Biomass
Biorefinery
Network

4th BBNet Conference

The future prospects for biorefining: Feedstocks, technologies and products

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The Future of Biorefining

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Center for Bioenergy Innovation
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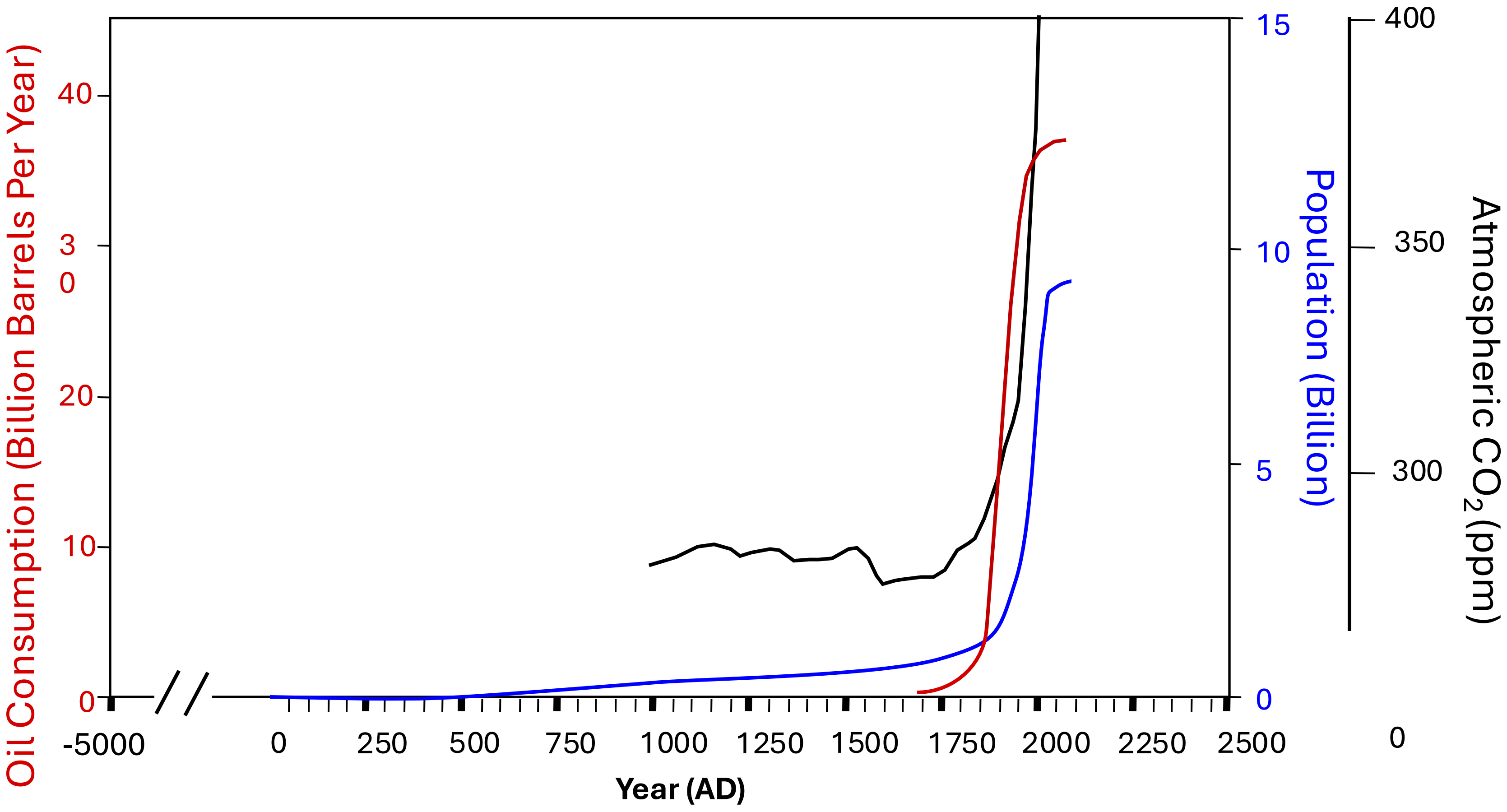
4th Meeting of the Biomass Biorefining Network
Sheffield, UK
October 15, 2025

Affirmation
Challenges
Thoughts on the path forward
Some directions I am excited about

terragia DARTMOUTH cbi THE CENTER FOR BIOENERGY INNOVATION A2G Advanced 2nd Generation BIOFUEL LABORATORY UNICAMP

Affirmation

The world is changing fast



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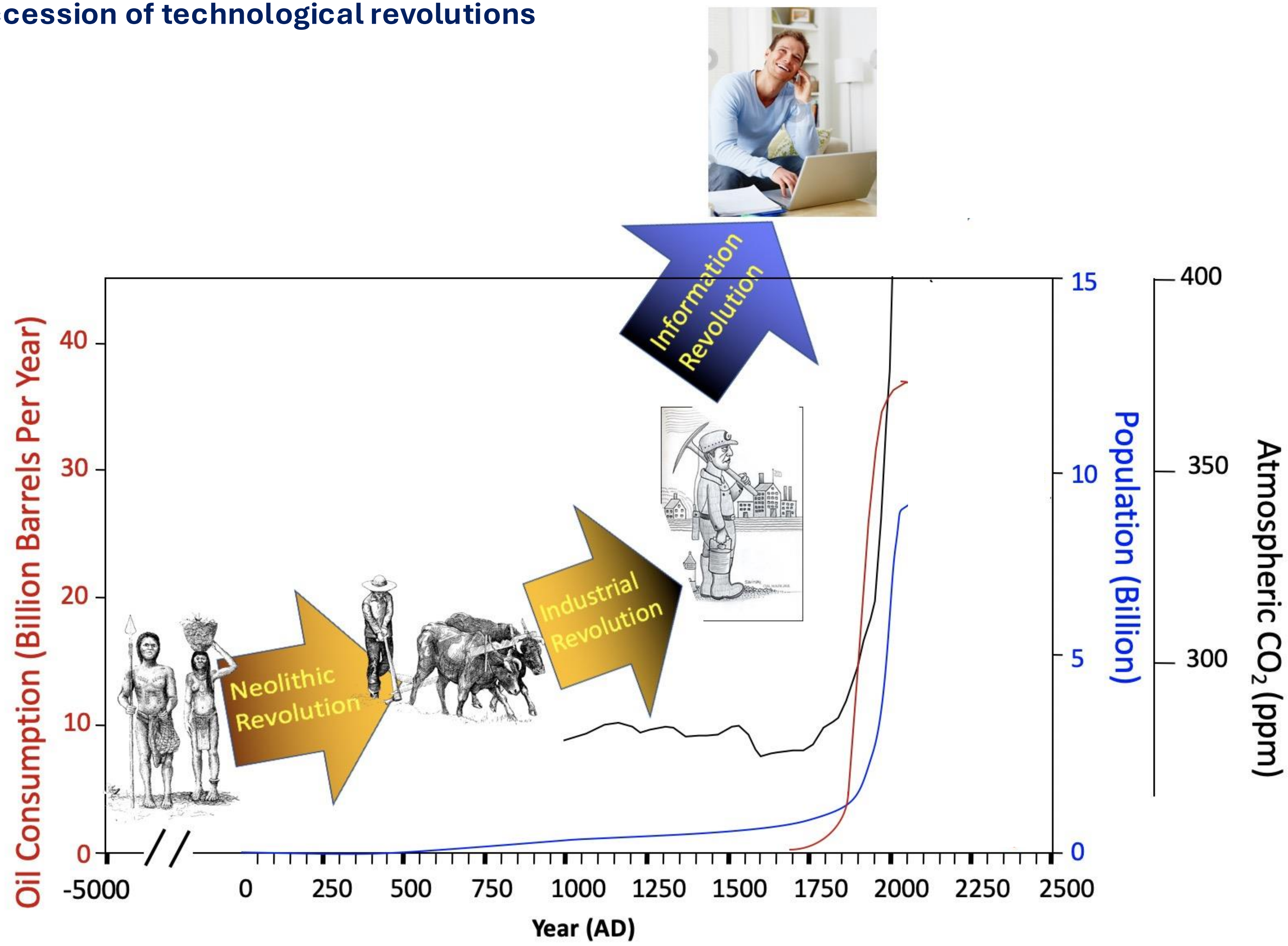
The world is changing fast - enabled by a succession of technological revolutions



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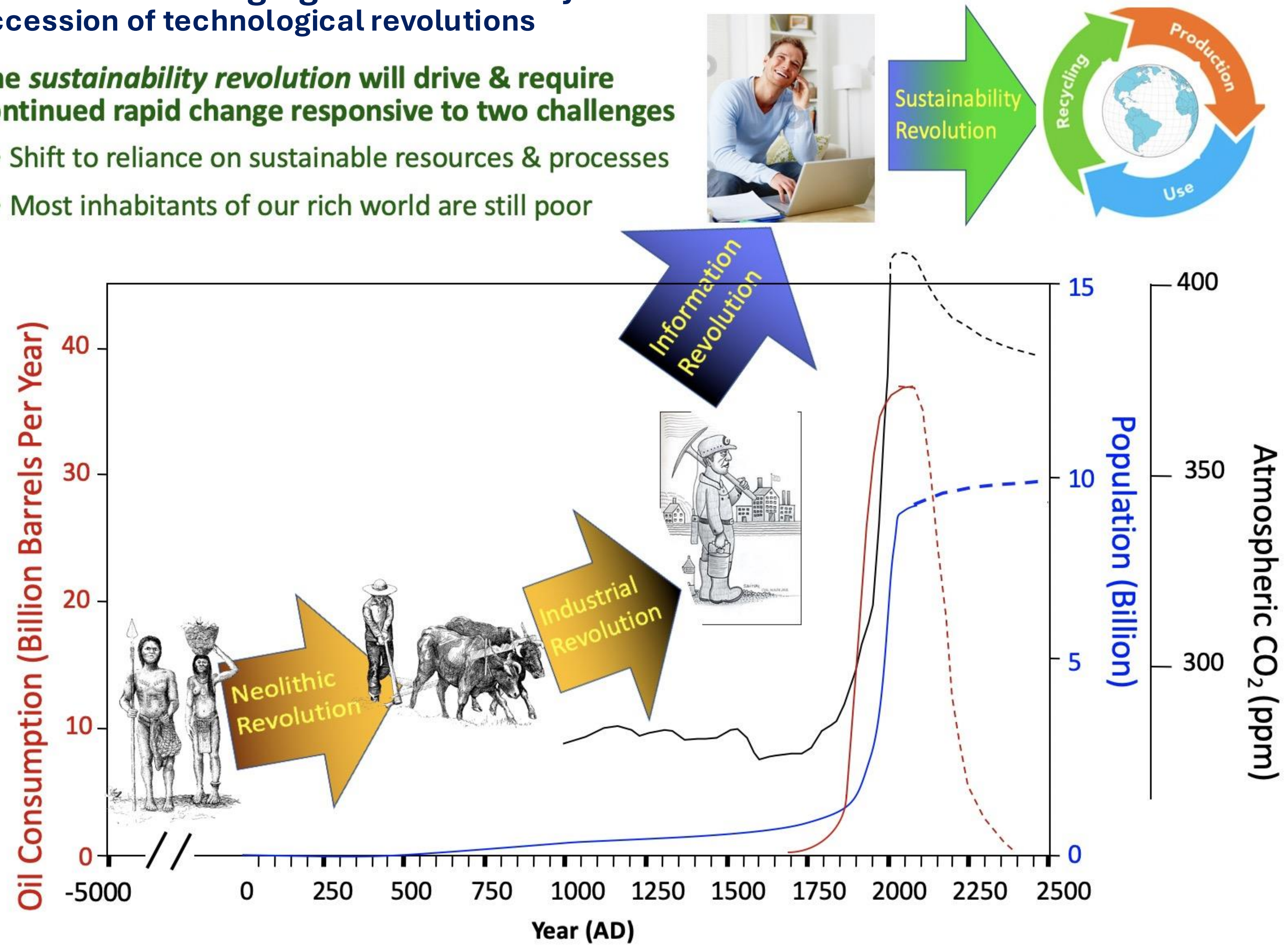
The world is changing fast - enabled by a succession of technological revolutions

The *sustainability revolution* will drive & require continued rapid change responsive to two challenges

- Shift to reliance on sustainable resources & processes
- Most inhabitants of our rich world are still poor



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Biomass Feedstocks

Starch-rich (grains)
e.g. maize, wheat

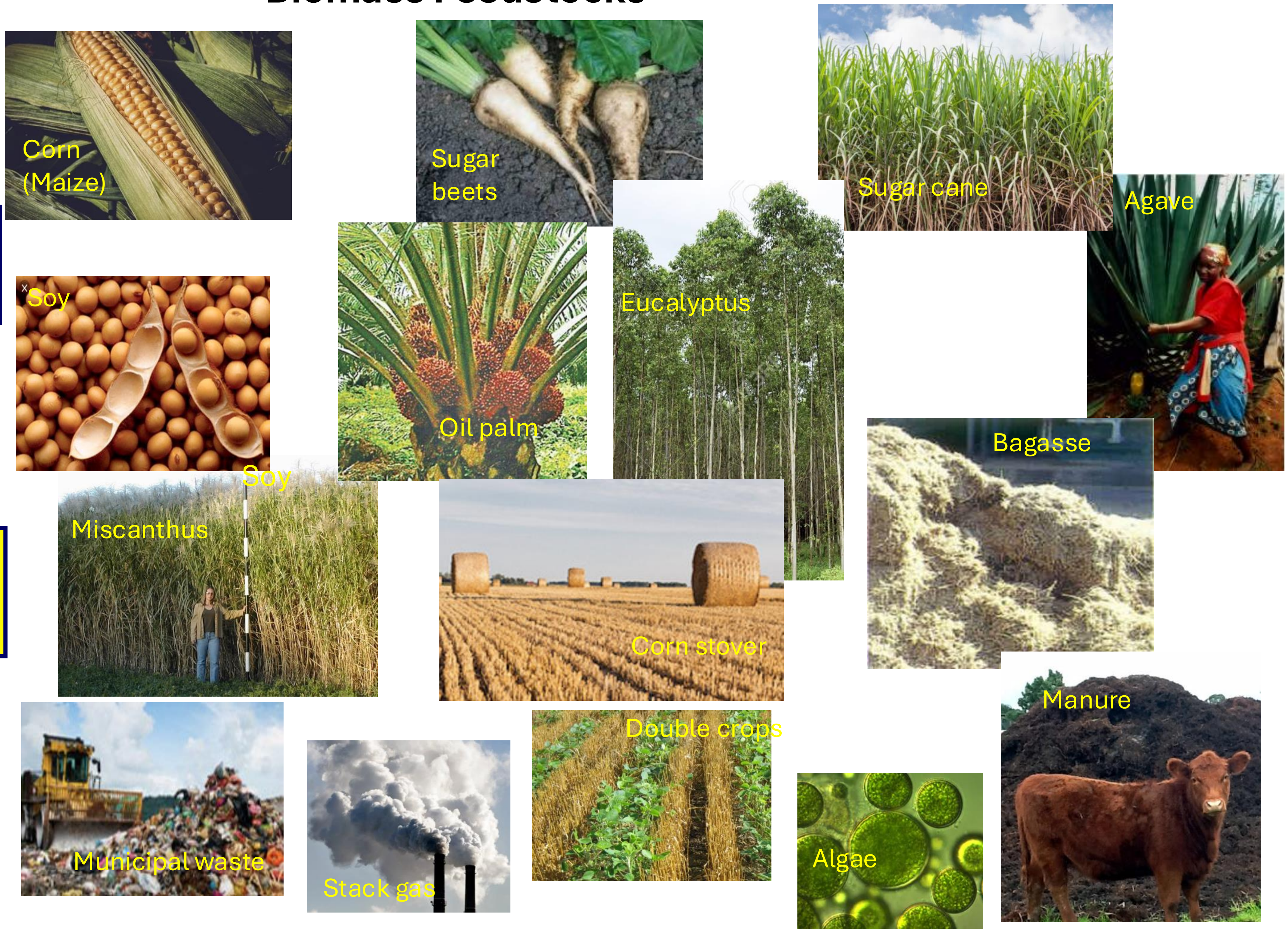
Sugar-rich
sugar cane, sugar beets

Oil-Rich
oil palm, soy, rapeseed

Lignocellulose
Residues (stalks, paper sludge)
Crops (Woody, herbaceous)

