microorganisms - such as bacteria or algae - or enzymes to produce hydrogen through metabolic processes. While these approaches have shown promising results at laboratory and pilot scales, they remain relatively early-stage and face uncertainty related to scale-up, process stability, and hydrogen yields.

**Photochemical pathways** use light, often in combination with catalysts or photoelectrochemical systems, to split molecules and generate hydrogen. These pathways are the least mature, with most activity limited to research and early demonstration efforts.

Given current technology readiness and the objective of identifying pathways that could plausibly be deployed in the near term, this assessment focuses exclusively on thermochemical hydrogen production pathways.

## Thermochemical Process Overview

Although thermochemical pathways include several distinct technologies, they generally follow a common process structure.

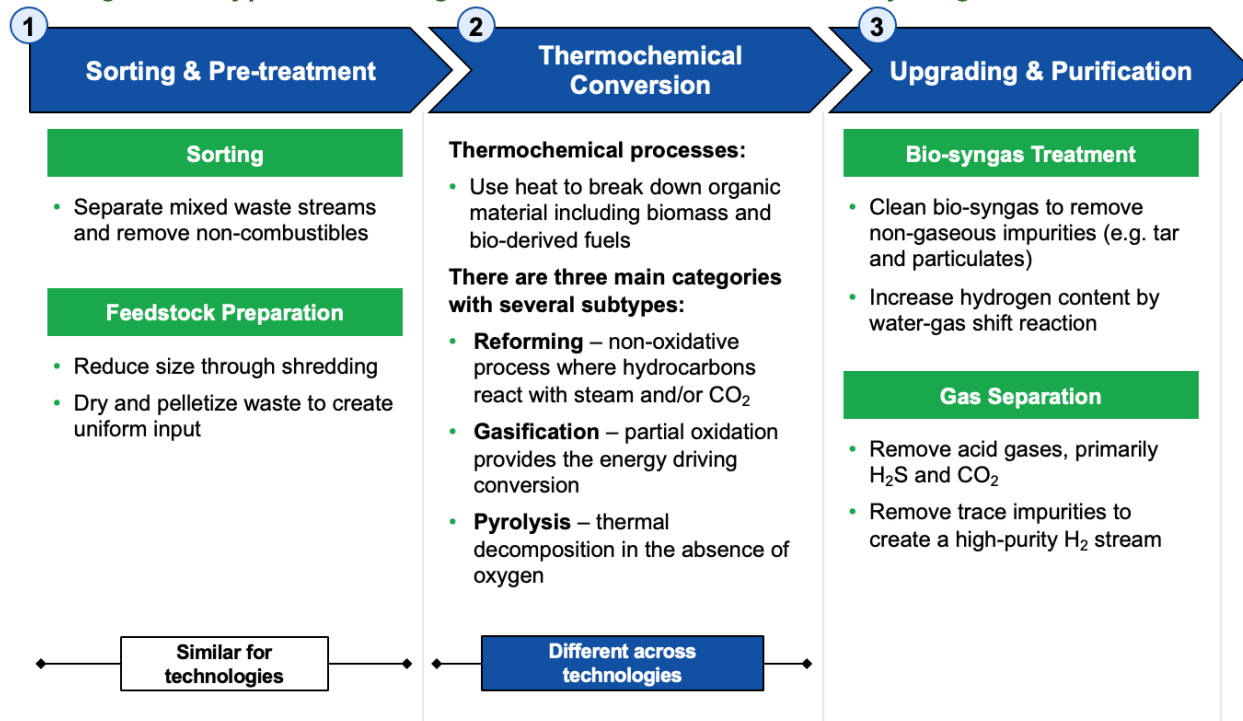
The process begins with a carbon-containing feedstock, which may be fossil-based (such as natural gas) or biogenic (such as biomass or waste materials). For mixed or heterogeneous feedstocks, preprocessing steps- including sorting, drying, and size reduction- are typically required prior to conversion.

The prepared feedstock is then exposed to high temperatures, sometimes in the presence of controlled amounts of oxygen, steam, or catalysts. Under these conditions, complex molecules are broken down into simpler gases - primarily hydrogen, carbon monoxide, and carbon dioxide. The primary thermochemical conversion processes considered in this assessment are reforming, gasification, pyrolysis, and hybrid approaches across these primary categories.

These conversion processes produce a synthetic gas (syngas), which undergoes downstream processing such as water-gas shift reactions and gas separation to increase hydrogen content and yield a high-purity hydrogen stream suitable for end use.

While all thermochemical pathways can produce hydrogen after appropriate treatment and purification, they differ significantly in terms of the types of feedstocks they can utilize and the co-products or byproducts they generate. These differences influence system complexity, operational requirements, and the potential value or handling needs of non-hydrogen outputs.

**Figure 1. Typical Building Blocks of Thermochemical Hydrogen Production**



## Thermochemical Pathway Types

**Table 1. Overview of Thermochemical Pathway Types, Inputs, and Outputs**

|                              | Specific Technology              | Organic Feedstock Inputs   | Non-hydrogen outputs  |
|------------------------------|----------------------------------|--|---|
| <b>Reforming<sup>1</sup></b> | Steam Methane Reforming (SMR)    | Landfill gas, biogas, vaporized biomass-derived liquids (e.g., biogenic naphtha)                         | CO <sub>2</sub> , trace CO/CH <sub>4</sub>  |
|                              | Steam/ CO <sub>2</sub> Reforming | Varies based on specific technology considered; may include gaseous, liquid, or solid organic feedstocks | CO <sub>2</sub> , CO; solid carbon or char may be produced in some configurations |

<sup>1</sup> Terminology for thermochemical hydrogen production pathways is not applied uniformly across the literature. For purposes of this analysis, reforming is defined as non-oxidative thermochemical conversion, while gasification includes processes that rely on intentional oxygen addition and partial oxidation to drive conversion.

