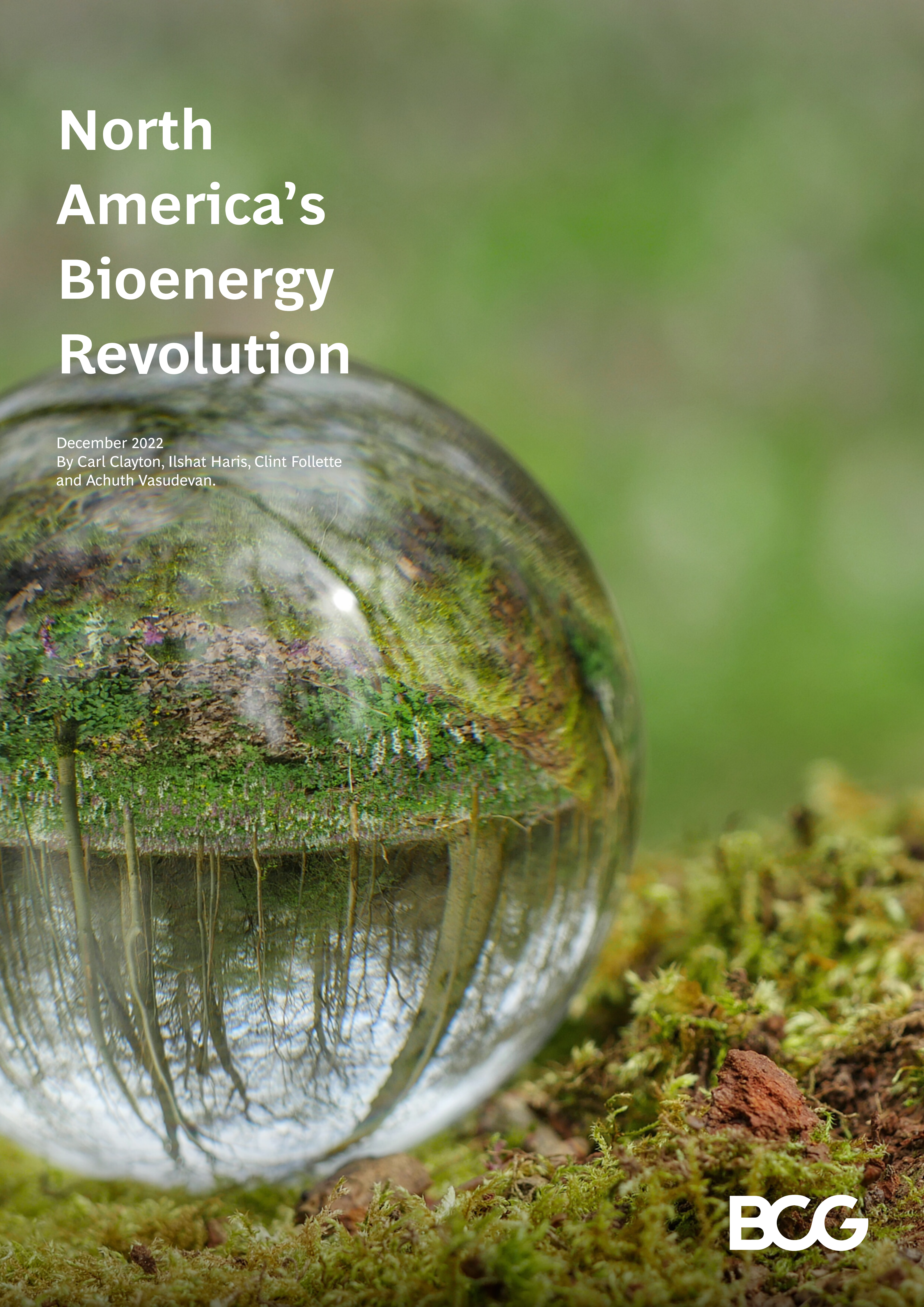

North America's Bioenergy Revolution

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By Carl Clayton, Ilshat Haris, Clint Follette and Achuth Vasudevan.