Mixed wastes
Manure, municipal, stack gas

Algae



Feedstock Cost & Processing Margin for Petroleum and Cellulosic Biomass

$$M = Processing\ Margin = Product\ revenue - Feedstock\ cost$$

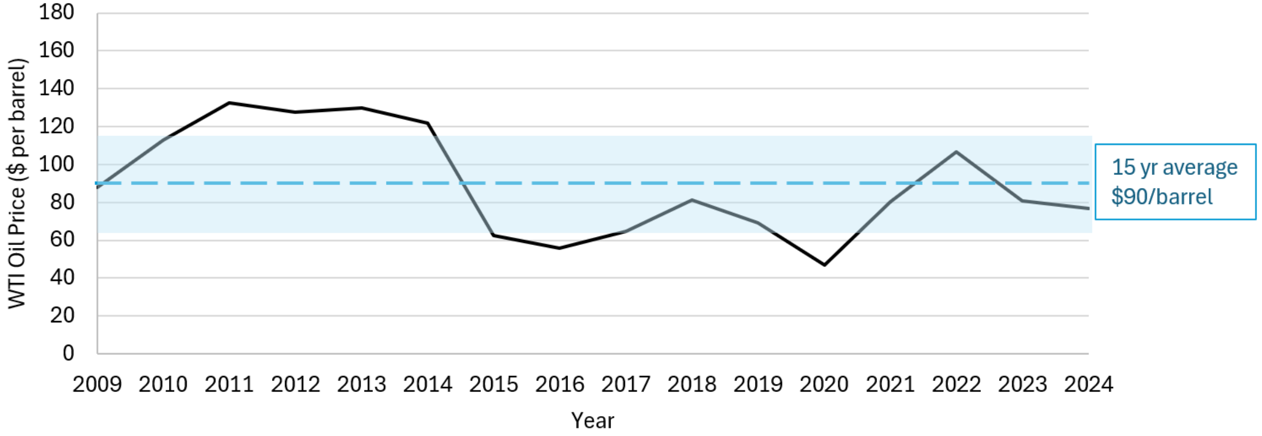
$$= \frac{1}{E}\sum_i Y_i P_i - F$$

Petroleum

Product	Y_i (kg Product/Barrel)	P_i (\$/kg Product)	Y_iP_i (\$/Barrel)
Gasoline	57.2	0.91	52.3
Diesel	39.8	0.88	34.9
Kerosene	13.5	0.91	12.2
Petroleum coke	6.1	0.11	0.7
Asphalt and road oil	5.4	0.43	2.3
Hydrocarbon gas liquids	3.2	0.53	1.7
Residual fuel oil	2.7	0.57	1.5
Lubricants	1.3	3.90	5.0

Sum: 111

$$\left(\frac{\$111}{barrel}\right)\left(\frac{1\ barrel}{6.12\ GJ}\right) = \$18.1/\text{GJ}$$



$$\left(\frac{\$90}{Barrel}\right)\left(\frac{1\ Barrel}{6.12\ GJ}\right) = \$14.7/\text{GJ}$$

Biomass

Assume mature conversion technology → product slate with same revenue as petroleum

Bagasse : $\left(\frac{\$36}{ton}\right)\left(\frac{1\ ton}{17.GJ}\right) = \$2.1/\text{GJ}$

Billion ton study : $\left(\frac{\$130}{ton}\right)\left(\frac{1\ ton}{17\ GJ}\right) = \$7.6\ /\text{GJ}$

All product & feedstock prices in 2024 dollars.
Petroleum yields & prices are 15-year averages from the EIA.
Brazilan bagasse price from MF Rural, accessed April 29, 2025
https://www.mfrural.com.br/produtos/3-345/nutricao-animal-cana-de-acucar-bagaco?srsltid=AfmBOoosJfvnfp_3cDzZzOVeJuTm8E_cK-DPRXCPUH8duICV6fvXyJ0P

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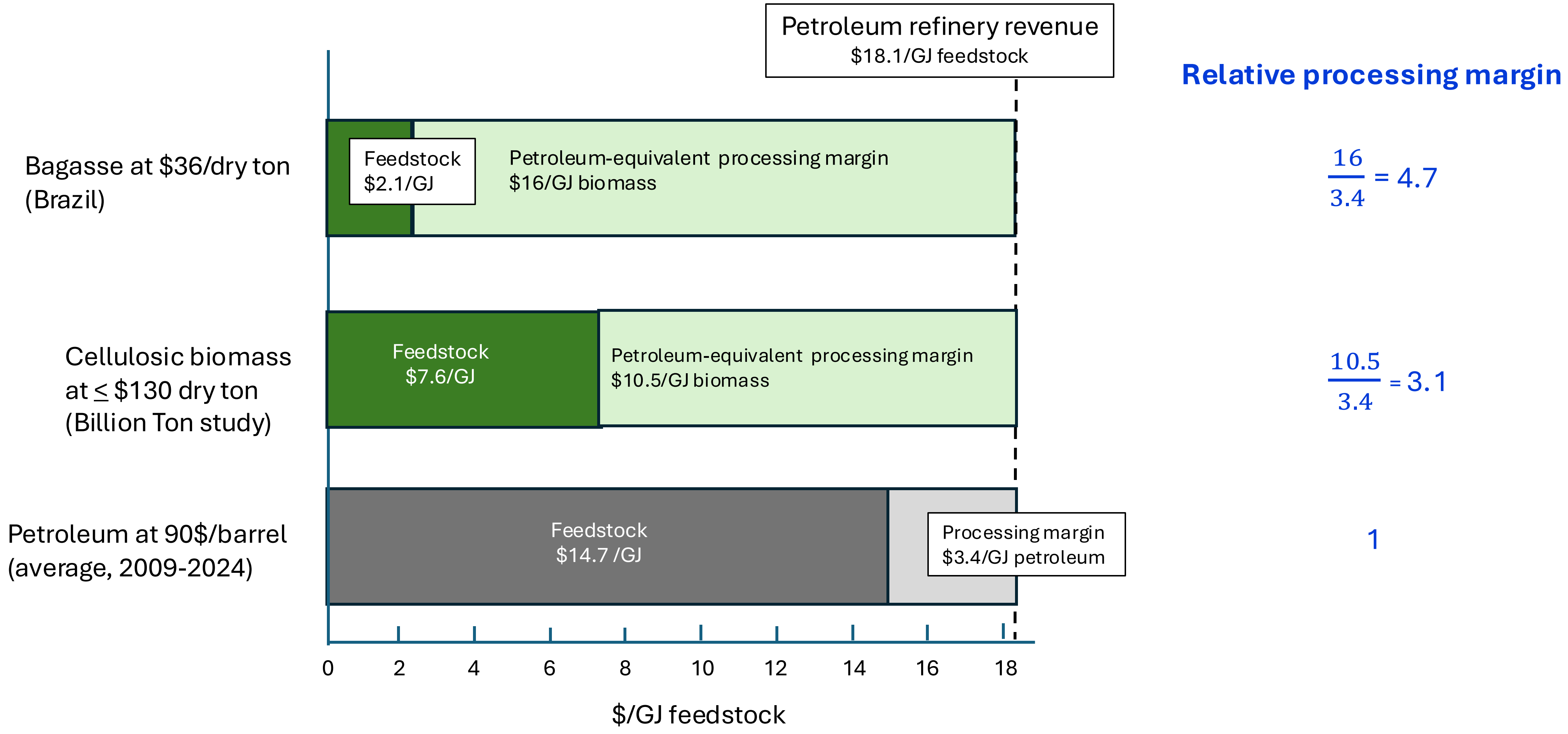


Cellulosic biomass compared to petroleum ($/GJ)

- Lower feedstock cost
- Higher processing margin

de Martino Costa and Lynd
In-preparation.

Biorefining

A Compelling Vision and A World of Possibility

https://ic-ce.com/article-circular-economy-and-sustainability/

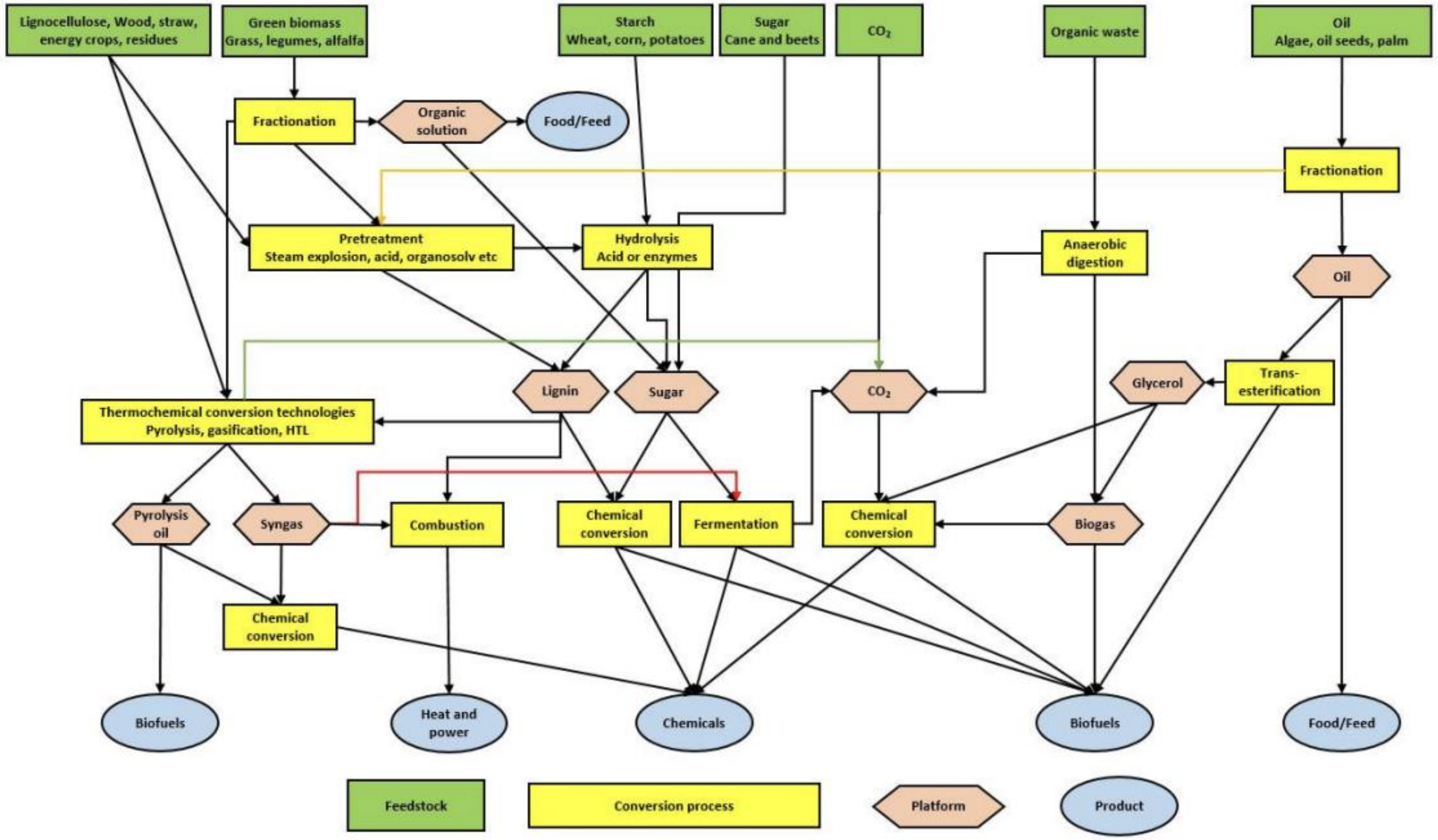


Figure 3. Conversion technologies for biomass based on IEA Bioenergy Task 42 biorefinery classification system (16)

https://task42.ieabioenergy.com/wp-content/uploads/sites/10/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf

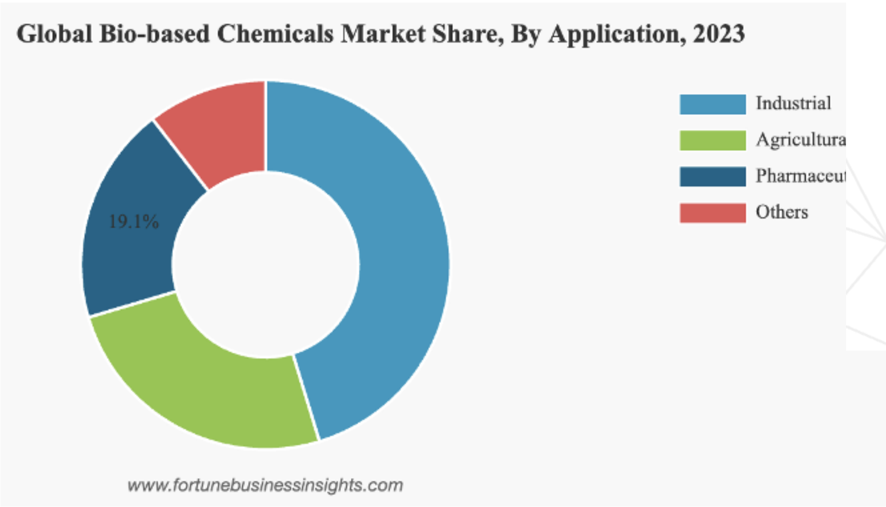
Biorefining
A Compelling Vision, A World of Possibility and Tangible Impact

FORTUNE BUSINESS INSIGHTS

GLOBAL BIO-BASED CHEMICALS MARKET S

Market Size & Forecast:

- 2023 Market Size: USD 73.16 billion
- 2024 Market Size: USD 99.86 billion
- 2032 Forecast Market Size: USD 207.95 billion
- CAGR: 9.6% from 2024–2032



Source: https://www.fortunebusinessinsights.com/bio-based-chemicals-market-106586

LIST OF KEY COMPANIES PROFILED

- BASF SE (Germany)
- Vertec BioSolvents Inc. (U.S.)
- AGAE Technologies, LLC (U.S.)
- TOTAL (France)
- ADM (U.S.)
- DuPont (U.S.)
- Evonik Industries (Germany)
- Toray Industries, Inc. (Japan)
- Cargill, Incorporated (U.S.)
- GF Biochemicals Ltd. (Italy)
- Mitsubishi Chemical Corporation (Japan)
- DSM (Netherlands)

Table 2. Select Currently Produced Biobased Molecules

BIOBASED CHEMICAL	CAPACITY (KTA)	FERMENTATION	CATEGORY[1]
ethanol	80,800	yes	1
citric acid	2000	yes	1
sorbitol	1800	no	1
glycerol	1500	no	1
lysine	1100	yes	1
lactic acid	>600	yes	1
furfural	360	no	1
sebacic acid	200	no	1
xylitol	190	no	1
propylene glycol	120	no	1
itaconic acid	90	yes	1
1,3-propanediol	77	yes	1
epichlorohydrin	540	no-derivative	2
ethylene	200	no-derivative	2
ethylene glycol	175	no-derivative	2

[1]Category 1 molecules cannot be cost-effectively produced from hydrocarbons. Category 2 molecules have lower environmental footprints from biomass compared to production from hydrocarbons and may support comparable or slightly higher pricing than the equivalent petrochemical.