|                     | Specific Technology                      | Organic Feedstock Inputs   | Non-hydrogen outputs  |
|---------------------|--|--|---|
| <b>Gasification</b> | Fixed-bed gasification                   | Forestry biomass, agricultural biomass   | CO <sub>2</sub> , CO, trace CH <sub>4</sub> , tars and particulates |
|                     | Fluidized-bed gasification               | Wet municipal waste (food waste, manure, sludge, fats, oils, and greases), dry municipal waste (clean urban wood, paper, yard waste) | CO <sub>2</sub> , CO, trace CH <sub>4</sub> , tars and particulates |
|                     | Entrained-flow gasification              | Wet municipal waste, dry municipal waste   | CO <sub>2</sub> , CO, trace CH <sub>4</sub> , tars and particulates |
|                     | Plasma gasification                      | Wet municipal waste, dry municipal waste, plastic, rubber  | CO, CO <sub>2</sub> , trace CH <sub>4</sub> , slag                  |
|                     | Partial Oxidation (POX)                  | Landfill gas, biogas, vaporized biomass liquids  | CO <sub>2</sub> , trace CO/CH <sub>4</sub>                          |
|                     | Autothermal Reforming (ATR) <sup>2</sup> | Landfill gas, biogas, vaporized biomass liquids  | CO <sub>2</sub> , trace CO/CH <sub>4</sub>                          |
| <b>Pyrolysis</b>    | Methane pyrolysis                        | Landfill gas, biogas   | Solid carbon, CO, trace CH <sub>4</sub>                             |

## Reforming

Reforming is the most established thermochemical pathway for hydrogen production, with steam methane reforming (SMR) being the dominant global production method today. In reforming processes, carbon-containing feedstocks are converted into hydrogen-rich synthesis gas through high-temperature, non-oxidative reactions with steam and/or carbon dioxide. This reaction produces hydrogen and carbon monoxide, which can then be processed through a water-gas shift reaction to increase hydrogen yield.

SMR and related reforming technologies are highly mature, widely deployed, and relatively efficient. Their primary limitations are feedstock availability and carbon management, which is why reforming pathways are frequently evaluated in conjunction with carbon capture technologies rather than as standalone decarbonized solutions.

Reforming processes typically produce a comparatively clean syngas, which reduces the complexity of downstream gas cleanup and hydrogen separation.

<sup>2</sup> Some processes incorporate elements of both reforming and gasification. For consistency, this analysis groups autothermal reforming with gasification based on its reliance on partial oxidation, notwithstanding its conventional naming.

For this assessment, the reforming pathways considered include:

- Steam methane reforming (SMR), and
- Steam/CO<sub>2</sub> Reforming.

## Gasification

Gasification is a technological process that can convert any carbon-based raw material into syngas by contacting the feed with oxygen and steam at elevated temperatures in a gasifier. Partial oxidation provides the primary energy driving conversion.

Extensive gas cleanup can be required to remove particulates, tars, and other contaminants prior to hydrogen separation. Despite these challenges, gasification offers significant feedstock flexibility making it a potentially attractive option in regions with abundant biomass or waste resources.

This assessment includes the following gasification technologies:

- Fixed-bed gasifiers,
- Fluidized-bed gasifiers,
- Entrained-flow gasifiers,
- Plasma gasifiers,
- Partial oxidizers, and
- Autothermal reformers.

## Pyrolysis

Pyrolysis is a thermochemical process that occurs in the absence of oxygen. In this process, the feedstock is heated until it thermally decomposes into a combination of solid char, liquid bio-oils, and gaseous products, including hydrogen.

Pyrolysis is generally a less mature dedicated hydrogen production pathway because hydrogen is often produced as a secondary or co-product rather than as the primary output. However, pyrolysis can be attractive in systems where co-products such as biochar or liquid fuels have independent market value, potentially improving overall project economics.

For this assessment, methane pyrolysis is included as a relevant pathway. Although biomass pyrolysis is commercially deployed, it was excluded because hydrogen cannot be recovered in meaningful quantities and is typically treated as a waste product rather than a usable output.

# Feedstock Availability

This analysis evaluates the availability of organic feedstocks in Idaho, Montana, Oregon, and Washington that could plausibly support hydrogen production under different supply and demand scenarios. Feedstock quantities are drawn from the DOE Billion Ton Report, which estimates biomass resources that are currently unused and available without displacing existing markets or planned uses.<sup>3</sup> Three scenarios from the DOE Billion Ton Report were utilized to estimate low, medium, and high feedstock availability and associated production potential:

- The **near-term scenario** is the basis for the low estimate. This scenario includes resources that are completely unused currently and can be used in the next 5-10 years without competing with demand from other existing uses. This scenario does include landfill gas that is not yet contracted for.
- The **mature market medium scenario** is the basis for the medium estimate. This scenario includes a 1% growth in purpose grown energy crop yield improvements indicating a minor supply growth.
- The **mature market high scenario** is the basis for the high estimate. This scenario includes a more aggressive 3% growth in purpose grown energy crop yield improvements indicating a higher supply growth but also paired with higher demand.

While the total quantity of available biomass in the Pacific Northwest is substantial, its composition and physical characteristics impose constraints on hydrogen conversion options. Feedstocks were categorized into seven groups based on physical and chemical characteristics - including moisture content, lignin/cellulose composition, material state, and contamination level - which influence their suitability for different hydrogen production pathways:

- **Agricultural Biomass:** Dry residues such as straw, corn stover, and husks. These are low-moisture, lignocellulosic materials that are widely available but seasonally constrained.
- **Forestry Biomass:** Woody residues from logging, thinning, and forest management activities. These materials are low-moisture, lignin-rich, and typically require chipping or preprocessing.
- **Wet Municipal Waste:** High-moisture organic waste streams including food scraps, manure, wastewater sludge, and fats, oils, and greases. These materials are well suited for biological or gas-phase conversion pathways.
- **Dry Municipal Waste:** Wood, paper, cardboard, and yard waste from municipal solid waste streams. These materials are relatively dry and behave similarly to biomass in thermochemical systems.
- **Landfill Gas:** Methane-rich gas collected from existing landfills. Because it is already gaseous and energy-dense, it can be efficiently converted to hydrogen using established reforming technologies.