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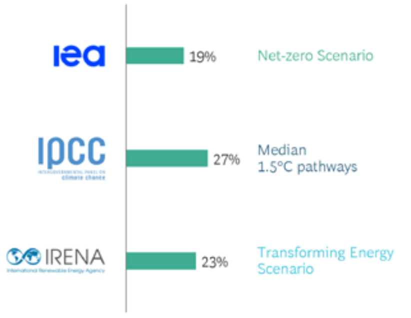
Since the US Department of Energy's landmark 2016 report, Advancing Domestic Resources for a Thriving Bioeconomy, North America has been on the cusp of reinventing how it uses natural resources. Through agriculture, forestry waste and algal materials, the United States alone has the potential to produce at least one billion dry tonnes of biomass annually without adverse environmental impact (Exhibit 1). This biomass can be used throughout the economy, changing how the country produces and uses fuel, energy, and critical everyday products. The Bioenergy Revolution is here: technology, policy, and market forces are establishing the backbone of a bio-based transition towards a more sustainable and carbon negative future.

Exhibit 1: Bioenergy — Why Now | Tailwinds supporting bioenergy

① Key climate change mitigation measure

Modern and sustainable forms of bioenergy play an important role in the roadmap to reach net-zero emissions by 2050 and limit rise in global temperatures to 1.5°C

Modern bioenergy share of 2050 global energy supply



② Positive regulatory policy

Regulatory changes could further accelerate bioenergy adoption by increasing feedstock supply and financial incentives

Federal level

- Renewable Fuel Standard program incentivizes low carbon fuel production via bioenergy pathways (e.g., cellulosic biofuel, advanced biofuels)
- CFPC (~ a forthcoming successor of BTC) incentivizes biomass-based transportation fuels by providing up to $1/gal ($1.75 for SAF) in tax credits

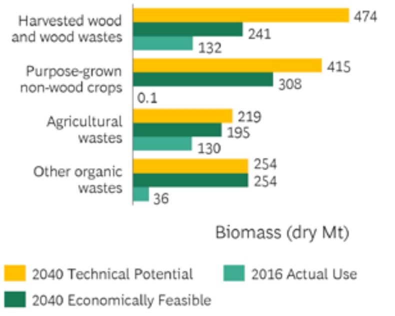
State level

- In CA, government regulations are poised to ban agricultural waste burning by 2025
- LCFS program (CA) which includes biofuel production incentivizes lower CI fuel. Likely similar rollouts in OR, WA, CO, etc.

② Feedstock availability

Roughly a billion dry metric tons of biomass could be economically feasible for bioenergy use in 2040

Current and Future Annual U.S. Biomass Feedstock Production Estimates



Source: IEA; IPCC; IRENA; Surveying the BECCS landscape report; BCG analysis

Achieving this transformation, however, will need a sustainability-first approach along the entire value chain, rethinking feedstock cultivation, harvesting and land use. It requires a consistent, maintained approach to feedstock sourcing, focusing primarily on local usage, protecting biodiversity, and minimizing competition for land and food supply. This paper introduces biomass as an important low-carbon energy source in North America, describes some of the key technology pathways and regulatory / market forces, and closes with recommendations for businesses looking to enter and succeed in this emerging market.

What is biomass?

Biomass in this context refers to plant- or animal-based renewable organic material, which can be used mainly as fuel to generate electricity or heat. "First generation" biomass development focused on starch- and sugar-based crops harvested primarily for biofuels. This development and associated production management policies are designed to protect against land use changes that would impact food, water quality, climate restoration and protection, and general ecosystem concerns. These conditions highlight the need to limit expansion of 1st generation biomass feedstocks, while improving the sustainability of current land use.