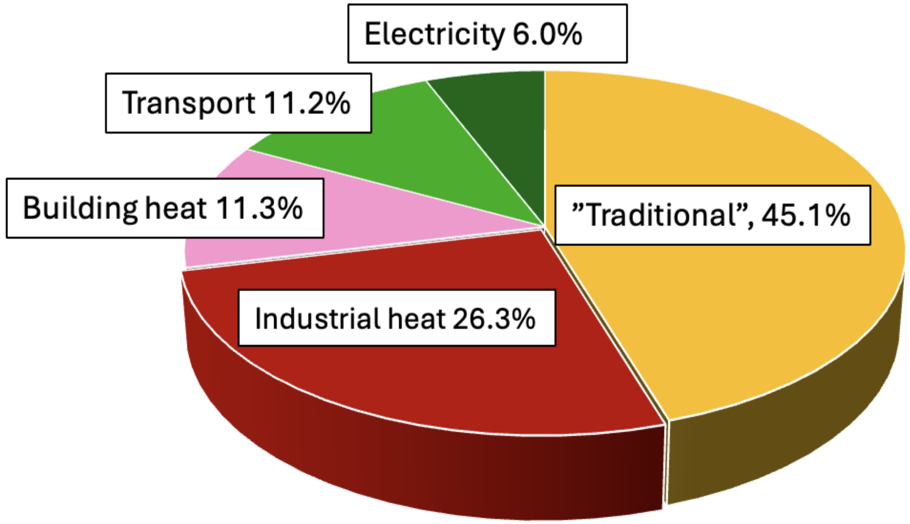
Danielson et al. 2020. Industrial biotechnology—An industry at an inflection point. *Industrial biotechnology*, *16*(6), pp.321-332.

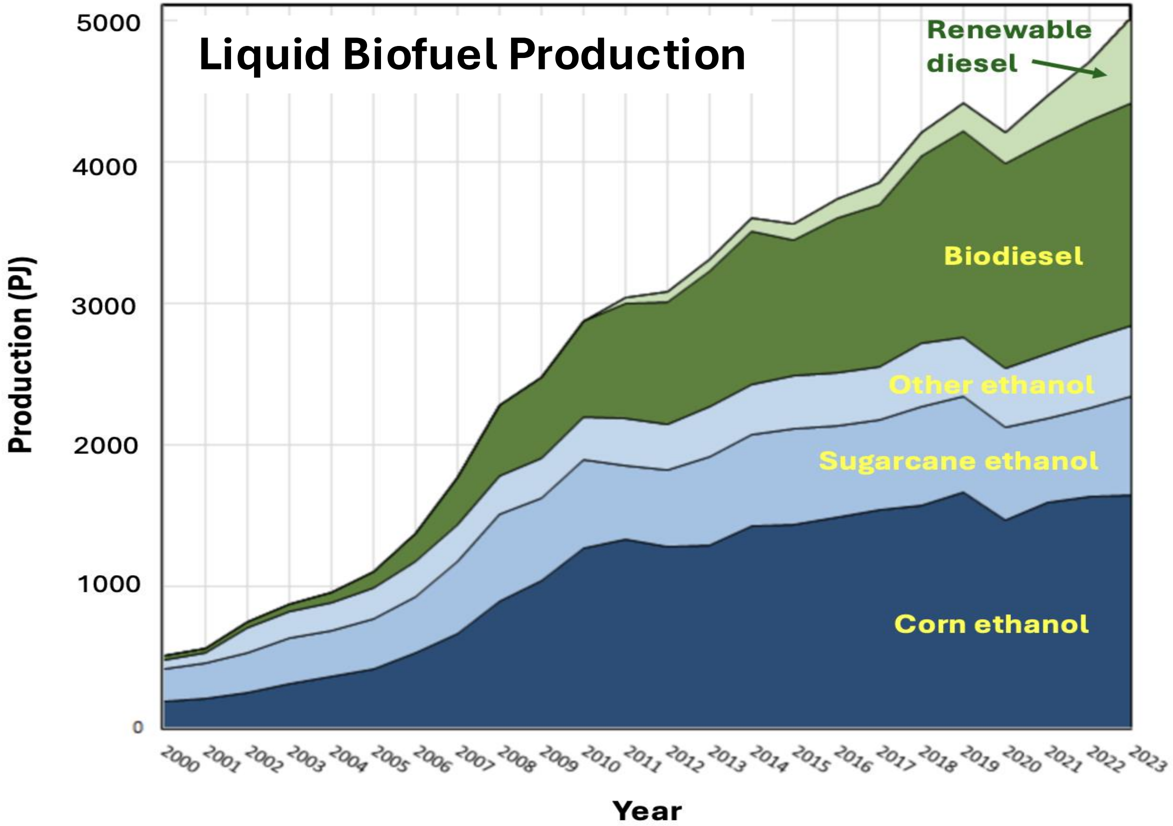
Bioenergy & Biofuels Today

Bioenergy

37 EJ

55% of renewable energy





Liquid Biofuels

5 EJ

3.9% global transport (all modes)

2.1 MM barrels oil equivalent/day

Biogas: 0.8 EJ

Examples of rapid biofuel growth

Fuel	Feedstock	Country	Period Start	Period End	Production Start (MML)	Production End (MML)	Fold increase	CAGR
Ethanol	Corn	United States	2000	2009	6,526	41,315	6.3	22.8%
Ethanol	Corn	Brazil	2018	2023	842	4,740	5.6	41.3%
Renewable diesel	VO + FOG	United States	2018	2023	1,156	9,816	8.5	53.4%

Lynd, Arifi, de Martino Costa, Fulton. in-preparation review.

Benefits of Biofuels From Current (“First Generation”, “1G”) Feedstocks

Employment

US. Corn ethanol* → >72,400 direct jobs (61,000/EJ), 322,000 indirect jobs
Coal → 45,000 direct jobs, 16-fold fewer per EJ

Brazil.** Sugarcane production for ethanol and sugar is the largest agricultural sector employer, has more positive social indicators compared to the overall agricultural sector, has led to an increase in aggregate municipal income, and through multiplier effects has enabled improved indicators of health, education, and quality of life.

On-the-ground examples of 1G biofuels with outstanding sustainability metrics

Near net-zero facilities***

Lantmannen wheat ethanol plant (Sweden)

Marquis Energy Industrial Complex (USA)

Corn ethanol industry in Brazil

nature sustainability

Article

https://doi.org/10.1038/s41893-024-01424-5

Contribution of double-cropped maize ethanol in Brazil to sustainable development

Accepted: 8 August 2024

Angelo C. Gurgel[1], Joaquim E. A. Seabra[2], Sofia M. Arantes[3], Marcelo M. R. Moreira[3], Lee R. Lynd[4] & Rosana Galindo[2]

Abstract. …We find that this system provides renewable and affordable energy (5 billion litres of ethanol, 600 GWh of electrical power) and feed (4 million tons of distillers dried grains), reduces greenhouse gas emissions (9.3 million to 13.2 million tCO2e), saves land (160,000 ha), boosts regional income and consumption, improves food security and benefits ecosystems and human health.

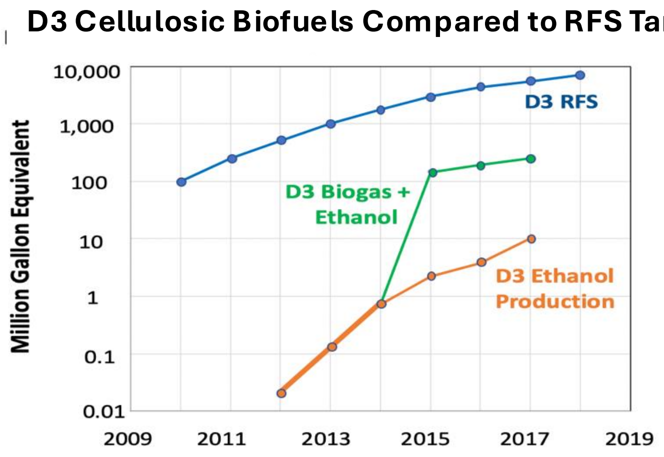
Key role in fostering cellulosic biofuel deployment

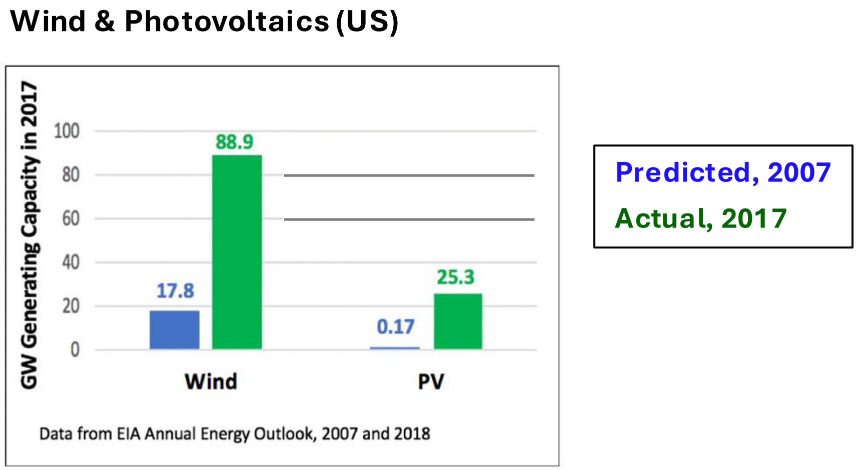
* Renewable Fuels Association
** Moraes et al., Env. Development, 2015.
*** https://www.lantmannenbiorefineries.com/; https://marquisinc.com/carbon-and-sustainability/

Challenges

Cellulosic Biofuels 1.0

Cellulosic biofuels fell far short or expectations while other renewables exceeded them (Lynd, Nature Biotech., 2017)





Technology. Over estimated technological readiness →

- Premature scale-up
- Investment & policies targeting deployment rather than innovation
- Costly, unprofitable, operationally challenging demo plants – all abandoned but one (Raizen, Brazil)

Land

- Land converted to energy crops: Anticipated negative direct & indirect impacts (ecosystem services, habitat, food vs fuel...) → diminished policy support
- Harvesting crop residues: decreased soil carbon, fertility compared to leaving them in the field

Climate benefits challenged. Indirect land use change, carbon debt, opportunity cost

Changing Expectations for Biofuels in IEA Deep Decarbonization Scenarios

Comparison of 2012 and 2023 IEA scenarios*

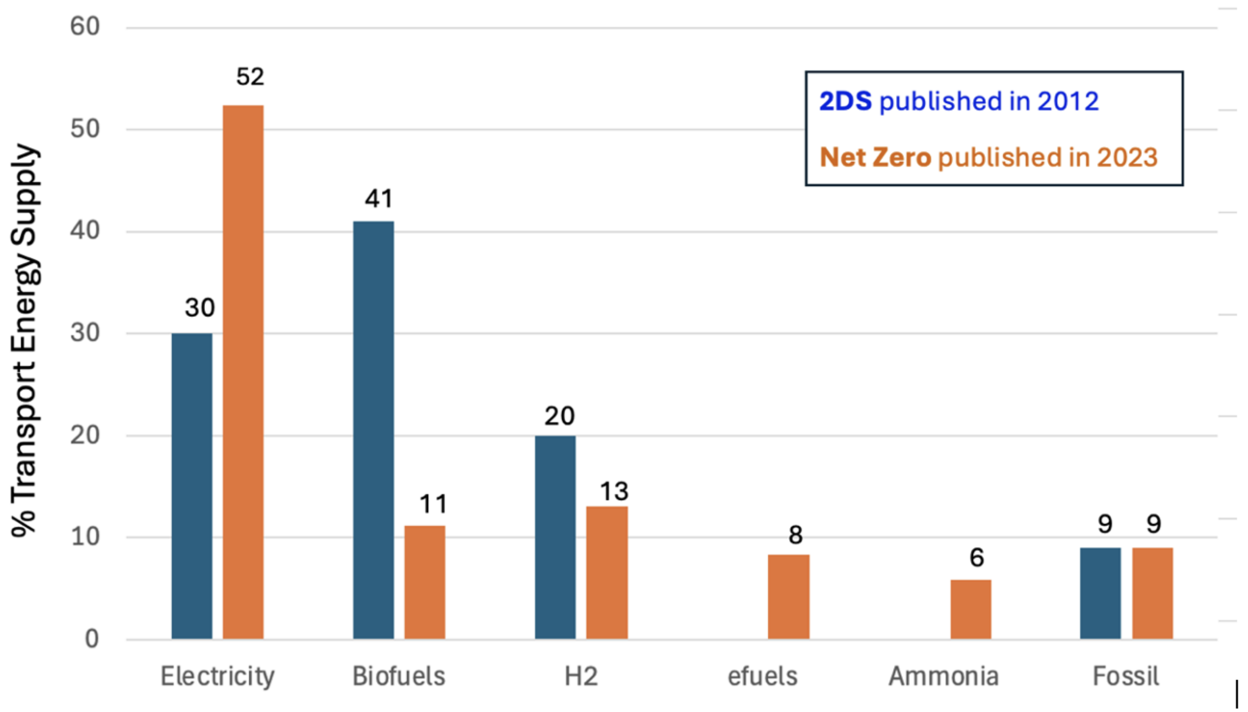


Figure 3. Comparison of the energy provided by various transportation energy carriers in the IEA 2DS for 2075 published in 2012 and the IEA Net Zero Scenario for 2050 published in 2023. Comparison is made to the 2DS for 2075 because the percent fossil fuel replacement is the same as the 2050 Net Zero scenario whereas fossil fuel replacement is much smaller for the 2DS in 2050.

2012→2023

Continued need for options in addition to electricity + H_2 for long trips in heavy vehicles.

Less confidence that biofuels will meet this need.

Liquid cellulosic biofuels fell short of initial RFS goals by 1000-fold

*We attribute lowered expectations for biofuels primarily to production from cellulosic feedstocks falling far short of anticipated levels rather than advancement of efuels or ammonia for transport.**

* Lynd, Arifi, de Martino Costa, Fulton. in-preparation review.

Unmet Expectations for Biorefining is Not Limited to Biofuels

CellPress
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Trends in
Biotechnology

Opinion

Innovation trends in industrial biotechnology

Jens Nielsen,[1,2,4,5,*] Christian Brix Tillegreen,[1] and Dina Petranovic[2,3]

Why has the bio-based large-scale production of commodity chemicals lagged behind expectations?