<sup>3</sup> U.S. Department of Energy, *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources*, led by M. H. Langholtz (Oak Ridge, TN: Oak Ridge National Laboratory, 2024), ORNL/SPR 2024/3103, <https://www.energy.gov/documents/beto-2023-billion-ton-report>.

- **Plastics:** Petroleum-based, energy-dense materials found in municipal and industrial waste streams. These can be converted into hydrogen-rich gas through high-temperature thermochemical processes, though mixed materials may require sorting or cleanup.
- **Rubber & Leather:** Durable waste materials such as tires and leather goods that contain complex organic compounds. These can be converted through advanced thermochemical pathways but typically require more intensive processing.

Textile waste was excluded, as no commercially viable pathway was identified that could use this as a feedstock for hydrogen production.

**Table 2. Feedstock Availability (Trillion BTU) in the Pacific Northwest Under Low, Medium, and High Scenarios**

| <b>Feedstock Type</b>  | <b>Low Scenario<br/>(Trillion BTU)</b> | <b>Medium Scenario<br/>(Trillion BTU)</b> | <b>High Scenario<br/>(Trillion BTU)</b> |
|--|--|---|---|
| <b>Agriculture Biomass (dry lignocellulosic)</b>                 | 77.0                                   | 140                                       | 188                                     |
| <b>Forestry Biomass (woody biomass)</b>                          | 41.9                                   | 59.5                                      | 59.5                                    |
| <b>Wet Municipal Waste (food waste, manure, sludge, FOG)</b>     | 50.6                                   | 108                                       | 108                                     |
| <b>Dry Municipal Waste (clean urban wood, paper, yard waste)</b> | 43.5                                   | 65.5                                      | 65.5                                    |
| <b>Landfill gas</b>  | 28.2                                   | 0   | 0                                       |
| <b>Plastics</b>  | 40.4                                   | 56.8                                      | 56.8                                    |
| <b>Rubber &amp; Leather</b>                                      | 6.7                                    | 9.7                                       | 9.7                                     |

## Preconversion Losses

Hydrogen production potential depends not only on the theoretical availability of feedstocks but also on the fraction of material that is actually deployable after collection, storage, transport, and preprocessing. These losses - collectively termed preconversion losses - include dry matter degradation, moisture-driven volatilization, sorting inefficiencies, contamination removal, size reduction, and dewatering or drying. Quantitative data from literature on preconversion losses is generally limited.

For dry and woody biomass, storage and handling losses are well documented:

- Dry matter losses ranged from 8% to 28% depending on moisture content during aerobic storage.<sup>4</sup>
- Forestry residues and wood chips stored outdoors with higher moisture content can lose up to 21% over several months.<sup>5</sup> These losses include microbial degradation and some handling.

For other feedstocks, including wet and dry municipal waste, plastics, and rubber/leather, quantitative preconversion losses are largely absent from peer-reviewed studies. The literature documents operational challenges - sorting, contaminant removal, size reduction, and dewatering - but does not report numeric mass loss percentages.<sup>6</sup>

Landfill gas is a unique case: as an already gaseous feedstock, preconversion losses are minimal and primarily associated with compression and purification. Literature reports capture efficiencies above 90% for well-engineered, capped landfills, supporting a small numeric loss under optimal conditions.<sup>7</sup>

Given the limited available evidence on preconversion losses by specific feedstocks, this analysis applies a uniform preconversion loss range of 10–25 % across all organic feedstocks. This range:

1. Encompasses documented biomass losses from literature, where available;
2. Represents a reasonable estimate for less-documented feedstocks; and
3. Provides a consistent adjustment that captures real-world feedstock attrition without implying unrealistic precision.

<sup>4</sup> Wendt, Lisa M., et al. "Effects of Storage Moisture Content on Corn Stover Biomass Stability, Composition, and Conversion Efficacy." *Frontiers in Bioengineering and Biotechnology* 8 (2020): 716. <https://pmc.ncbi.nlm.nih.gov/articles/PMC7371782/>.

<sup>5</sup> Whittaker, Carly, et al. "Dry Matter Losses and Greenhouse Gas Emissions from Outside Storage of Short Rotation Coppice Willow Chip." *BioEnergy Research* 9, no. 3 (2016): 812–826. <https://link.springer.com/article/10.1007/s12155-015-9686-y>.

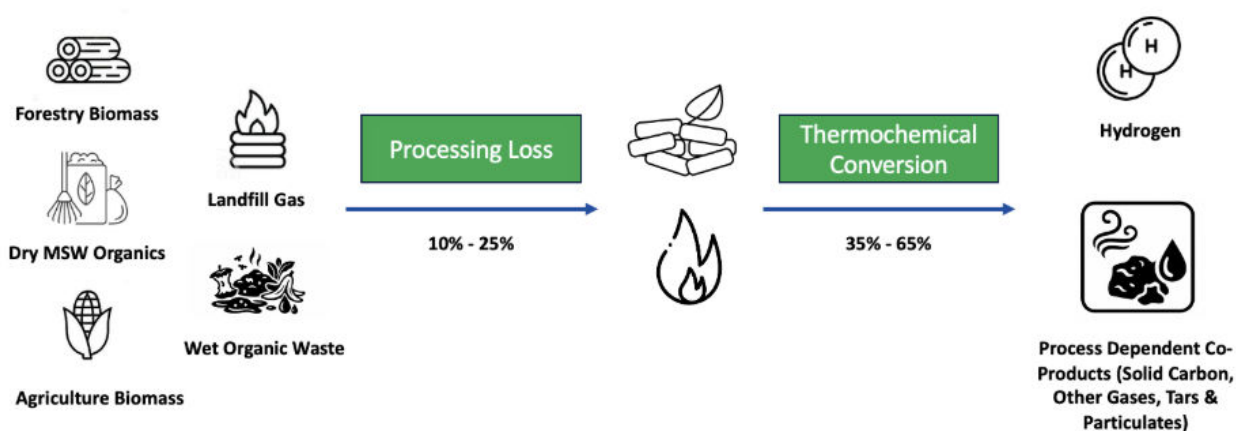
<sup>6</sup> U.S. Department of Energy, Bioenergy Technologies Office, *Advancing the Bioeconomy: From Waste to Conversion-Ready Feedstocks Workshop Summary Report* (Washington, DC: DOE, 2021), <https://www.energy.gov/sites/default/files/2021/02/f82/beto-municipal-solid-waste-report.pdf>.