"Second generation" biomass is lignocellulosic, encompassing non-edible plants and waste materials. It is the most abundant, sustainable feedstock available around the world, broadly classified as:

1. **Agricultural residues: e.g.,** corn stover, straw, bagasse, animal wastes
2. **Woody biomass: e.g.,** forestry and sawmill residues, hardwood, softwood, bark
3. **Herbaceous energy crops: e.g.,** switchgrass, miscanthus, willow, hemp
4. **Municipal and industrial wastes: e.g.,** municipal solid waste (MSW), pulp residue, paper and cardboard

Lignocellulosic biomass is composed of carbohydrate polymers in hemicellulose and cellulosic sugars, and an aromatic polymer in lignin, which contain the core building blocks to produce energy and a wide variety of liquid fuels and chemicals. Each material type contains distinctive physical and chemical characteristics. These present both opportunities and challenges, requiring consideration of how best to pair feedstock with an optimal pre-treatment and technology pathway (Exhibit 2).

Exhibit 2: Three distinct choices | Optimal pathways depend primarily on choice of feedstock, pre-treatment & process technology and target end-product

① Feedstock

Forest biomass	Forest management Sawmill residue Shrub and chaparral
Agriculture residue	Waste crop residues Harvesting by-products
Municipal solid waste	Dry waste Green waste Food waste
Gaseous waste	Dairy manure Wastewater Landfill gas
Algae	Macroalgae Microalgae
Energy crops	Miscanthus Switchgrass Eucalyptus
Food crops	Corn Sugarcane Wheat
Oils & Fats	Soyabean oil Used cooking oil Animal fats

② Technology

- Pre-treatment processes (Physical, chemical, biological)
- Gasification
- Combustion
- Pyrolysis
- Hydrothermal liquefaction
- Hydroprocessing
- Fermentation
- Anerobic digestion

② Product

- Hydrogen
- Liquid biofuels (incl. bioethanol, renewable diesel, vegetable oil and liquid hydrocarbons)
- Grid electricity
- Heat
- Biogas/ Renewable natural gas (RNG)
- Biochar
- Chemicals

▌ Pre-Treatment processes ▌ Thermochemical processes ▌ Biochemical processes

Source: BCG analysis

Along with the technology pathway and corresponding product selection, certain mixes of geographies and feedstock will become common, stimulating local learning and innovation. For example, the US Midwest's thriving agricultural sector favors certain technology pathways, while in the South forestry and sawmill residues are much more prominent.

A critical factor in the long-term opportunity for biomass is ensuring that sustainability is front and center of feedstock sourcing strategies. This includes avoiding primary woody biomass for lower-value uses and pushing to achieve dual use1 of managed forests and agricultural residues.

Siting projects close to feedstock sources maximizes beneficial climate impact, and supports a controlled, forward-looking approach to Scope 3 emissions. This will become increasingly important in optimizing products' carbon intensity.

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1. Dual use means actively managing the use of both primary biomass and its waste products. Typically, primary biomass goes to the construction industries and other high-value users, whereas the waste and thinning can be used for feedstock. In some scenarios, the waste is either left to rot (increasing the risk of forest fires) or is controllably burnt on with zero value. Dual use would ensure the productive use of such waste and thinning

Technology pathways driving a more sustainable future

Historically, the primary use case for bioenergy has been the production of power and process heat through combustion, directly in the power generation sector, or indirectly as a co-benefit and use case in key bio-based industries like pulp and paper. These legacy use cases enjoy an additional boost today through the application of carbon capture and storage (CCS). When applied to processes with sustainably sourced feedstock, it can create additional process value through carbon removal credits over and above the US 45Q CCS Tax Credit scheme.

A novel opportunity arises for the pulp and paper sector to decarbonize products, applying negative carbon intensity via captured process flue gas emissions, while creating additional value by trading voluntary carbon market offsets. A similar theory also applies to other combustion use cases where biomass waste is used for heat and power, such as the bioethanol market. The critical factor is ensuring robust standards at each end of the value chain: sustainably sourced local feedstock, and permanent geologically stored CO_2, satisfying the three main carbon market conditions:

1. **Measurement, reporting and verification:** accurate, transparent, and replicable measurement of CO_2 removed, calculated net of leakages and emissions generated from biomass sourcing and handling activity
2. **Permanence:** ability to remove CO_2 emissions for the stated life span (>1000 years) with mitigation actions in place to avoid reversal
3. **Additionality:** ensuring that the emissions removed via CCS would not have occurred in the absence of a market for removal credits

We are witnessing major developments where the highest value products, with the largest potential value pools, are exploring potentially profitable routes to market. Promising areas include the production of liquid fuels like sustainable aviation fuel, biochemicals, and the production of hydrogen through two major thermochemical technology pathways, gasification and pyrolysis.