BIOTECHNOLOGY

Enabling commercial success of industrial biotechnology

Commercial-scale research translation has been muted

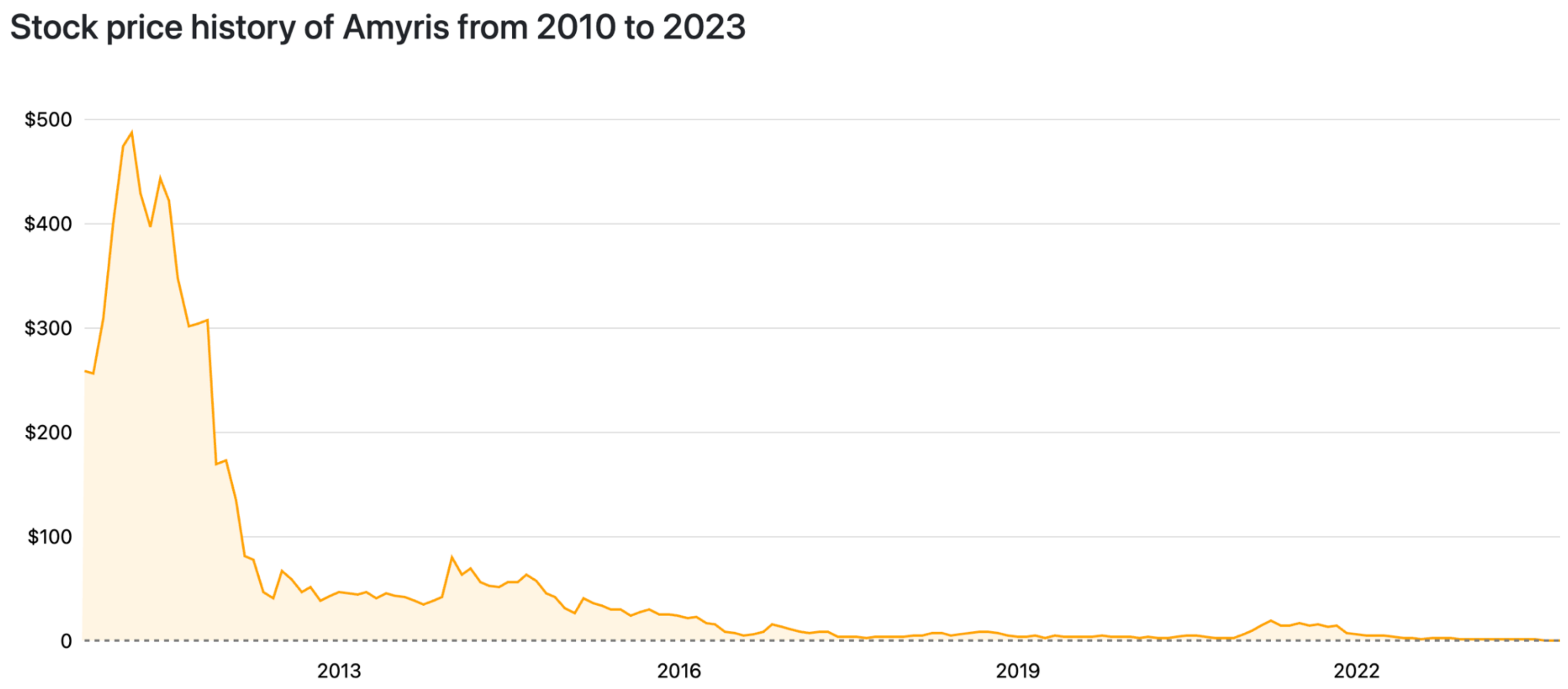
By Bradley W. Biggs[1], Hal S. Alper[2], Brian F. Pfleger[3], Keith E. J. Tyo[1], Christine N. S. Santos[4], Parayil Kumaran Ajikumar[4], Gregory Stephanopoulos[5]

SCIENCE

24 DECEMBER 2021 • VOL 374 ISSUE 6575

Academic interest is strong and growing, with several high-profile demonstrations of metabolic engineering. However, few academic successes have become commercial successes. The low success rate of translating research stifles job growth, prevents new products from reaching consumers, and leaves societal and ecological benefits of industrial biotechnology unrealized.

Post-IPO Values of Industrial Biotechnology Companies Exhibits a Troubling Trend



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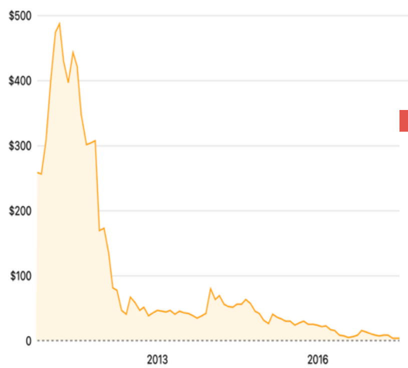
Stock price history of Amyris from 2010 to 2023



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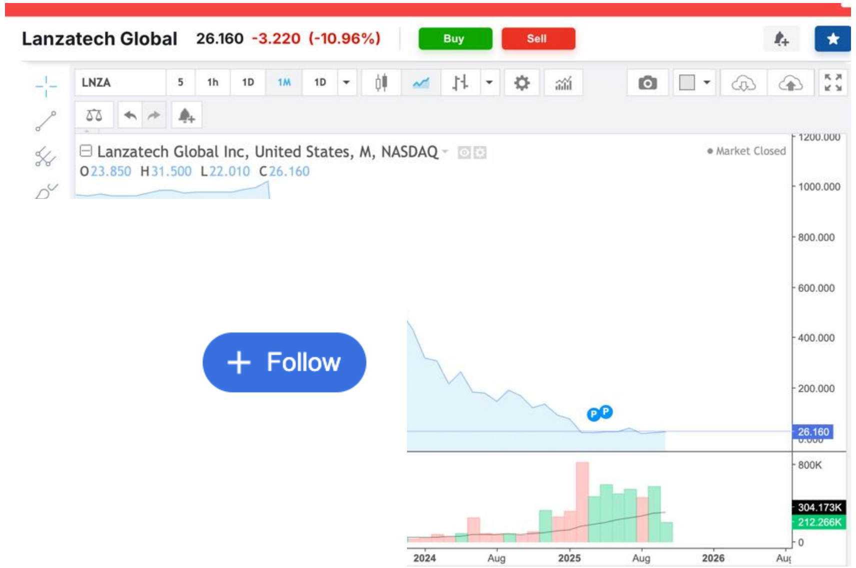

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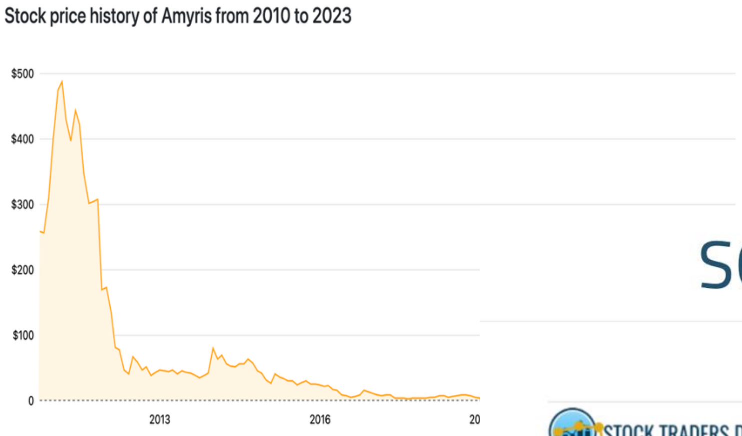

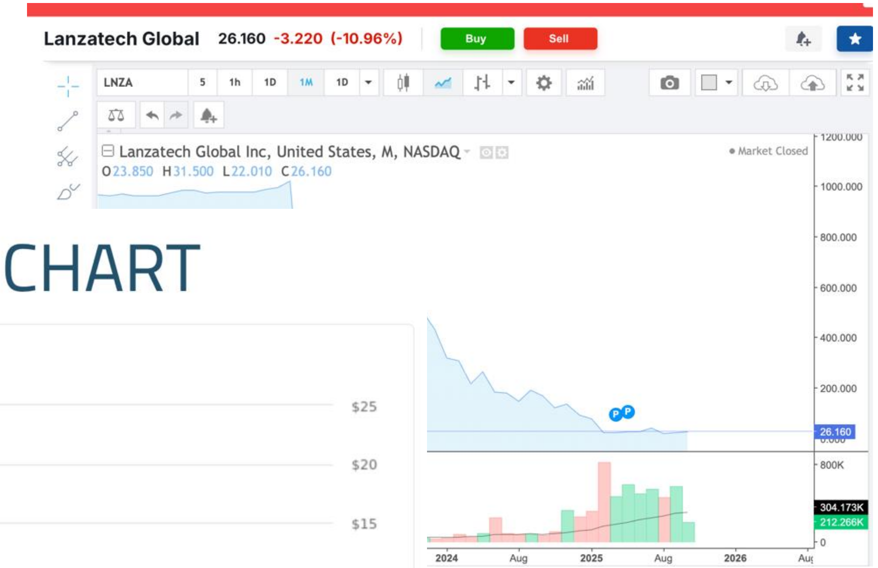

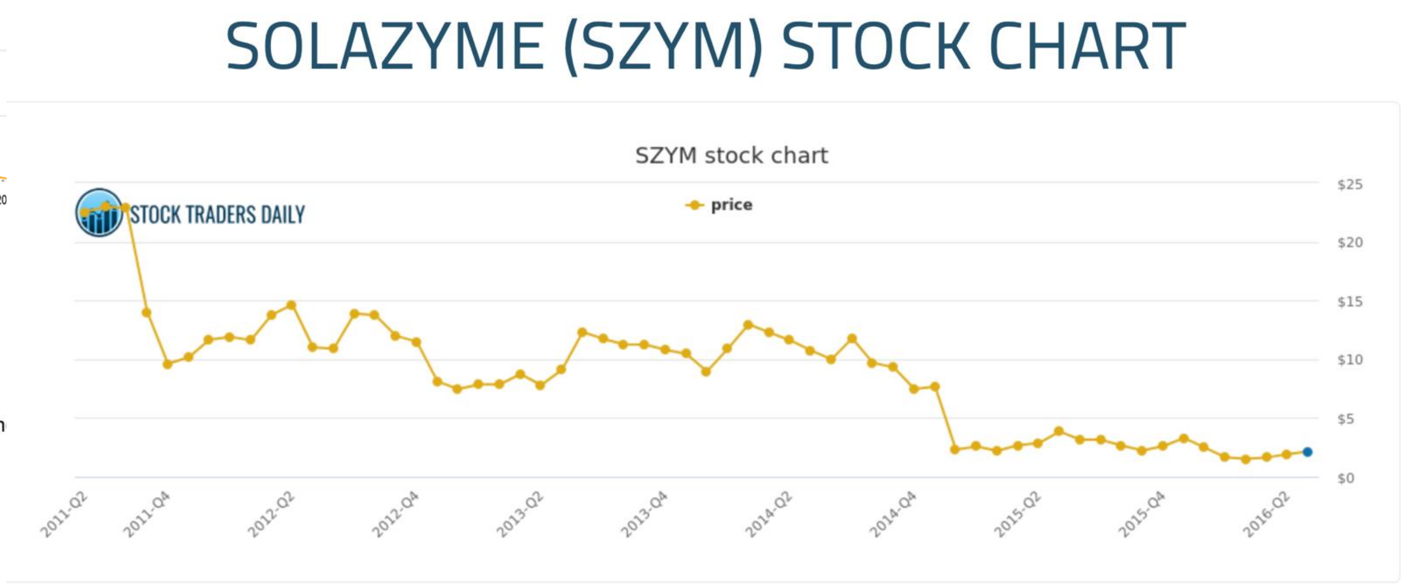

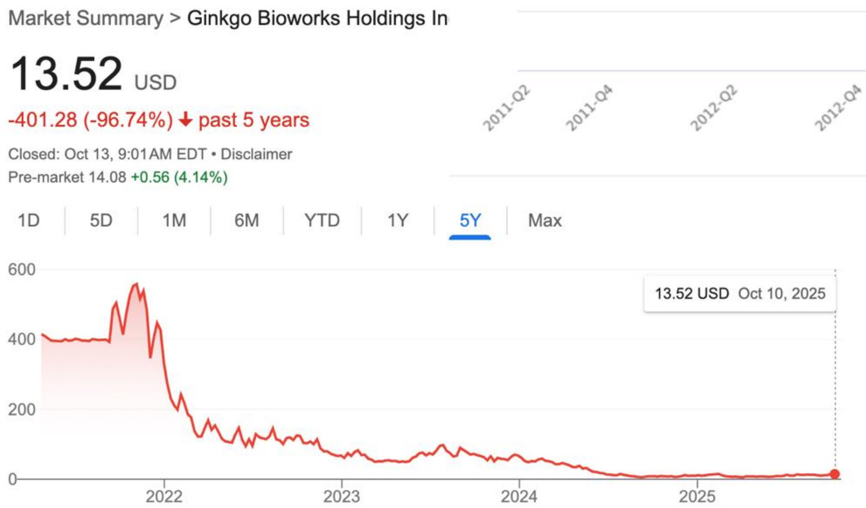

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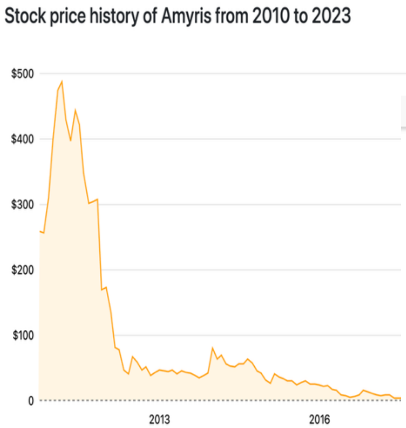