<sup>7</sup> Heico Scharff, "Efficiency of Landfill Gas Collection for Methane Emission Reduction," *Waste Management & Research* 32, no. 6 (2014): 508–519, <https://www.tandfonline.com/doi/full/10.1080/20430779.2012.730798>; Morton A. Barlaz et al., "Controls on Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance," *Journal of the Air & Waste Management Association* 59, no. 12 (2009): 1399–1404, <https://pubmed.ncbi.nlm.nih.gov/20066905/>.

# Hydrogen Production Potential

Hydrogen production potential was estimated using a technology neutral average thermochemical conversion efficiency, applied uniformly across all organic feedstocks. Rather than assigning each feedstock to a single “preferred” technology, this approach recognizes that many organic materials can be processed through multiple thermochemical pathways, enabling a consistent assessment of hydrogen potential. It reflects the performance of mature thermochemical processes under typical operating conditions while capturing variability due to feedstock composition, moisture content, and system scale. Based on published studies, a conversion efficiency range of 35–65 % (LHV) was applied.<sup>8</sup>

Figure 2. Estimates of Organic Fuel Production Potential Assumed a Uniform Range of Processing Loss and Conversion Efficiency Rates



Applying the conversion efficiency range to post-processing feedstock availability yields an estimated hydrogen production between 675,000 and 1,045,000 metric tons under a near term outlook. There is potential for increased production under more aggressive supply and demand scenarios.

Table 3. Range of Hydrogen Production Potential (metric tons/yr) Under Low, Medium, and High Scenarios

| Scenario | Hydrogen Production Range (metric tons/yr) |
|----------|--|
| Low      | 675,000 – 1,045,000                        |
| Medium   | 1,029,000 – 1,593,000                      |
| High     | 1,142,000 – 1,767,000                      |

<sup>8</sup> Yang, S., Zhang, X., & Xu, Y. (2020). *Thermochemical hydrogen production from biomass: A review*. International Journal of Hydrogen Energy, 45(10), 6250–6267. <https://www.sciencedirect.com/science/article/pii/S0360319919329477>; IEA Bioenergy Task 33. (2025). *Biomass gasification for hydrogen production*. [https://www.ieabioenergy.com/wp-content/uploads/2025/03/IEA-Bioenergy\\_T33\\_Bio-H2\\_Final\\_v2.pdf](https://www.ieabioenergy.com/wp-content/uploads/2025/03/IEA-Bioenergy_T33_Bio-H2_Final_v2.pdf); RHC Technical Review (2024). *Industrial thermochemical hydrogen production from biomass*. <https://hgjz.cip.com.cn/EN/10.16085/j.issn.1000-6613.2024-1899>

When placed in the context of regional hydrogen planning, organic feedstock pathways could play a meaningful role in meeting near-term supply needs. For comparison, it has been estimated that there will be approximately 1 million metric tons per year of hydrogen demand in the Pacific Northwest by 2030,<sup>9</sup> indicating that organic pathways could supply a substantial share of this demand even under business-as-usual feedstock availability scenarios.

## The Value Stack of Organic Pathways

Organic-based hydrogen pathways can generate value through multiple mechanisms beyond the sale of hydrogen itself. Because hydrogen production costs remain relatively high across emerging organic pathways, project viability may depend on the ability to capture multiple present or future value streams rather than relying on hydrogen sales alone. Additive value streams include feedstock handling, carbon co-products, and avoided greenhouse gas emissions. Not all of these value streams are fully monetizable under current market or policy conditions; however, they remain important considerations for long-term financial viability as markets, regulations, and end-use applications evolve. Importantly, the relevance and magnitude of each value stream vary substantially by feedstock type, conversion pathway, system design, and regulatory context.

### Feedstock Use

Certain organic feedstocks- particularly municipal organic wastes and, in some cases, plastics or rubber- can exhibit negative feedstock costs. These materials are typically subject to disposal fees, known as tipping fees, when delivered to landfills or processing facilities. Average landfill tipping fees in the Pacific Northwest range from roughly \$30 per ton in Idaho and Montana, to over \$75 per ton in Washington, with Oregon in between.<sup>10</sup>

If those same materials are instead delivered to a hydrogen facility, that disposal cost can be redirected. Depending on how contracts are structured, the hydrogen system may either receive a tipping fee directly or capture value by offering a lower-cost alternative to disposal. In addition to disposal pricing, landfill capacity constraints increasingly influence feedstock economics, as several regional landfills are approaching capacity limits. Under these conditions, tipping fees reflect not only operating costs but the scarcity value of remaining disposal capacity, suggesting upward pressure on future waste management costs.

Diverting feedstocks locally may also reduce transportation requirements associated with hauling waste to distant landfill sites creating incremental avoided emissions and logistical cost savings beyond the tipping fee itself.

<sup>9</sup> Pacific NorthWest Economic Region (PNWER) and Deloitte, *Pacific Northwest Low-Carbon Hydrogen Analysis* (Bellevue, WA: PNWER, July 2025), [https://www.pnwer.org/uploads/2/3/2/9/23295822/pnwer\\_pacific\\_northwest\\_low-carbon\\_hydrogen\\_analysis.pdf](https://www.pnwer.org/uploads/2/3/2/9/23295822/pnwer_pacific_northwest_low-carbon_hydrogen_analysis.pdf).

<sup>10</sup> Environmental Research & Education Foundation, *Analysis of MSW Landfill Tipping Fees, 2023*, <https://www.erefndn.org/analysis-of-msw-landfill-tipping-fees/>.