The gasification process converts biomass within an oxygen or air deficient environmental to produce a synthesis gas (syngas) composed of carbon monoxide, hydrogen, and other light hydrocarbons. Then standard process conversion techniques can be applied to produce hydrogen and capture the CO_2. The main alternative is to produce liquid fuel products and other chemicals via synthesis process applications such as Fischer-Tropsch.

Pyrolysis is the thermal degradation of any biogenic material, which thermally decomposes the material to bio-liquids, biochar, and gaseous products. The pyrolysis process can be tuned to produce varying levels of these three primary conversion streams based on temperature and vapor residence time. Liquid synfuels and biochar tend to be the main output products, with the gases used internally to provide self-sufficient process heat.

Both of these routes create options for developers to design around local feedstock availability and energy demand, or broader global demand for net-zero fuels and chemicals.

Market forces increasing the attractiveness and deployment of bioenergy solutions

The Inflation Reduction act has accelerated policy increasing the attractiveness of bioenergy solutions. It mandates a clear focus on low carbon intensity products. Through biomass and carbon capture applications, negative carbon intensity products, energy and fuels can be transformational:

1. Section 45 Tax Credits:

a. Section 45Q: Carbon oxide sequestration tax credit: $85/t for permanent sequestration (full bonus credit of the base if prevailing wage and apprentices' requirements met), $185/t for DAC, $65/t for Utilization & Enhanced Oil or Gas Recovery

b. Section 45V: Clean Hydrogen Production Tax Credit: tiered to award up to $3kg/H2 (full bonus credit of the base if prevailing wage and apprentices' requirements met) if the hydrogen has a lifecycle carbon intensity of less than 0.45kg/CO2e

2. Clean Fuel Tax Credits:

Section 40a: Biodiesel, Renewable Diesel & Alternative Fuels: extends a $1/gallon biodiesel & renewable diesel tax credit extension including an additional alternative fuels & 2nd generation biofuel income tax credit

b. Section 40b: Sustainable Aviation Fuel Tax Credit: for ASTM International Standard fuels at $1.25/gallon, topped up to $1.75/gallon if the fuel reduces lifecycle carbon intensity by more than 50% vs fossil alternatives

c. Section 45Z: Clean-Fuel Production Act: available for low-emissions transmission fuel with $1/gallon for biofuels & $1.75-gallon for sustainable aviation fuels (full bonus credit of the base if prevailing wage and apprentices' requirements met) & fuel emissions less than 75kgCO_2/MMBtu