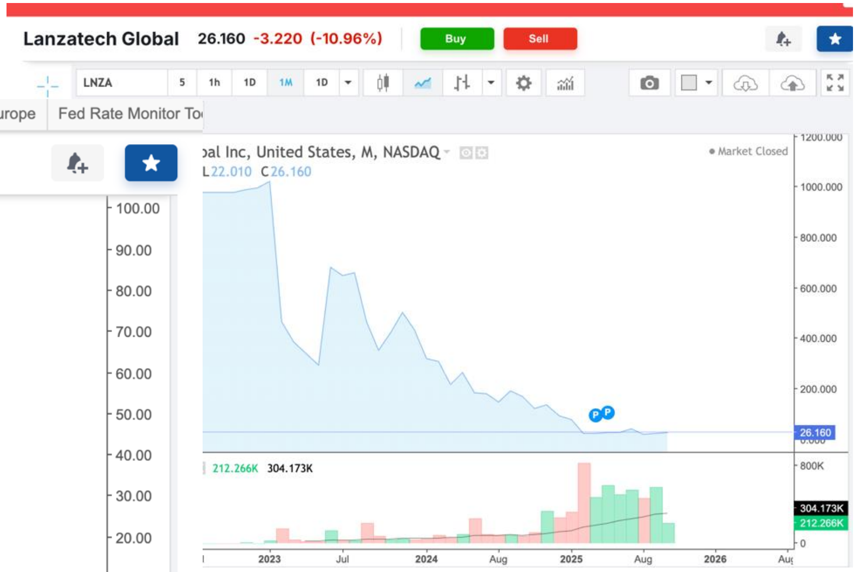

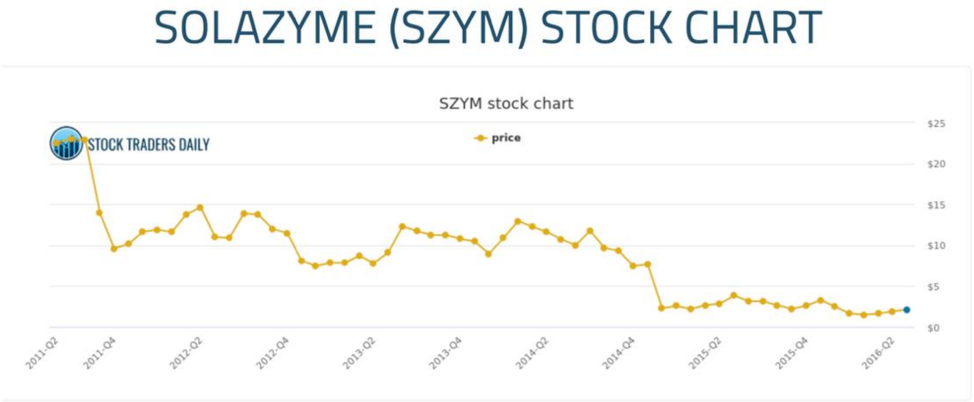

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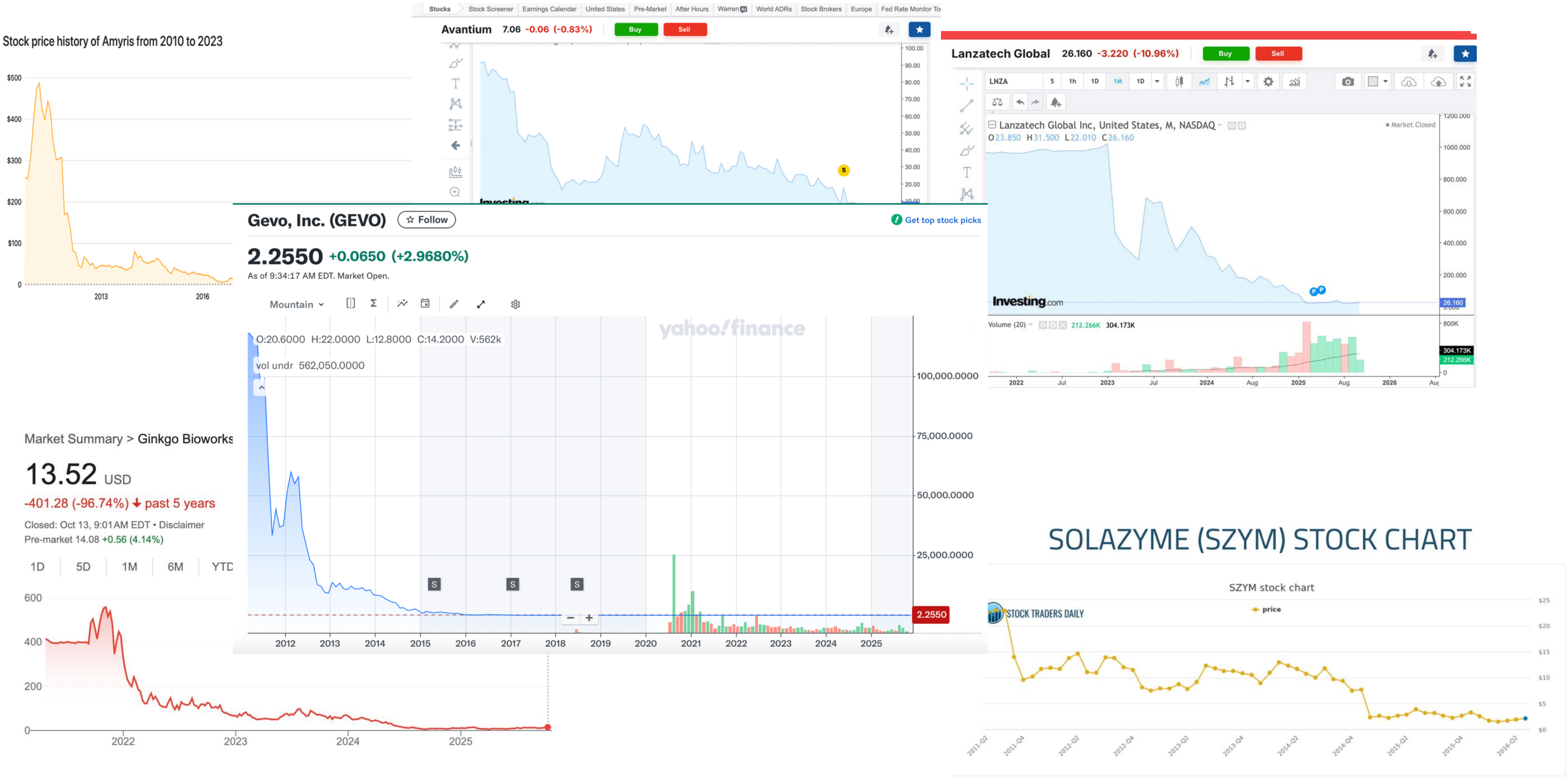

Thoughts on the Path Forward

Key Factors and Lessons for Biorefining Success

Feedstocks & Products

Ideal feedstock features, especially for new technologies

- Easily converted
- Aggregated year-round at an industrial processing facility
- Consistent quality
- Low net cost considering coproducts

Cellulosic biofuel 1.0 demo projects had few of these features with the exception of Raizen, the only one standing today

Low-cost, high volume products, especially fuels, require low-cost, high volume feedstocks ***e.g. lignocellulose***

Higher cost, lower volume products do not
Limited incentive to produce from lignocellulose

Commodity → specialty products
vs
Specialty → commodity products
I see more precedent in the former

Multiproduct biorefining is a great vision and destination,
commercial viability is more often proven one product at a time

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Technology

The community has been working on some processing concepts for a long time with more than incremental further improvements possible but by no means assured

We need to be open to different approaches if we want different results

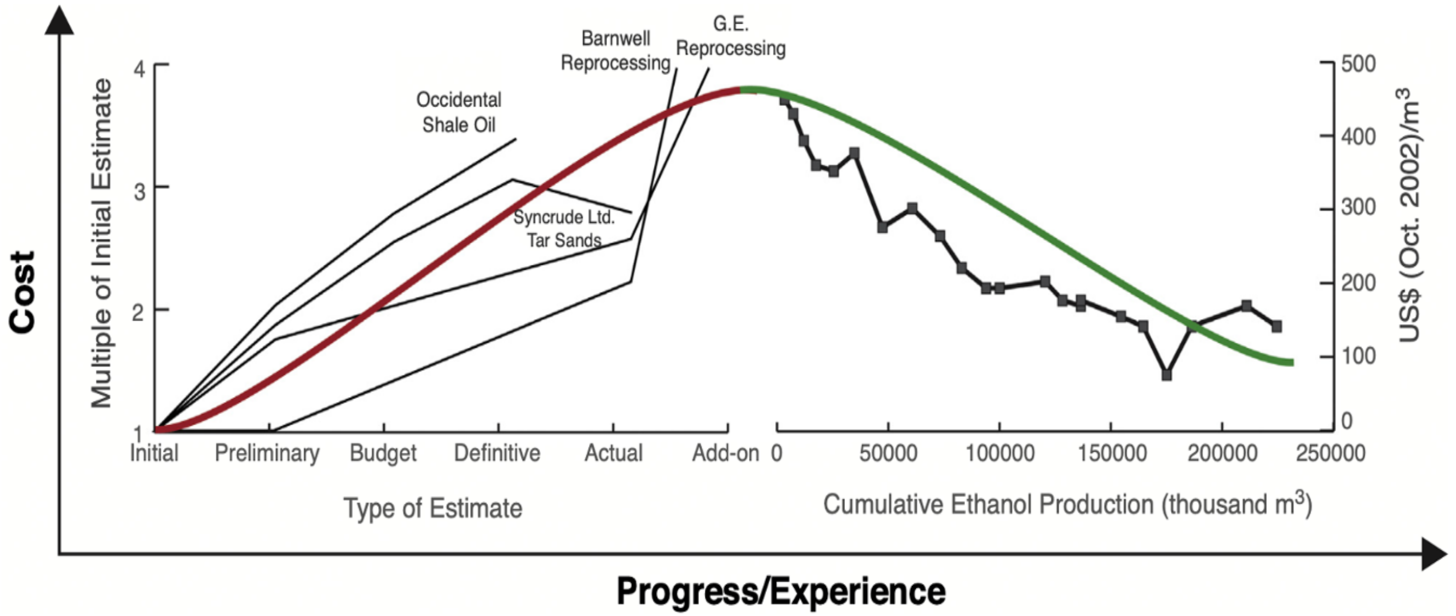
Important to accurately assess where we are on the Rand-Goldemberg curve

"Rand Curve"

Merrow et al. A Review of Cost Estimation in New Technologies. RAND Corporation; 1979.

"Goldemberg Curve"

Goldemberg et al. Ethanol learning curve—the Brazilian experience. Biomass Bioenergy 2004,



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Business model

Tentative taxonomy

Model	Examples	Difficulty
Reagent for established process	Novenesis, Lallamand/Mascoma DuPont	Least
New product or process	Ethanol Lactic acid 1,3-propane diol Amino acids etc.	Intermediate
Industry service provider	Diversa Ginkgo Zymergen	Most

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Business model

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Partnerships

Small & large companies bring different skills, assets

In the transition toward the bio-based production of chemicals, large chemical companies have not only the advantage of having significant R&D capabilities, but also, more importantly, extensive engineering competence for manufacturing on a very large scale and depreciated fermentation plants.
Nielsen et al., Trends in Biotechnology, 2022.

"All of our successes have been collaborative. I did not say that all of our collaborations have been successful."
Antonio Stuchi, then of Raizen

Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

REVIEW

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Cite this: *Energy Environ. Sci.*, 2022, **15**, 938

Toward low-cost biological and hybrid biological/catalytic conversion of cellulosic biomass to fuels†

Lee R. Lynd, ‡*[ab] Gregg T. Beckham, ‡*[ac] Adam M. Guss, [ad] Lahiru N. Jayakody, [e] Eric M. Karp, [c] Costas Maranas, [af] Robert L. McCormick, [g] Daniel Amador-Noguez, [ah] Yannick J. Bomble, [ai] Brian H. Davison, [ad] Charles Foster,[af] Michael E. Himmel,[ai] Evert K. Holwerda, [ab] Mark S. Laser,[ab] Chiam Yu Ng,[af] Daniel G. Olson, [ab] Yuriy Román-Leshkov, [aj] Cong T. Trinh, [ak] Gerald A. Tuskan, [ad] Vikas Upadhayay,[af] Derek R. Vardon, [l] Lin Wang[af] and Charles E. Wyman [am]

Key contributors

Gregg Beckham, Co-coordinator

Adam Guss, Cellular transformations

Costas Maranas, Product survey

Lahiru Jayakody, Product inhibition

Eric Karp, Product recovery

Bob McCormick, Fuel utilization

Gregg, Yuriy Roman, Catalytic processing

Key features of promising bioprocesses

- Biorefining at a scale sufficient to impact climate will likely involve fuels as primary products, chemicals & biomaterials as co-products, lignocellulose as the preferred feedstock
- Microbial processing of cellulosic biomass will likely occur in the presence of solids, rather than involving solids-free sugar syrups, giving rise to challenges and constraints specific to lignocellulose
- Anaerobic processing involves lower costs than aerobic, making it more promising for fuel production

- **Anaerobic processing involves lower costs than aerobic processing**

Table 2 Capital and operating costs for aerobic and anaerobic processes, taken from Biddy *et al.* 2016[40] (ref. which modeled lipid production for a biofuel intermediate

	Aerobic	Anaerobic	
CapEx			
Bioreactor vessel	$52 460 771	$5 589 903	
Bioreactor air compressor	$1 631 302	$0	
Bioreactor agitator	$0	$347 713	
Bioreactor cooler	$932 368	$351 837	
Seed train equipment	$2 663 748	$3 511 609	
Recirculation/transfer pump	$389 057	$103 570	
Total	**$58 077 246**	**$9 904 632**	**5.9 X**
OpEx			
Bioreactor system including agitator	$1 916 323	$191 674	
Chiller system	$2 909 972	$1 220 396	
Total	**$4 826 295**	**$1 412 070**	**3.4 X**

Lynd, Beckham et al., Energy & Env. Sci., 2022.

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Cite this: *Energy Environ. Sci.*, 2022, **15**, 938

Toward low-cost biological and hybrid biological/catalytic conversion of cellulosic biomass to fuels†

Lee R. Lynd, ‡*[ab] Gregg T. Beckham, ‡*[ac] Adam M. Guss, [ad] Lahiru N. Jayakody, [e] Eric M. Karp, [c] Costas Maranas, [af] Robert L. McCormick, [g] Daniel Amador-Noguez, [ah] Yannick J. Bomble, [ai] Brian H. Davison, [ad] Charles Foster,[af] Michael E. Himmel,[ai] Evert K. Holwerda, [ab] Mark S. Laser,[ab] Chiam Yu Ng,[af] Daniel G. Olson, [ab] Yuriy Román-Leshkov, [aj] Cong T. Trinh, [ak] Gerald A. Tuskan, [ad] Vikas Upadhayay,[af] Derek R. Vardon, [l] Lin Wang[af] and Charles E. Wyman [am]

Key contributors

Gregg Beckham, Co-coordinator

Adam Guss, Cellular transformations

Costas Maranas, Product survey

Lahiru Jayakody, Product inhibition

Eric Karp, Product recovery

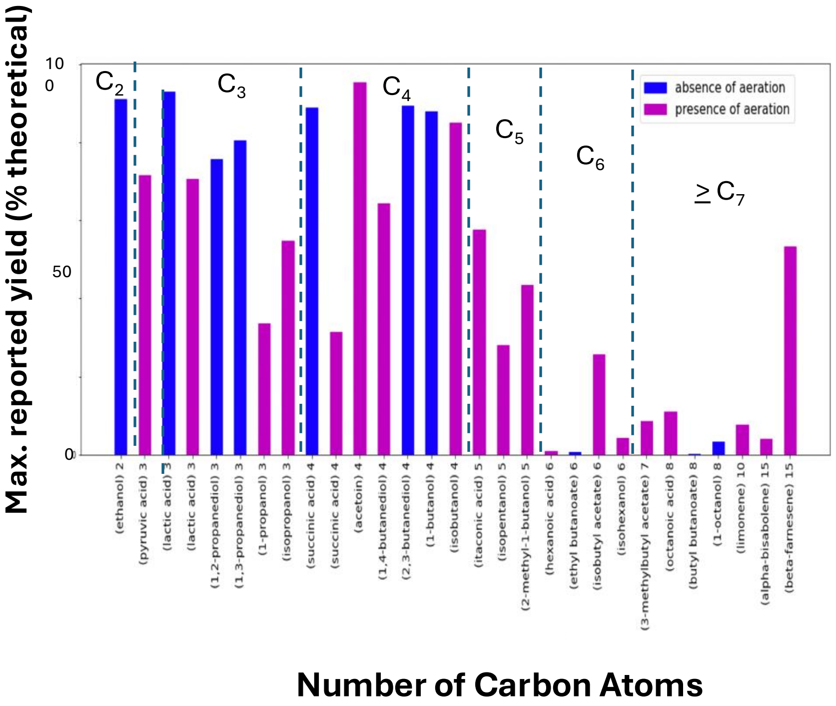
Bob McCormick, Fuel utilization

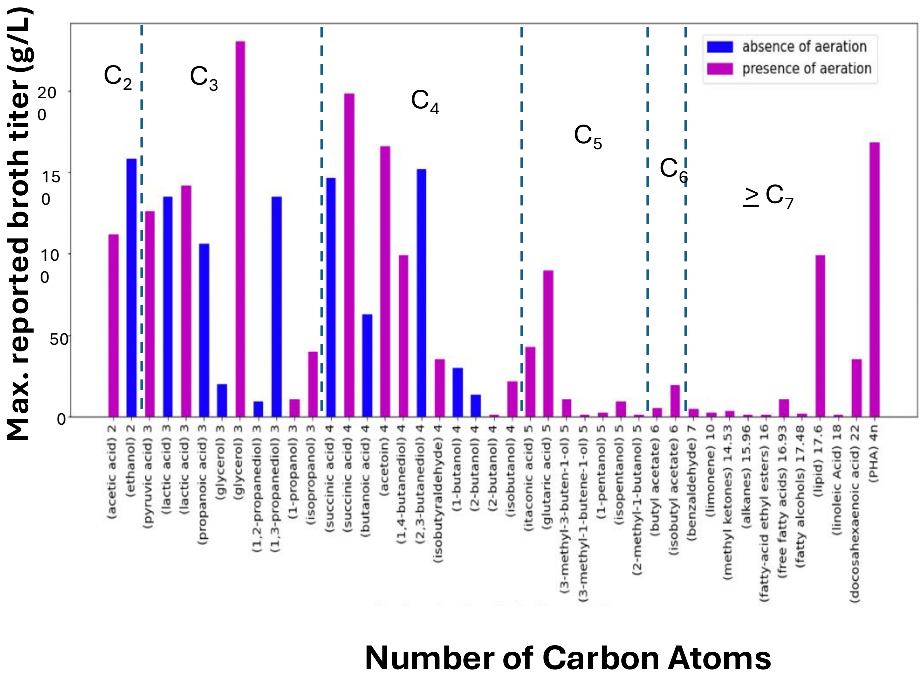
Gregg, Yuriy Roman, Catalytic processing

Key strategic points

- Small biomolecules are inherently less expensive to produce than large molecules, especially from lignocellulose.
- There are alternative processing paradigms with potential to produce low molecular weight fuels or fuel precursors at much lower cost than the thermochemical pretreatment/fungal cellulase paradigm
- Catalytic conversion of low molecular weight intermediates, notably ethanol, to hydrocarbon fuels is a promising approach to bridge the gap between the fuel molecules that are most readily produced biologically and those that the world would most value from biomass.