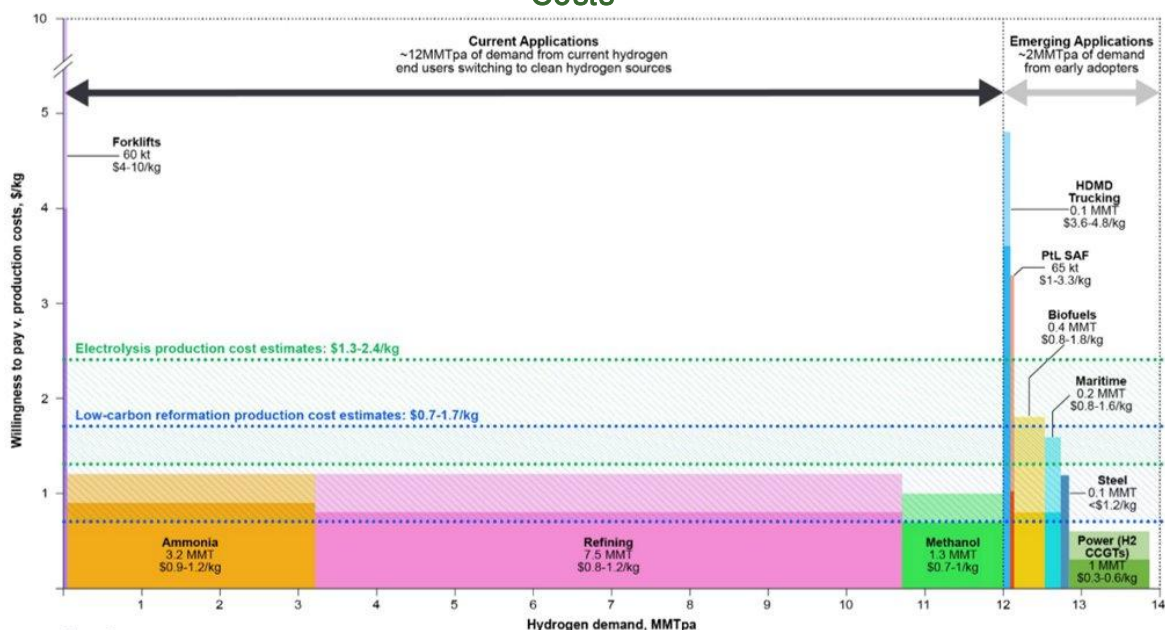
## Hydrogen

Hydrogen is a versatile energy carrier and industrial feedstock, with potential uses across transportation, power, industry, and chemical production, and more. However, hydrogen value is inherently application-specific. In some applications, hydrogen is competing directly with low-cost fossil fuels and is valued primarily on an energy basis. In others, it displaces higher-cost inputs or provides emissions benefits that users are willing to pay for.

Analyses by the U.S. Department of Energy indicate that willingness to pay for clean hydrogen can range from less than \$1 per kilogram in applications where clean hydrogen is replacing fossil-based hydrogen to as much as \$5 per kilogram in higher-value or harder-to-decarbonize uses.<sup>11</sup>

Accordingly, hydrogen cannot be treated as having a single uniform market value; its realized price depends on end-use context.

**Figure 3. Comparison of Clean Hydrogen Willingness to Pay versus Production Costs<sup>12</sup>**



## Carbon Co-Products

Carbon co-products represent one of the areas where organic-based hydrogen pathways diverge most significantly, as different conversion pathways produce fundamentally different forms of carbon. These differences have important implications for whether carbon outputs can be treated as monetizable co-products or must instead be managed as process byproducts or emissions.

<sup>11</sup> U.S. Department of Energy, Pathways to Commercial Liftoff: Clean Hydrogen – 2024 Update (Washington, DC: U.S. Department of Energy, December 2024), [https://climateprogramportal.org/wp-content/uploads/2025/02/Pathways-to-Commercial-Liftoff\\_Clean-Hydrogen\\_December-2024-Update.pdf](https://climateprogramportal.org/wp-content/uploads/2025/02/Pathways-to-Commercial-Liftoff_Clean-Hydrogen_December-2024-Update.pdf).

<sup>12</sup> U.S. Department of Energy, Pathways to Commercial Liftoff: Clean Hydrogen – 2024 Update.

In general, higher-value carbon co-products can materially reduce the effective cost of hydrogen production by offsetting system capital and operating costs; however, these markets are often limited in scale and may not absorb large production volumes without price erosion.

Among the pathways considered in this analysis, methane pyrolysis is the only pathway that meaningfully produces solid carbon as an intentional and potentially monetizable output. In methane pyrolysis systems, solid carbon is generated alongside hydrogen as a primary product rather than as a residual material. However, even within methane pyrolysis, the characteristics of solid carbon outputs vary with operating conditions such as temperature, residence time, and reactor configuration. These variations affect carbon morphology, purity, and surface properties, which in turn determine whether the material meets specifications for downstream markets. As a result, only a subset of solid carbon outputs from methane pyrolysis are suitable for established, higher-value applications, while other outputs may currently have limited uses or require additional processing to become marketable.

Biochar and carbon black have established end uses and peer-reviewed value benchmarks, though reported prices vary widely based on material quality, specifications, and application. Biochar is primarily used as a soil amendment and for long-term carbon storage in soils, while carbon black is used as a reinforcing material in rubber products and as an industrial pigment. Activated carbon also has well-defined applications in water and air purification and industrial adsorption; however, its value is highly application-specific and depends on properties such as surface area and pore structure. However, the potential end uses for solid carbon continue to expand beyond traditional markets. There is emerging interest in applications such as cement and construction materials, soil amendments or fertilizer substitutes (including amorphous carbon applications), and niche advanced-material markets.

In contrast, reforming and gasification pathways primarily convert carbon into gas-phase products, including carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>). Any solid carbon produced in these systems - such as tar, particulates, or residual char - is typically unintentional and operationally undesirable. These solids are not treated as co-products and generally do not contribute to system value. Gas-phase carbon from reforming and gasification may be vented, captured and stored, or captured and utilized depending on system design, regulatory requirements, and economic considerations. However, gas-phase carbon does not behave as a commodity co-product in the same way solid carbon can.