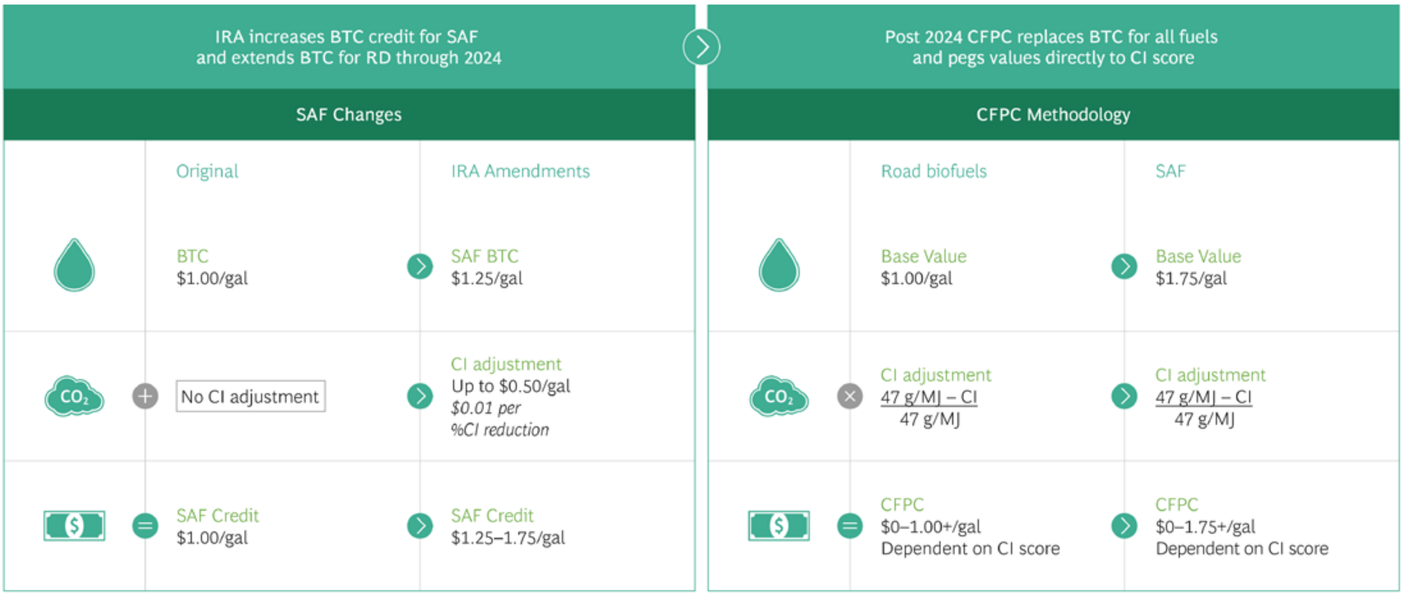
Note that sections 45Q, 45V, and 45Z cannot be 'stacked' with each other, which means projects need optimize decisions on which tax pathway to pursue. For example, combustion may benefit most from 45Q, hydrogen production from 45V, and liquid fuels from 45Z.

The voluntary carbon market supplies an additional tailwind to any biogenic CCS application. This market is accelerating with the growing urgency to meet the Paris Agreement's Nationally Determined Contributions, and more corporations committing to Science Based Targets, and pushing to acquire high quality carbon removal credits.

Case study: lignocellulosic biomass's role in meeting sustainable aviation fuel (SAF) demand

The IRA's incentives have created a favorable economic environment for SAF developers to accelerate their projects forward. The emerging focus on carbon intensity creates an attractive market opportunity for SAF produced from Lignocellulosic biomass (Exhibit 3), with added value creation from CCS.

Exhibit 3: IRA increases incentive for SAF and replaces BTC with CI based Clean Fuel Production Credit after 2024



IRA increases BTC credit for SAF and extends BTC for RD through 2024

SAF Changes

	Original	IRA Amendments
	BTC $1.00/gal	SAF BTC $1.25/gal
+	No CI adjustment	CI adjustment Up to $0.50/gal *$0.01 per %CI reduction*
=	SAF Credit $1.00/gal	SAF Credit $1.25–1.75/gal