Potential Products of Biological Lignocellulose Conversion





Seven anaerobic products are more reduced than glucose, and have at least one of the following desired features:

- Reported yield > 75% theoretical
- Reported titers > 40 g/L
- Boiling point < water

All of these products have ≤ 4 carbons

Small biomolecules are less expensive to produce biologically than large molecules

Especially anaerobically

Especially from lignocellulose

Lynd, Beckham et al., Energy & Env. Sci., 2022.

Potential Products of Biological Lignocellulose Conversion

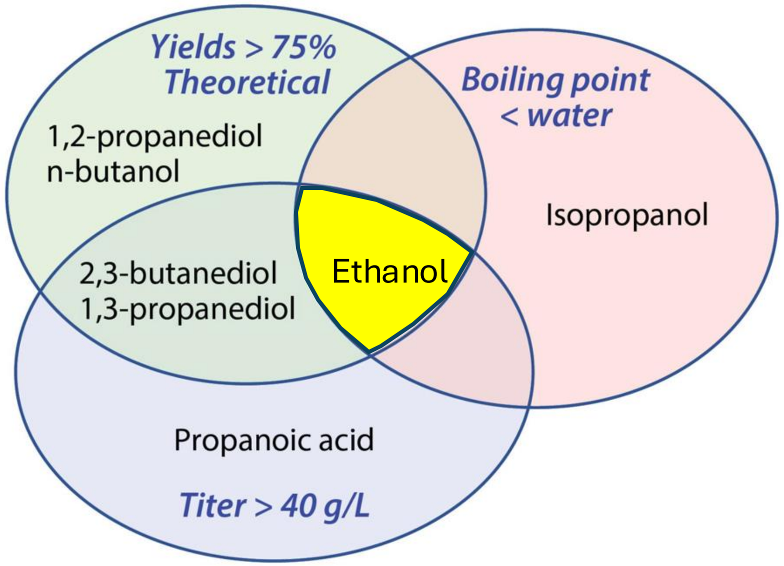
Seven anaerobic products are more reduced than glucose, and have at least one of the following desired features:

- Reported yield > 75% theoretical
- Reported titers > 40 g/L
- Boiling point < water

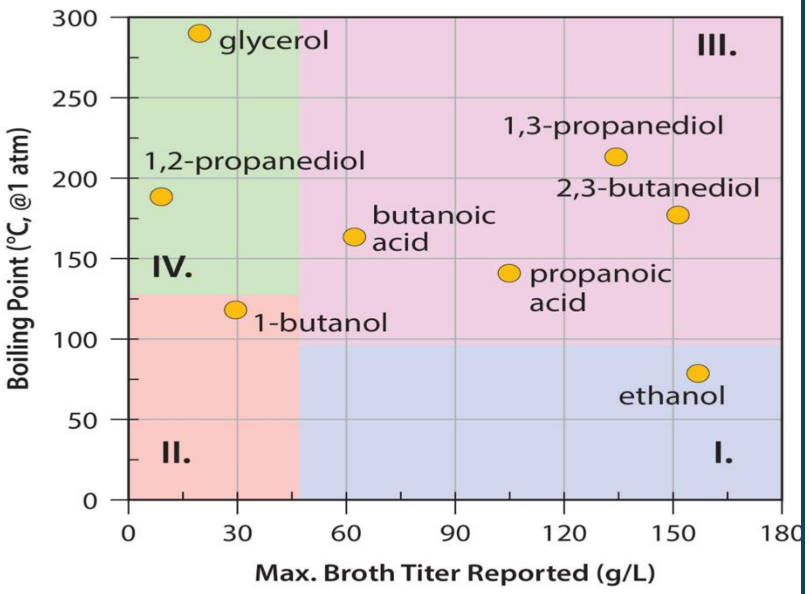
All of these products have ≤ 4 carbons

Ethanol

The only product that has all three properties



In a class by itself for easy product recovery



Ethanol occupies a singular space in the bioproduct landscape, is the lowest cost liquid fuel or fuel intermediate produced biologically today, and is in our view likely to remain so.

Lynd, Beckham et al., Energy & Env. Sci., 2022.

A Key Dilemma

Small molecules are less expensive to produce biologically than large molecules

Yet the fuel molecules that the world would most value obtaining from lignocellulose are large – needed for aviation and heavy-duty transport

Hybrid processing is a promising path to resolution

1. Fermentation ***2. Catalytic Upgrading***

Lignocellulose → Small molecules (e.g., ethanol) → Hydrocarbon Fuels

Technology for Converting Ethanol to Hydrocarbons is Rapidly Being Developed

1 Fermentation | *2. Catalytic Upgrading*

Lignocellulose → Ethanol, Perhaps other small moleculs → Hydrocarbon Fuels

- Many companies (Gevo, Honeywell, SAFFIRE, Lanzajet, Neste, Vertimass, World Energy);
50 off-take agreements in last 2 years

- For SAF from lignocellulose, biological production of ethanol followed by upgrading to hydrocarbons is among the most promising routes and low-cost, scalable, cellulosic ethanol is the key missing piece.
James Bielenberg, Exxon

Honeywell

Honeywell Revolutionizes Ethanol-To-Jet Fuel Technology to Meet Rising Demand for Sustainable Aviation Fuel

- Honeywell's new solution represents critical development in global drive to meet 2030 sustainable aviation fuel (SAF) mandates
- Provides a cost-effective path for producing lower greenhouse gas emission (GHG) jet fuel from ethanol

Gevo discusses plans for ethanol-to-SAF production

By Erin Voegele | March 01, 2022

Patrick Gruber, CEO of Gevo Inc., provided an update of the company's plans to produce sustainable aviation fuel (SAF) and other renewable hydrocarbons from ethanol during a fourth quarter earnings call held Feb. 24.

Keeps Getting' Better, Part 2 - Project Eyes Using Ethanol To Make Bioethylene, Renewable Alkylate, SAF

Tuesday, 10/11/2022 Published by: Housley Carr

...in Pasadena, TX ...Next Wave Energy Partners...is now completing an ethylene-to- ... ethanol- ... company ... ylate ... depending

BUILDING EUROPE'S FIRST OF ITS KIND ALCOHOL-TO-JET PRODUCTION PLANT

Building Europe's first of its kind Alcohol-to-Jet production plant

Sustainable aviation fuel produced from waste-based ethanol resources

The FLITE consortium, led by SkyNRG and with LanzaTech as the technology provider, will build the first-of-its-kind LanzaJet™ Alcohol to Jet (AtJ) facility. The facility will convert waste-based ethanol to sustainable aviation fuel (SAF) at a scale of over 30,000 tons/yr. The project received €20 million in grant funding from the EU H2020 programme and is a major milestone on the path to a net-zero emission for the aviation industry.

Technoeconomic and life-cycle analysis of single-step catalytic conversion of wet ethanol into fungible fuel blendstocks

John R. Hannon[a], Lee R. Lynd[b,c,1], Onofre Andrade[d], Pahola Thathiana Benavides[e], Gregg T. Beckham[b,f], Mary J. Biddy[b,f], Nathan Brown[g], Mateus F. Chagas[h], Brian H. Davison[b,i], Thomas Foust[f], Tassia L. Junqueira[h], Mark S. Laser[c], Zhenglong Li[i], Tom Richard[j], Ling Tao[f], Gerald A. Tuskan[b,i], Michael Wang[e], Jeremy Woods[k], and Charles E. Wyman[a,b,l]

Proceedings of the National Academy of Science. 117:12576-12583 (2019).

"Life-cycle greenhouse gas emission reductions for CADO-derived hydrocarbon blendstocks closely follow those for the ethanol feedstock."

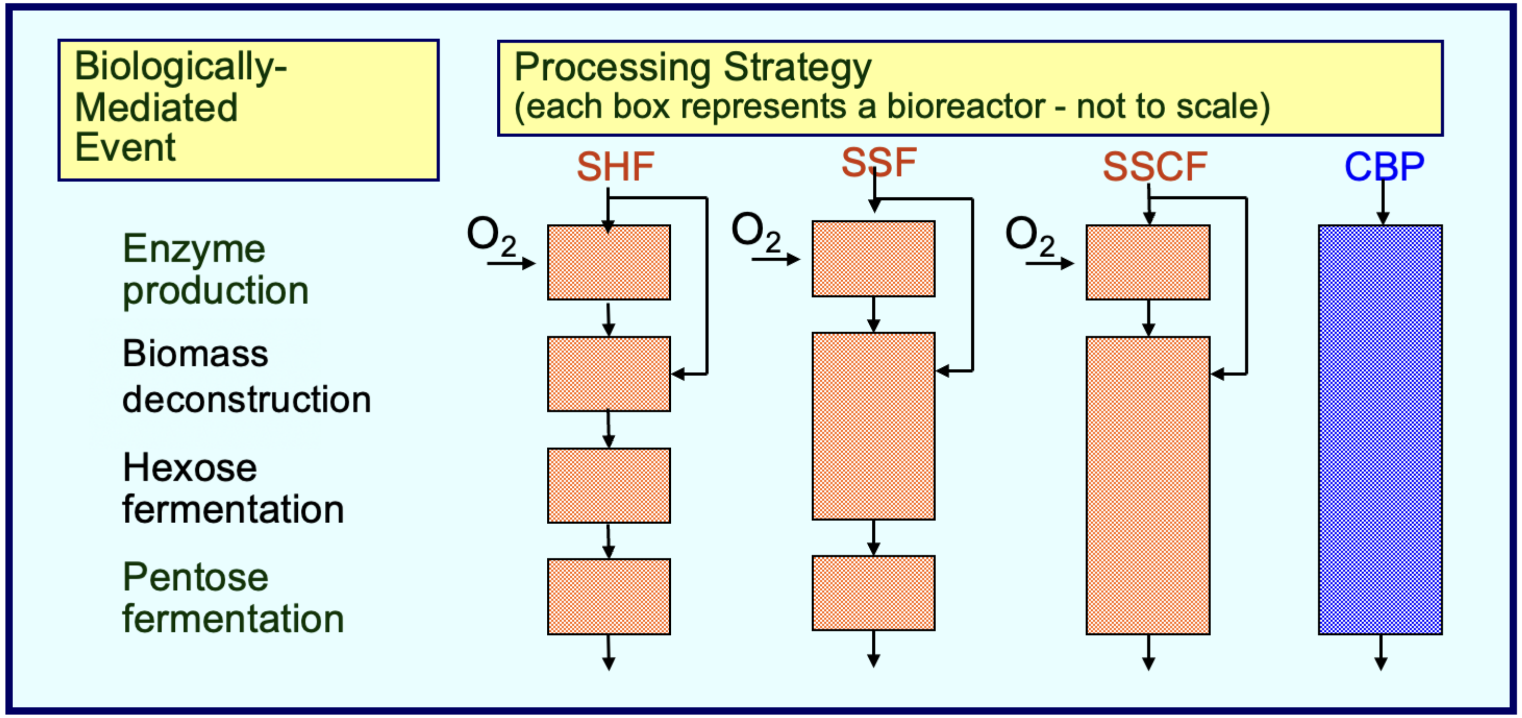
Table 2. GHG emissions for production of jet fuel by application of CADO to ethanol made from starch, sugar, cane cellulosic material, and corn stover and by conventional production from petroleum

		From ethanol				From petroleum	
		Emission (gCO_2 e/MJ of fungible blendstock)					
Ethanol feedstock	Conversion technology	Feedstock production and ethanol conversion	Catalytic conversion of ethanol	Jet fuel use	WTWa*	PTWa	WTWa
First generation						73.2	87.3
Corn starch†	Current	45.5	6.7	0.2	52.4 −40.0%		
Cane sugar‡	Current	23.8	3.2	0.2	27.2 −68.8%		
Second generation							
Cane cellulosic‡,§	Current	14.5	3.2	0.2	17.9 −79.5%		
Cane cellulosic‡,§	Projected	13.9	3.2	0.2	17.3 −80.2%		
Corn stover¶	Current	23.2	3.2	0.2	26.6 −69.5%		
Corn stover¶	Projected	0.13	3.2	0.2	3.53 −96.0%		

GHG emissions of ethanol upgrading < 10%, in most cases < 5%, of fossil fuel base case.

Some directions I am excited about

Consolidated bioprocessing (CBP). One-step biological conversion of lignocellulose without added enzymes, .



Modified from Lynd et al., MMBR, 2002.

SHF: Separate Hydrolysis and Fermentation

SSF: Simultaneous Saccharification and Fermentation

SSCF: Simultaneous Saccharification and Cofermentation

CBP: Consolidated Bioprocessing

Motivations to consolidate process steps

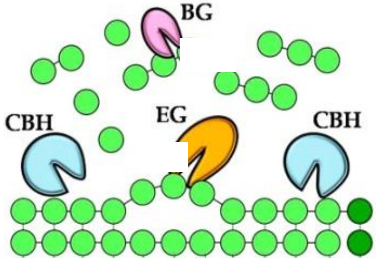
- Lower CapEx, OpEx
- Biomass deconstruction more effective by live microbes than added enzymes (enzyme-microbe synergy)

What are nature's best biocatalysts at lignocellulose deconstruction?