The economic relevance of gas-phase carbon co-products, if any, arises from system integration or separate emissions management frameworks rather than from direct product markets. In certain integrated system concepts, captured CO<sub>2</sub> streams may instead be purified for commercial applications such as food-grade carbon dioxide production,<sup>13</sup> though realization of this value depends on meeting purity requirements and proximity to markets.

The carbon materials summarized in this analysis represent the most commonly cited and commercially relevant solid carbon categories discussed in the peer-reviewed literature and related technical assessments. They are not intended to represent an exhaustive list of all possible carbon

<sup>13</sup> For example, GODOT builds and operates hydrothermal carbonization processors paired with a gasification unit that utilizes agricultural feedstocks to produce hydrogen, food-grade carbon dioxide, and carbon ash. See GODOT, "Our Services," <https://godot.energy/services>. (accessed February 19, 2026).

materials that could be produced, but rather the categories most frequently referenced when evaluating monetizable solid carbon from hydrogen pathways.

**Table 4. Common Market Uses for Potential Carbon Co-Products**

| Co-Product                        | Common Market Uses  |
|-----------------------------------|---|
| Amorphous carbon                  | Soil amendment and long-term carbon storage in soils  |
| Carbon black                      | Reinforcing material in rubber products; industrial pigments  |
| Graphitic carbon                  | Batteries; refractories; lubricants   |
| Fibrous/filamentary carbons       | Thermal composites; specialty materials   |
| Nanostructured carbons            | Conductive additives for batteries; electronics; sensors; specialty coatings                                      |
| Carbon monoxide (CO)              | Chemical feedstock  |
| Carbon dioxide (CO <sub>2</sub> ) | Capture and storage or utilization for enhanced oil recovery, fertilizer production, or food/beverage carbonation |

## Avoided Emissions

Avoided emissions represent reductions in greenhouse gas emissions relative to a defined baseline scenario. In organic hydrogen pathways, these reductions primarily arise from upstream feedstock management and at the end use level. Upstream, the potential for avoided emissions varies by feedstock but can result from diverting organic wastes that would otherwise decompose in landfills or open lagoons, thereby preventing methane release, or from avoiding emissions associated with unmanaged decay or open burning of agricultural and forestry residues. Additional avoided emissions may arise from reduced transportation needs when feedstocks are processed locally rather than hauled to distant disposal facilities, though these benefits are typically secondary relative to methane avoidance. Downstream, avoided emissions can occur when hydrogen or hydrogen-derived fuels displace fossil fuels in specific end uses. Importantly, avoided emissions are not intrinsic to hydrogen production itself; they depend on counterfactual assumptions about waste handling and fuel use in the absence of the project. Further, the extent to which avoided emissions translate into economic value depends on specific regulatory programs and market mechanisms, which vary by jurisdiction.

In cases involving methane-containing feedstocks, hydrogen production pathways may also compete with alternative decarbonization strategies that utilize methane directly, such as renewable natural gas deployment. Consequently, avoided emissions outcomes depend on demonstrating lifecycle emissions advantages relative to continued direct methane use rather than assuming diversion alone generates climate benefit.

In the Pacific Northwest, there is no single, unified carbon market through which avoided greenhouse gas emissions can be monetized. Instead, avoided emissions value is realized through a limited set of program-specific mechanisms, each with distinct eligibility requirements, crediting structures, and ownership rules. As a result, the ability to monetize avoided emissions depends strongly on regulatory context and contractual arrangements rather than on the emissions reductions themselves.

Diverting organic feedstocks into clean fuel pathways does generate avoided emissions that are counted in natural and working lands and waste-sector greenhouse gas inventories. Washington, Oregon, Idaho, and Montana all include landfill methane, agricultural methane, and forest-related emissions in their statewide inventories. However, these upstream avoided emissions rarely translate into direct project revenue under current clean fuel or carbon policies. In limited cases, avoided methane emissions can influence credit generation indirectly - for example, under California's Low Carbon Fuel Standard, avoided methane from manure-based biogas can reduce pathway carbon intensity and increase credit generation<sup>14</sup>- but comparable mechanisms are absent in the Pacific Northwest.

Avoided emissions associated with replacing fossil-based hydrogen production are primarily monetized through the federal Clean Hydrogen Production Tax Credit (§45V). This incentive accrues directly to the hydrogen producer but is contingent on meeting lifecycle emissions thresholds and on project timing, as only facilities that begin construction by January 1, 2028 qualify.<sup>15</sup> Avoided methane emissions from organic waste diversion may also be monetized through voluntary carbon offset programs, though credit ownership does not automatically accrue to the hydrogen producer. Instead, eligibility depends on contractual arrangements governing waste supply and emissions claims, with value potentially accruing to the project developer, waste generator, or another party.

Displacement of fossil fuels in end uses can generate clean fuel credits under state programs such as the Washington Clean Fuel Standard<sup>16</sup> and the Oregon Clean Fuels Program,<sup>17</sup> but these programs are narrowly scoped. Credits are generally limited to transportation end uses, hydrogen production pathways must be explicitly approved, and credit value typically accrues downstream to the fuel supplier or end user rather than to the hydrogen producer.

While avoided emissions can deliver meaningful system-level climate benefits, they rarely translate into commensurate project-level revenue, limiting their contribution to near-term project economics absent targeted policy solutions.

<sup>14</sup> California Air Resources Board, "Low Carbon Fuel Standard," accessed March 5, 2026, <https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard>.

<sup>15</sup> U.S. Internal Revenue Service, "Clean Hydrogen Production Credit," accessed February 19, 2026, <https://www.irs.gov/credits-deductions/clean-hydrogen-production-credit>.

<sup>16</sup> State of Washington, Department of Ecology, "Clean Fuel Standard," accessed February 19, 2026, <https://ecology.wa.gov/air-climate/reducing-greenhouse-gas-emissions/clean-fuel-standard>.

<sup>17</sup> Oregon Department of Environmental Quality, "Oregon Clean Fuels Program," accessed February 19, 2026, <https://www.oregon.gov/deq/ghgp/cfp/pages/default.aspx>.