Post 2024 CFPC replaces BTC for all fuels and pegs values directly to CI score

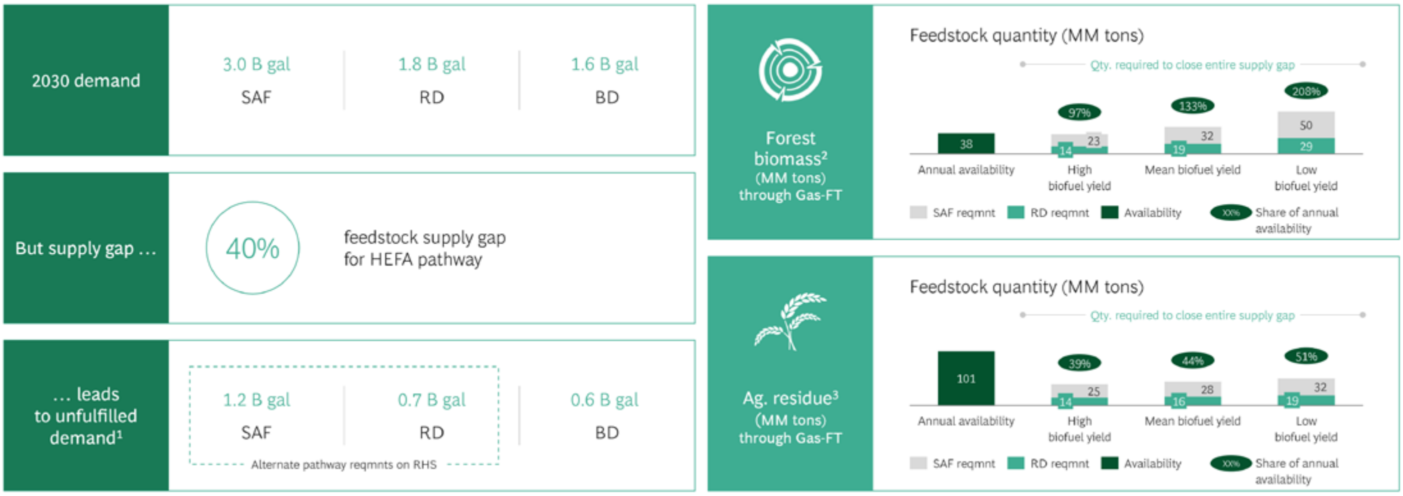
CFPC Methodology

	Road biofuels	SAF
	Base Value $1.00/gal	Base Value $1.75/gal
×	CI adjustment $\frac{47\ g/MJ - CI}{47\ g/MJ}$	CI adjustment $\frac{47\ g/MJ - CI}{47\ g/MJ}$
=	CFPC $0–1.00+/gal Dependent on CI score	CFPC $0–1.75+/gal Dependent on CI score

Source: Inflation Reduction Act (IRA); BCG Analysis

The hydrotreated esters and fatty acids (HEFA) route to SAF has been most prominent todate and will continue to grow with increasing demand. However, without accelerated delivery of other bio-based SAF routes like alcohol-to-jet (ATJ), or Gasification Fischer-Tropsch, demand is likely to outstrip supply. Fortunately, the biomass feedstock is already available and can be sustainably sourced to meet market needs (Exhibit 4).

Exhibit 4: Combination of Forest biomass and Ag. residue feedstocks would be required to help bridge RD and SAF gap through Gas-FT



HEFA pathway feedstock constraints likely to result in 1.9 B gal shortfall of SAF and RD in 2030 …

2030 demand	3.0 B gal SAF	1.8 B gal RD	1.6 B gal BD
But supply gap …	40% feedstock supply gap for HEFA pathway		
… leads to unfulfilled demand[1]	1.2 B gal SAF	0.7 B gal RD	0.6 B gal BD

Alternate pathway reqmnts on RHS

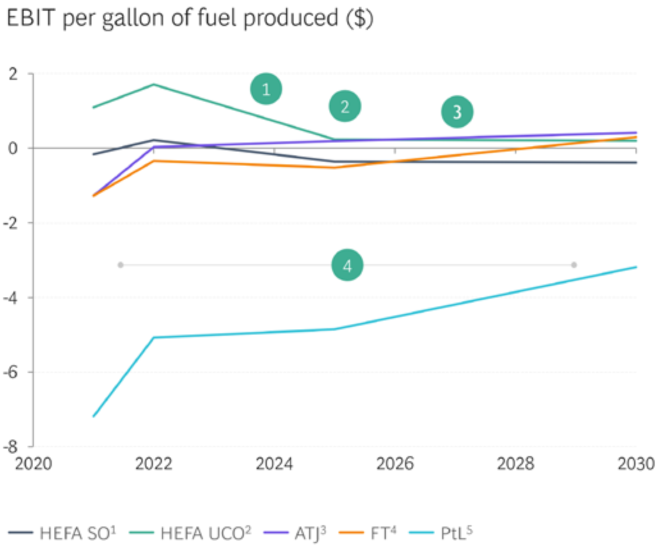
… but sufficient feedstock available to bridge gap through Gas-FT