Many options, molecular architectures, and model systems

Lots of interesting science

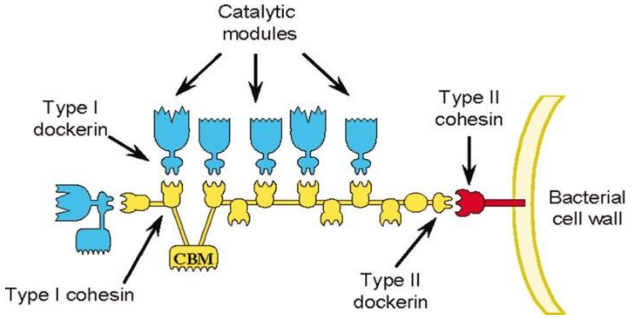
Non-complexed – e.g. *T. reesei*



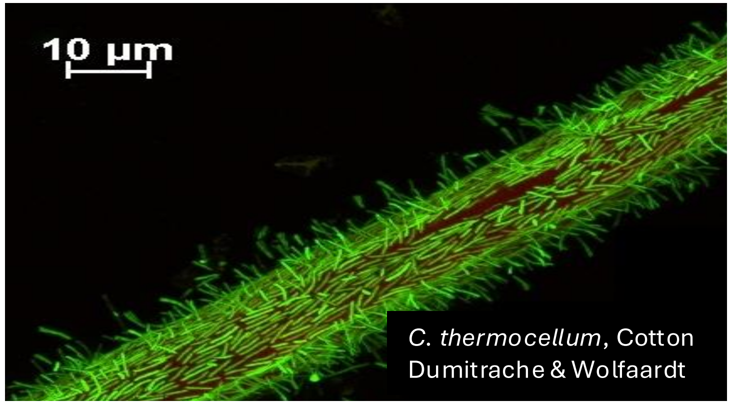
Ratanakhanokchai et al. in "Biomass now- Cultivation and Utilization"2013
http://www.intechopen.com/books/biomass-now-cultivation-and-utilization

Yeast SSF (added cellulase, not shown)
Dumitrache & Wofaardt

Complexed – e.g. *Clostridium thermocellum*



Modified from Carvalho *et al.*, 2003 PNAS



C. thermocellum, Cotton
Dumitrache & Wolfaardt

Foundational question that could have been asked a long time ago but was not asked

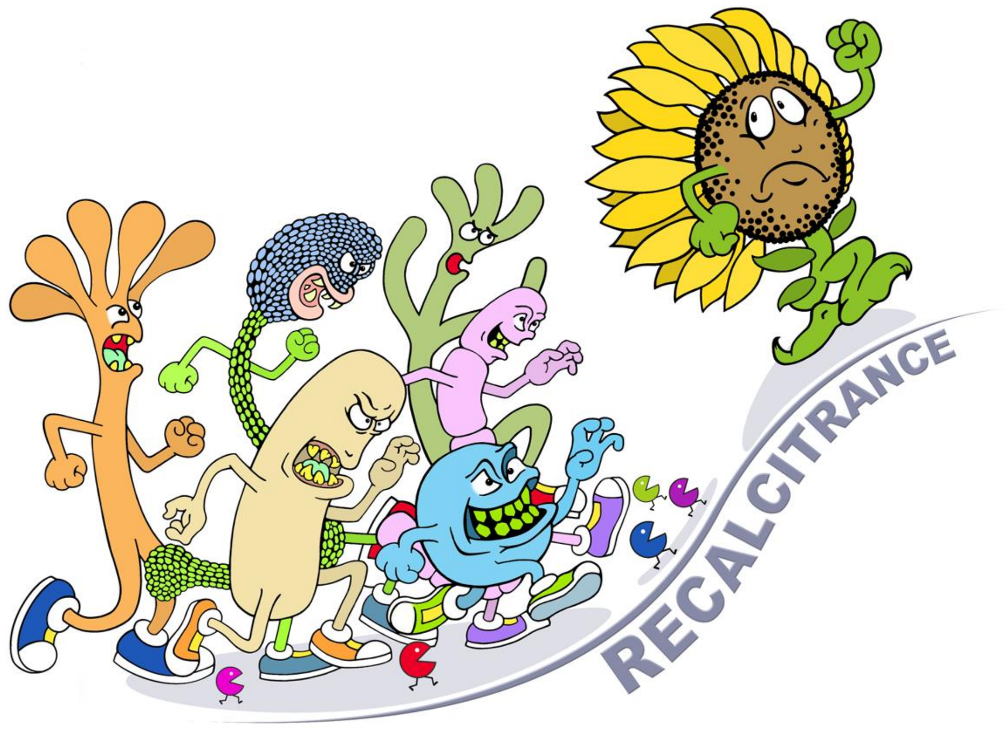
- Valid comparisons technically nuanced
- Never easy to get funding for
- Risk of making more enemies than friends

Feedstock Recalcitrance

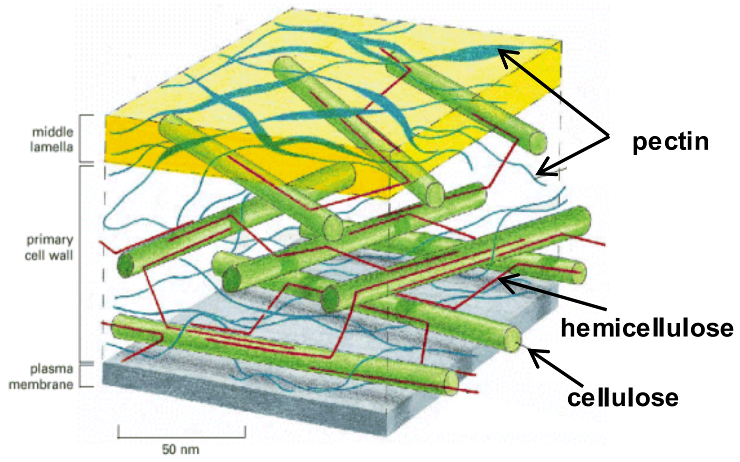
The Central Challenge of Processing Cellulosic Biomass

What: Difficulty of converting cellulosic biomass into reactive intermediates (Lynd *et al.*, *Biotechnol Prog.*, ‘99).

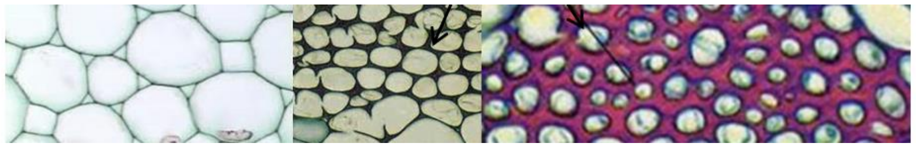
Plant cell walls have evolved over more than a billions years to withstand environmental and microbial assault.



The recalcitrance barrier is manifested in the high cost of thermochemical pretreatment and added enzymes.



(Alberts *et al.*, 2002, *Molecular Biology of the Cell 4th ed.*)



Parenchyma Collenchyma Sclerenchyma

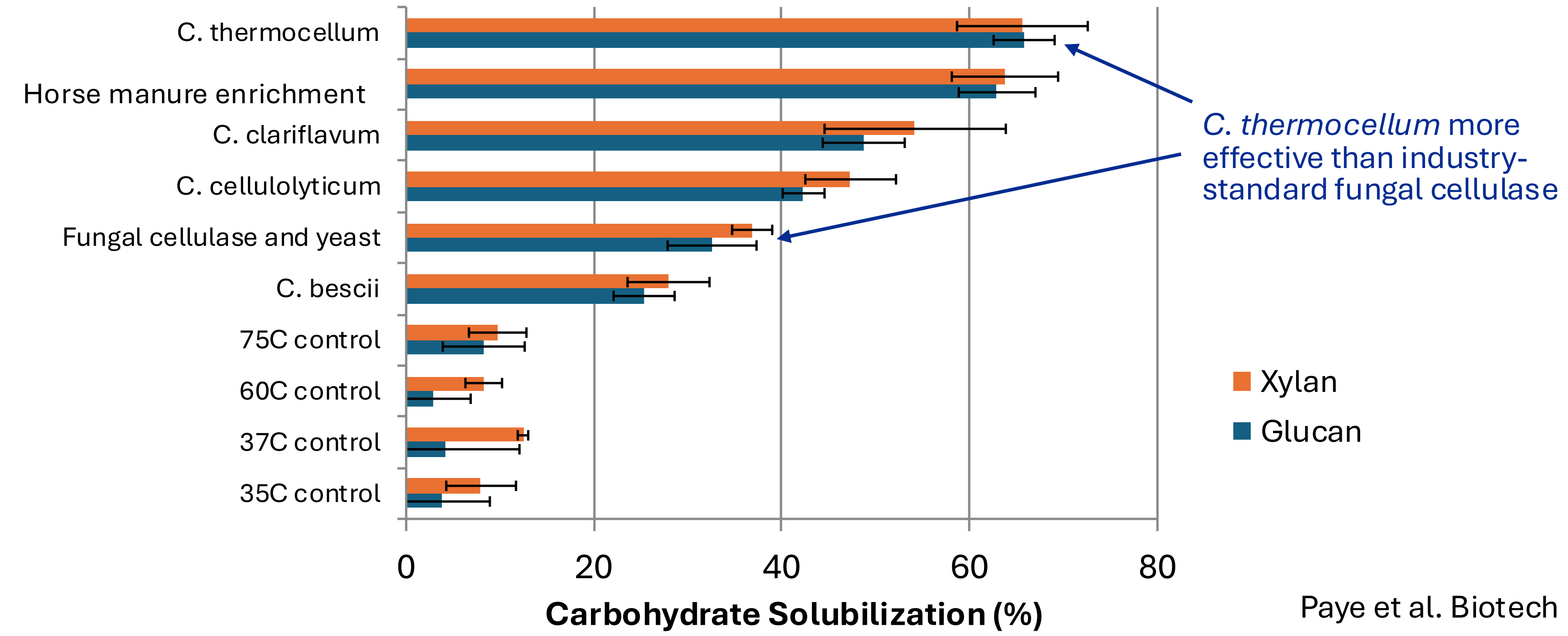
Lignification →

http://biologyintro2life.blogspot.com/2010/08/multicellular-organization-plants_18.html

What biocatalysts are most effective at lignocellulose deconstruction?

Initial exploration

Mid-season washed switchgrass, no pretreatment other than autoclaving



Paye et al. Biotech Biofuels. 2016

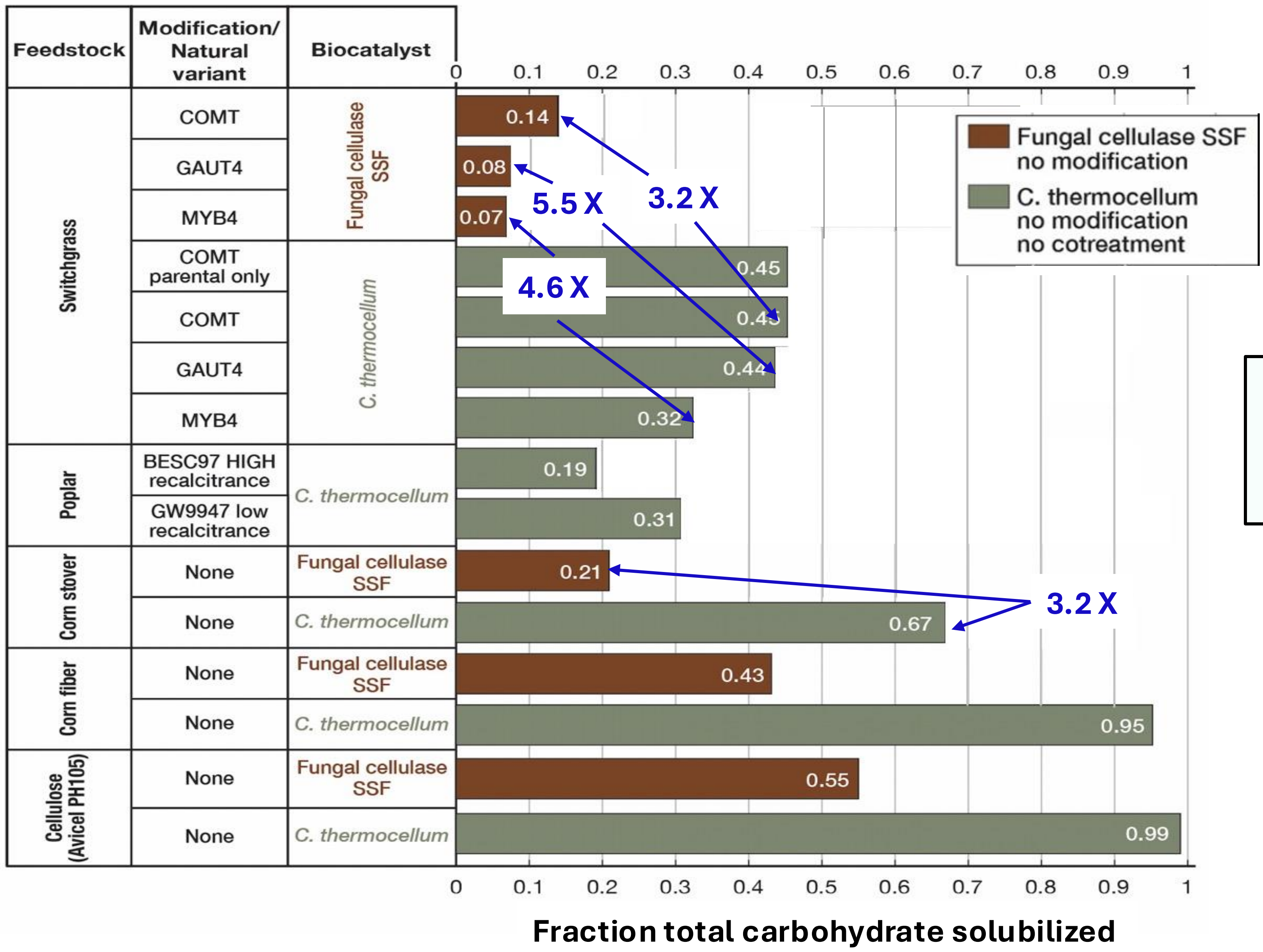
Extensive comparative studies undertaken subsequently[1,2,3,4]

- 5 different feedstocks
- > 10-fold range of catalyst loadings
- 10-fold range of substrate loadings
- > 10-fold range of particle size
- Presence or absence of yeast (SSF)
- Fungal cellulase incubation temp.

[1] Paye et al. Biotech Biofuels. 2016; [2]Shao et al., Biotech Biofuels. 2015.
[3] Lynd et al., Industrial Microorganisms. 2017; [4]Holwerda et al., Biotech Biofuels. 2019.

Results validated and cross-checked with several prominent labs.

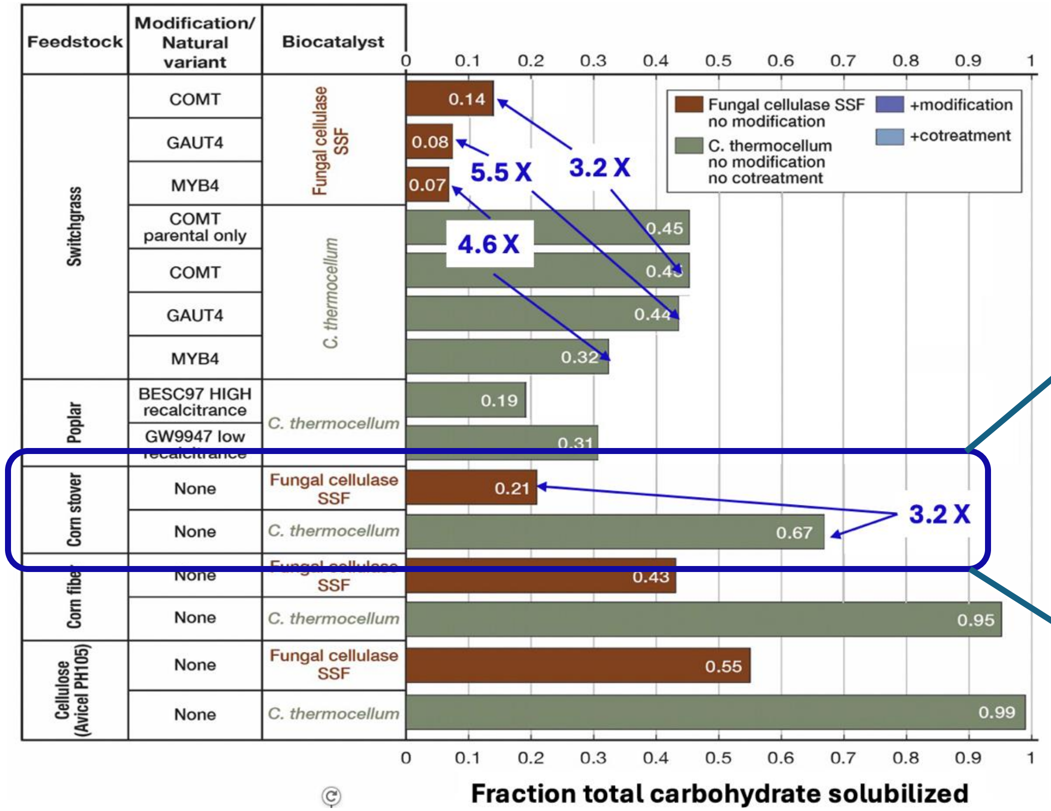
What biocatalysts are most effective at lignocellulose deconstruction?