**Table 5. Existing Monetization Pathways for Avoided Emissions**

| <b>Avoided Emissions Source</b>              | <b>Monetization Pathway</b>  | <b>Who Receives the Value</b>  | <b>How It Is Quantified</b>  | <b>Limitations</b>   |
|--|--|--|--|--|
| Avoided methane from organic waste diversion | Voluntary carbon offset programs (Verra, American Carbon Registry, Climate Action Reserve, etc.) | Entity with contractual rights to claim emissions (ex. developer, end user, landfill operator) | tCO <sub>2</sub> e avoided per ton of diverted feedstock                     | Credit issuance depends on third-party verification and clear ownership of the emissions claim |
| Replacing fossil-based hydrogen              | Federal Clean Hydrogen Production Tax Credit (§45V)  | Hydrogen producer  | tCO <sub>2</sub> e avoided per kg H <sub>2</sub> vs fossil hydrogen baseline | Projects must begin construction by Jan 1, 2028 to be eligible                                 |
| Displacing fossil fuels in end use           | Washington Clean Fuel Standard   |  |  |  |

## Workforce and Economic Development

In addition to delivering climate and environmental benefits, organic fuel facilities can generate employment and economic activity across multiple stages of the supply chain. These pathways provide an opportunity to support regional workforce development alongside climate and waste management goals. Rather than concentrating employment solely in facility operations, bioenergy systems distribute economic activity across feedstock production, transportation, construction, and long-term operations and maintenance.

Employment benefits are particularly pronounced upstream in the supply chain. Approximately 46 percent of direct jobs are generated through feedstock production, collection, and preprocessing activities, while an additional 35 percent are associated with construction, engineering, and procurement.<sup>18</sup> These patterns reflect the labor-intensive nature of developing organic fuel infrastructure, particularly during project construction and early deployment phases, when economic activity is most concentrated in local communities.

Long-term operations provide additional employment stability. Facility roles typically include plant operations, mechanical and electrical maintenance, and logistics coordination, creating skilled technical jobs that can complement existing regional industrial workforces.

Beyond direct employment, organic fuel systems can also support broader circular economy objectives by creating economic value from materials that would otherwise require disposal. Recycling and resource recovery activities associated with organic feedstocks can support substantially more employment than traditional disposal pathways, with some analyses suggesting

<sup>18</sup> BioEra, *U.S. Economic Impact of Advanced Biofuels Production* (Copenhagen: Climate Technology Centre & Network, February 2009), <https://www.ctc-n.org/sites/www.ctc-n.org/files/resources/economicimpactadvancedbiofuels.pdf>.

that recycling and recovery activities can support roughly ten times more employment than landfilling alternatives.<sup>19</sup>

Realizing these benefits, however, depends heavily on project design and regional workforce infrastructure. Workforce development programs, technical training pipelines, and partnerships with community colleges, labor organizations, and local employers can help ensure that local communities are able to participate in the economic opportunities created by organic fuel development.

## Community Considerations

As with any energy infrastructure project, the development of organic fuel facilities raises environmental and community considerations that extend beyond techno-economic performance. While emissions benefits are often emphasized in system-level assessments, site-specific environmental interactions and community experience frequently plays a decisive role in environmental review and public discourse.

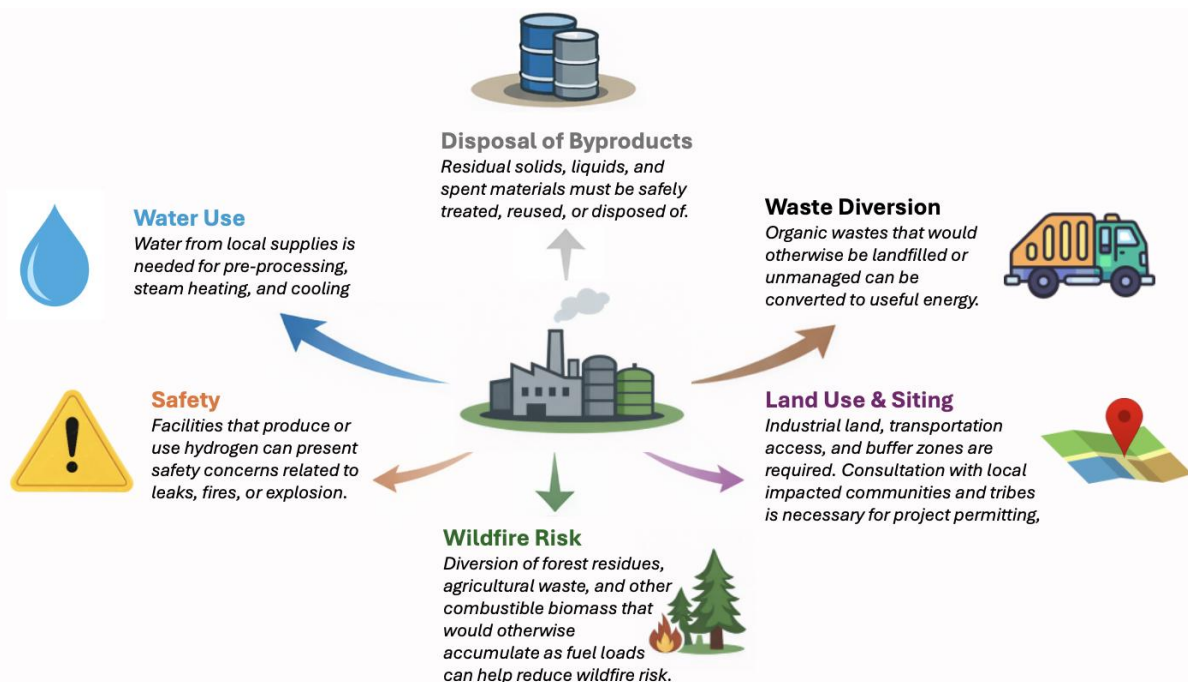
At a system level, organic fuel pathways are often discussed in terms of their potential to reduce greenhouse gas emissions relative to baseline waste management and fuel use. Diverting organic wastes from landfilling or unmanaged decomposition can avoid methane emissions, while production of low-carbon fuels may displace fossil fuel use in certain applications. In some contexts, sourcing forest residues or agricultural biomass for fuel production is also associated with reduction of wildfire risk by removing material that would otherwise contribute to fuel loads. However, the magnitude and relevance of these benefits vary widely depending on feedstock characteristics, baseline conditions, and scale, and are therefore highly context dependent.