1. Assumes supply gap impacts SAF, RD, BD bio-fuel production equally 2. Yield of 30–64 GGE/ton 3. Yield of 47–54 GGE/ton Note: Assumes SAF demand satisfied first through SAF optimized plants yielding 60:20:20 split between SAF, RD and light ends. Remaining RD shortfall fulfilled through RD optimized plants yielding 85:15 split between RD and light ends Source: NREL; BCG analysis

Source: NREL; BCG analysis

While the picture appears promising, the capacity gap requires more than feedstock assurance to satisfy market demand. Today's project pipeline shows a 1.8B gallon/yr supply gap. Regulatory support and mature individual components are facilitating the adoption of Gasification Fischer-Tropsch. A combination of continued investor interest and capital flow alongside continued regulatory expansion (e.g., California's Low Carbon Fuel Standard) can help technology keep up with the growing market demand. The current technology costs and capital required mean that regulatory support is critical in the early stages of deployment. But through deployment we expect to see cost parity in the medium term (Exhibit 5).

Exhibit 5: EBIT margin | Unit economics of ATJ and FT to catchup in mid-long term



Key takeaways

1. Upward cost and availability pressure on feedstock will make HEFA less desirable over time
2. ATJ surpasses HEFA to become the next economic pathway for SAF production
3. Improved CapEx and low feedstock costs will help FT to become an economic choice in long term
4. PtL gets boost from IRA shift to BTC value dependent on CI score but remains uncompetitive without RIN

   PtL economics improve significantly over time due to lower CapEx, increased production efficiency and lower cost of access to renewable electricity making

1. Feedstock based on Soybean Oil 2. Feedstock based on UCO 3. Feedstock based on sugarcane 4. Feedstock based on biomass 5. Feedstock based on green hydrogen and CO2 from point of source, BCG synfuel top-down cost model. OpEx based on IEA The Future of Hydrogen, Fraunhofer ISE Study: LCOE—Renewable Energy Technologies. Assumes 50% Solar PV and 50% onshore wind

Focus areas for corporations moving forward

The opportunity and landscape for bioenergy are clear, with North American industry and society strategically well placed next to an abundance of bioenergy feedstock. BCG sees six key focus areas for companies pursuing opportunities and wishing to accelerate their market growth:

1. **Strategic development:** centralize the new market opportunity, analyzing the optimal value pools and commercial strategy
2. **Sustainability at the center:** use local, sustainably sourced biomass feedstocks, siting projects as close as possible to feedstock
3. **Optimizing local supply with global demand:** Focus on production local to the feedstock source to minimize carbon intensity and maximize sustainability impact
4. **CCS enhancements:** create carbon negative end products and maximize the final use of each tonne of biomass as a long-term geological carbon sink
5. **Co-product augmentation:** focus all bioenergy projects and technologies on coproduct development to achieve the best use of biomass per tonne, whether it be Energy/Fuels/Pulp & Paper with CCS, or pyrolysis liquid products optimized with biochar for increased feedstock regeneration
6. **Sustainable partnerships:** identify optimal partners within the value chain, from forest and landowners, to sawmills and agriculture, to petrochemical and sub-surface resource extraction; focus on co-product synergies to create long term sustainable value.

About the Authors

Carl Clayton
Associate Director Low Carbon Solutions – London
Clayton.Carl@bcg.com

Ilshat Haris
Managing Director and Partner - Houston
Leads BCG's Bioenergy Business
Haris.Ilshat@bcg.com

Clint Follette
Managing Director and Senior Partner – Houston
Follette.Clint@bcg.com

Achuth Vasudevan
Project Leader – Houston
Vasudevan.Achuth@bcg.com

For Further Contact

If you would like to discuss this report, please contact the authors.

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