At the facility level, organic fuel production introduces localized environmental considerations that shape siting and permitting decisions. Processing organic feedstocks can require water for pre-processing, steam generation, and cooling, raising questions about water availability and wastewater treatment capacity in some locations. Facilities may also generate residual solids, liquids, and other byproducts that must be safely treated, reused, or disposed of. These operational requirements influence where facilities can be located, as projects typically require industrial land with transportation access and sufficient buffer zones to maintain compatibility with surrounding land uses.

Safety concerns are often the threshold issue in public engagement, particularly for hydrogen-producing facilities. Community members and local fire departments often identify safety as their primary concern during early project discussions. Familiarity with hydrogen infrastructure varies widely across jurisdictions: larger cities often have more institutional experience with hydrogen safety and fire codes, while smaller jurisdictions may have little or none. As a result, early engagement with fire departments, emergency responders, and local officials is critical both for permitting and for building the relationships needed to operate facilities safely.

<sup>19</sup> Institute for Local Self-Reliance, "Recycling Means Business," February 1, 2002, <https://ilsr.org/articles/recycling-means-business/>.

**Figure 4. Key Community Considerations that Influence Organic Fuel Facility Development**



These safety concerns are often compounded by the fact that hydrogen infrastructure is not yet fully integrated into many municipal planning and zoning frameworks. Because local codes frequently lack established standards for evaluating hydrogen facilities, planning departments, commissions, and elected officials may face uncertainty when reviewing project proposals. In this context, proactive and jurisdiction-specific community engagement becomes an important tool for addressing concerns before they escalate into organized opposition. Health Risk Assessments can provide a credible and transparent way to evaluate localized impacts - such as odors, NO<sub>x</sub>, and other pollutants - before project narratives become defined by uncertainty or misinformation.

Operational considerations beyond the facility boundary can also influence community response. In particular, supply chain logistics and transportation patterns are often an overlooked source of community concern. Even well-designed facilities may generate opposition if feedstock deliveries or product distribution routes pass through residential neighborhoods or other sensitive corridors. Rail and truck traffic associated with moving organic feedstocks and fuel products can sometimes be more disruptive than the facility itself, and these impacts should be evaluated and communicated transparently during project planning.

Certain feedstocks introduce additional considerations. The use of woody biomass, for example, can raise questions among communities and environmental organizations about ecosystem impacts and forest management practices. While some stakeholders view biomass removal as a tool for wildfire risk reduction, others question the ecological implications of biomass harvesting. Projects relying on woody biomass should therefore be prepared to demonstrate clear and defensible sourcing standards.

Regional governance and community relationships are also particularly important in the PNW. The region is home to numerous federally recognized tribes whose sovereignty, cultural interests, and environmental priorities must be respected throughout project development. Specifically in Washington, meaningful engagement with tribal governments is both a legal and practical prerequisite for project permitting.<sup>20</sup> Washington's Department of Commerce has also published an Environmental Justice Toolkit for hydrogen project developers that provides practical guidance for how to navigate tribal engagement, community outreach, and equity considerations.<sup>21</sup>

Community impacts are not secondary to project development, but rather, are central determinants of project viability. Successful organic fuel projects in the PNW will be those that proactively and transparently engage with local stakeholders, integrate safety and environmental considerations into early project design, and demonstrate clear community and regional benefits alongside climate performance.

## Conclusion

Clean fuel production from organic and waste feedstocks represents a meaningful near-term opportunity for the Pacific Northwest to address a set of overlapping challenges related to energy reliability, emissions reduction, and waste and biomass management. Across the region, organic feedstocks are already being generated at scale through municipal, agricultural, and forestry systems, and converting a portion of these materials into clean fuels offers a pathway to extract additional value while reducing environmental liabilities associated with landfilling, unmanaged decomposition, open burning, or fuel accumulation. At the same time, the scale of organic fuel production potential is shaped by inherent constraints related to feedstock availability, siting, and system integration. These pathways are therefore best understood as part of a diversified clean energy portfolio.

However, potential project development outcomes are influenced by more than just their emissions reduction potential. Site-specific environmental interactions - including water use, land use, residuals management, and local air quality - frequently play a decisive role in permitting and siting decisions. Community considerations such as health and safety, traffic and noise, and the distribution of benefits and burdens similarly shape public response and project viability. Together, these factors help explain why projects with comparable technical characteristics can face very different trajectories depending on local context and design choices.

Taken together, these findings point to the importance of a coordinated and context-sensitive policy approach. State policies that recognize the distinct characteristics of organic fuel pathways, align incentives with high-integrity environmental outcomes, and account for local environmental and community conditions can help distinguish projects that deliver durable climate and community

<sup>20</sup> Wash. Rev. Code § 43.158.150, "Clean Energy Coordinated Permitting Process—Tribal Consultation and Overburdened Community Engagement," <https://app.leg.wa.gov/RCW/default.aspx?cite=43.158.150>.

<sup>21</sup> Washington State Department of Commerce, "Environmental Justice Toolkit for Hydrogen Project Developers," September 5, 2025, <https://www.commerce.wa.gov/environmental-justice-toolkit-for-hydrogen-project-developers/>.

benefits from those that do not. Coordination across energy, waste, environmental, and land-use policy domains will be particularly important to avoid unintended tradeoffs and ensure that organic fuel development complements broader regional decarbonization goals.

Looking ahead to the 2027 legislative session, the Pacific Northwest has an opportunity to support the deployment of organic fuel pathways by clarifying credit eligibility, aligning clean fuel incentives with waste and land management goals, and establishing guardrails that prioritize high-benefit, low-risk projects. The feedstocks and technologies already exist across the region; what is needed now is a clearer policy framework to ensure they are deployed in ways that deliver durable climate, environmental, and community benefits.