C. thermocellum ~ 3- to 5-fold more effective than industry-standard fungal cellulase at lignocellulose deconstruction - no pretreatment other than autoclaving

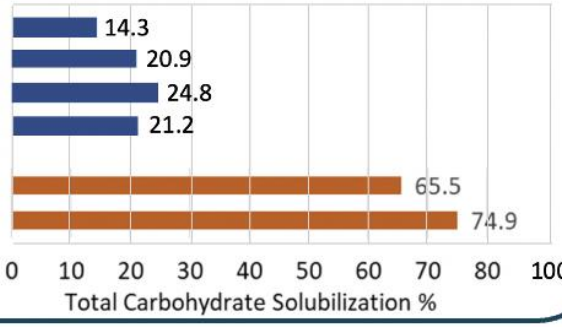
Modified from Lynd, Beckham et al., Energy & Env. Sci., 2022.

What biocatalysts are most effective at lignocellulose deconstruction?



Corn stover literature comparison

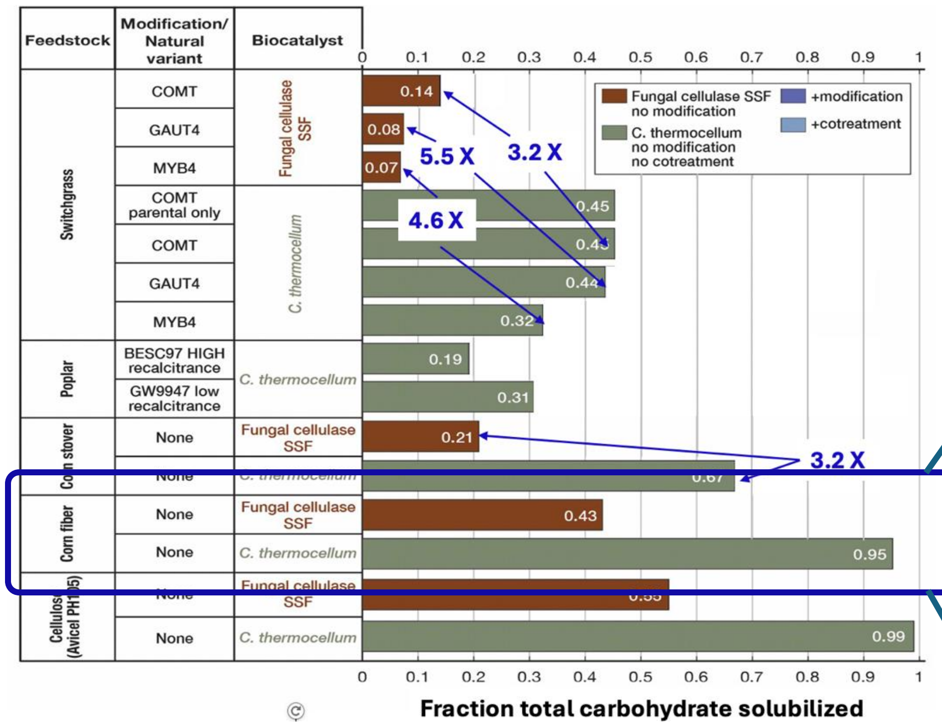
System	Source	Added Cellulase
Commercial fungal cellulase *(supplemented with β-glucosidase)*		
Genencor Spezyme CP	Kim and Lee, 2005	10 PFU/g glucan
		60 FPU/g glucan
	Teymouri et al., 2007	15 FPU/g glucan
Novozymes Ctec2	Lynd et al., 2016	5 mg/g solids
Thermophilic anaerobic cultures		
C. thermocellum	Kubis et al., 2022	None
Cococulture**	Kubis et al., 2022	None



* Supplemented with β-glucosidase.

** *C. thermocellum* and *T. thermosaccharolyticum*

What biocatalysts are most effective at lignocellulose deconstruction?



Corn fiber literature comparison

Table 1 Solubilization of corn fiber by various biocatalysts.

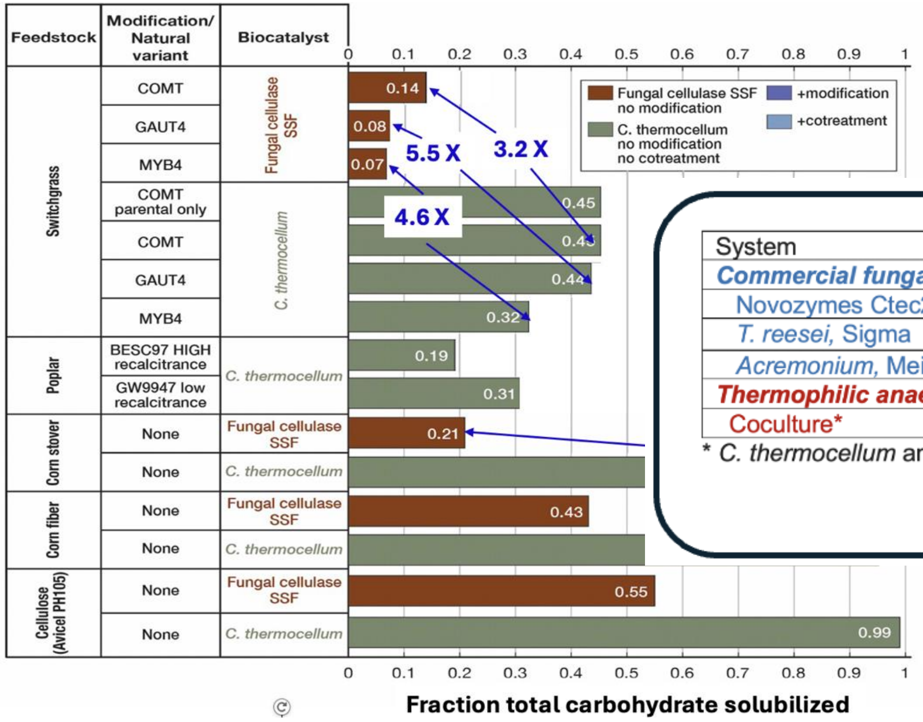
Biocatalyst	Corn fiber type	Solids loading (g/L)	% carbohydrate solubilization
None	DCB	10	10%[a]
CTEC2 (5 mg/g)	DCB	10	20 ± 2%
CTEC2 (20 mg/g)	DCB	10	23 ± 1%
C. thermocellum	DCB	10	95 ± 2%
C. thermocellum	WMCF	20	[b]91%
C. thermocellum + *T. saccharolyticum*	WMCF	10	96 ± 3%
C. thermocellum + *T. saccharolyticum*	WMCF	20	92 ± 2%

All the incubations were carried out for 5 days. [a]Denotes *n* = 2. [b]Denotes *n* = 1. For all other values, *n* = 3. Source data are provided as a Source Data file.

DCB: Destarched corn bran
WMCF: Wet milled corn fiber

Beri et al., Nature Comm, 2020.

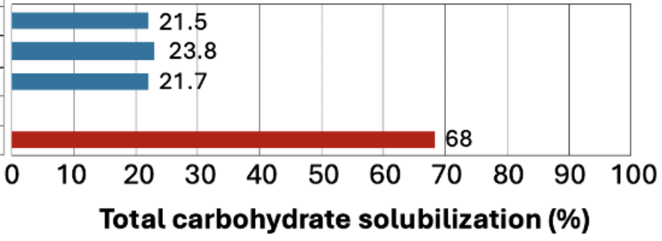
What biocatalysts are most effective at lignocellulose deconstruction?



Bagasse literature comparison

System	Source	Added Cellulase
Commercial fungal cellulase		
Novozymes Ctec2	Brar et al., 2020	6.6 mg/g solids + xylanase
T. reesei, Sigma	M. da Silva et al., 2015	15 FPU/g solids + β-glucosidase
Acremonium, Meiji Seika	A. da Silva et al., 2010	15 FPU/g solids
Thermophilic anaerobic bacteria		
Coculture*	Zambello et al., 2024	None

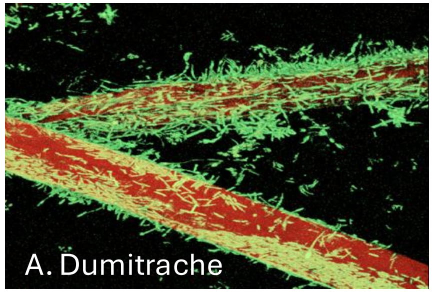
* *C. thermocellum* and *T. thermosaccharolyticum*



Nature offers biocatalysts that are substantially better at biomass deconstruction than the commercial fungal cellulase preparations tested

Toward understanding the effectiveness of *C. thermocellum*

Intimate association between cells and substrate



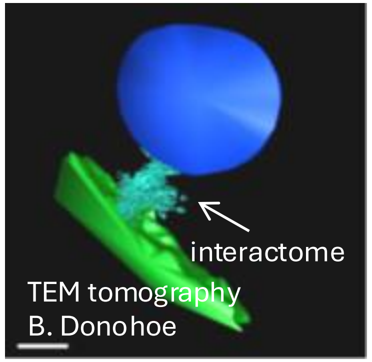
Primary catalytic entity: cellulose-enzyme-microbe complex

Quantitative evidence for enzyme-microbe synergy*

Local physical chemistry impacted by cell surface

Selective pressure for surface occupation, product uptake

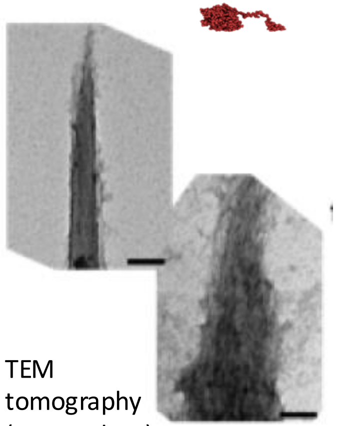
*(Lu et al., PNAS, 2006)



Non complexed cellulases

T. reesei Cel7A

Free enzymes



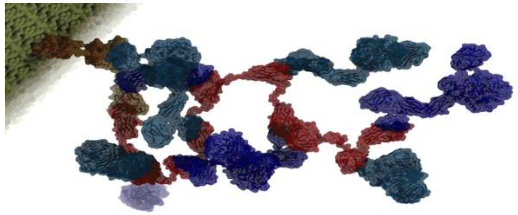
TEM tomography (B. Donohoe)

"Sharpening" from end-specific surface ablative action

***Brunecky et al. Science* 342, 1513-16 (2013)**

Access by virtue of small size

C. thermocellum cellulosome

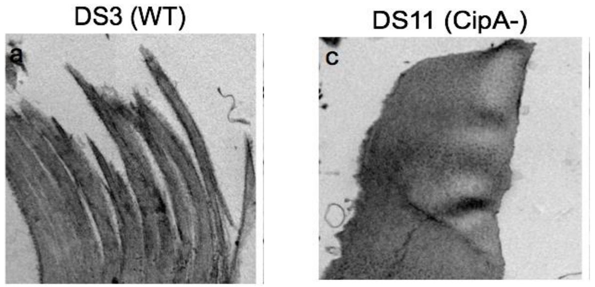


Free enzymes

Cell- tethered cellulosomes

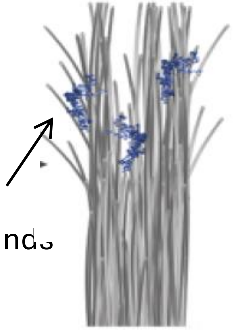
Untethered cellulosomes

Xu et al. Sci. Adv. 2016



TEM tomography (B. Donohoe)

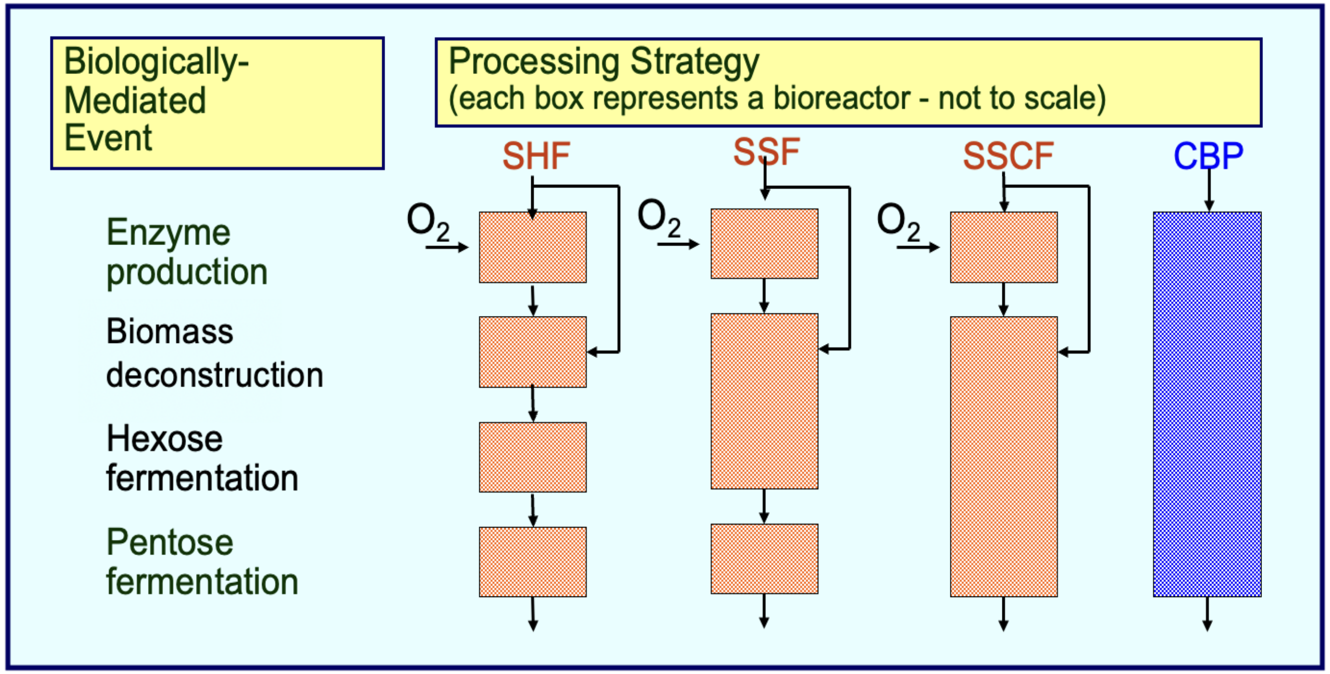
Splaying of microfibril ends



Access by unravelling cellulose bundles

Consolidated Bioprocessing (CBP)

One-step biological processing without added enzymes



Modified from Lynd et al., MMBR, 2002.

SHF: Separate Hydrolysis and Fermentation

SSF: Simultaneous Saccharification and Fermentation

SSCF: Simultaneous Saccharification and Cofermentation

CBP: Consolidated Bioprocessing

How best can biological deconstruction of cellulosic biomass be augmented?

The biofuel field's answer for the last 40 years: Thermochemical pretreatment

Nature's answer


Bioresource Technology 100 (2009) 5323–5331

Contents lists available at ScienceDirect

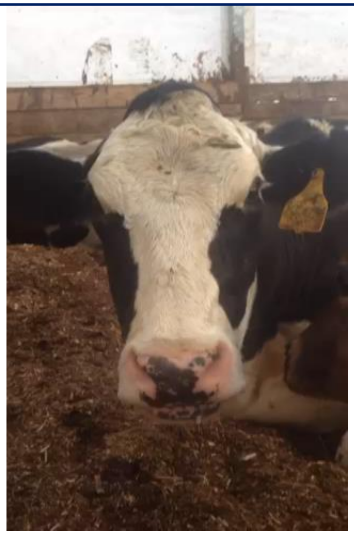
Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

ELSEVIER

Lessons from the cow: What the ruminant animal can teach us about consolidated bioprocessing of cellulosic biomass

Paul J. Weimer[a,b,*], James B. Russell[a,c], Richard E. Muck[a,d]



Rumination increases forage particle surface area up to 10^4-fold

Requires ~ 2% of metabolizable energy

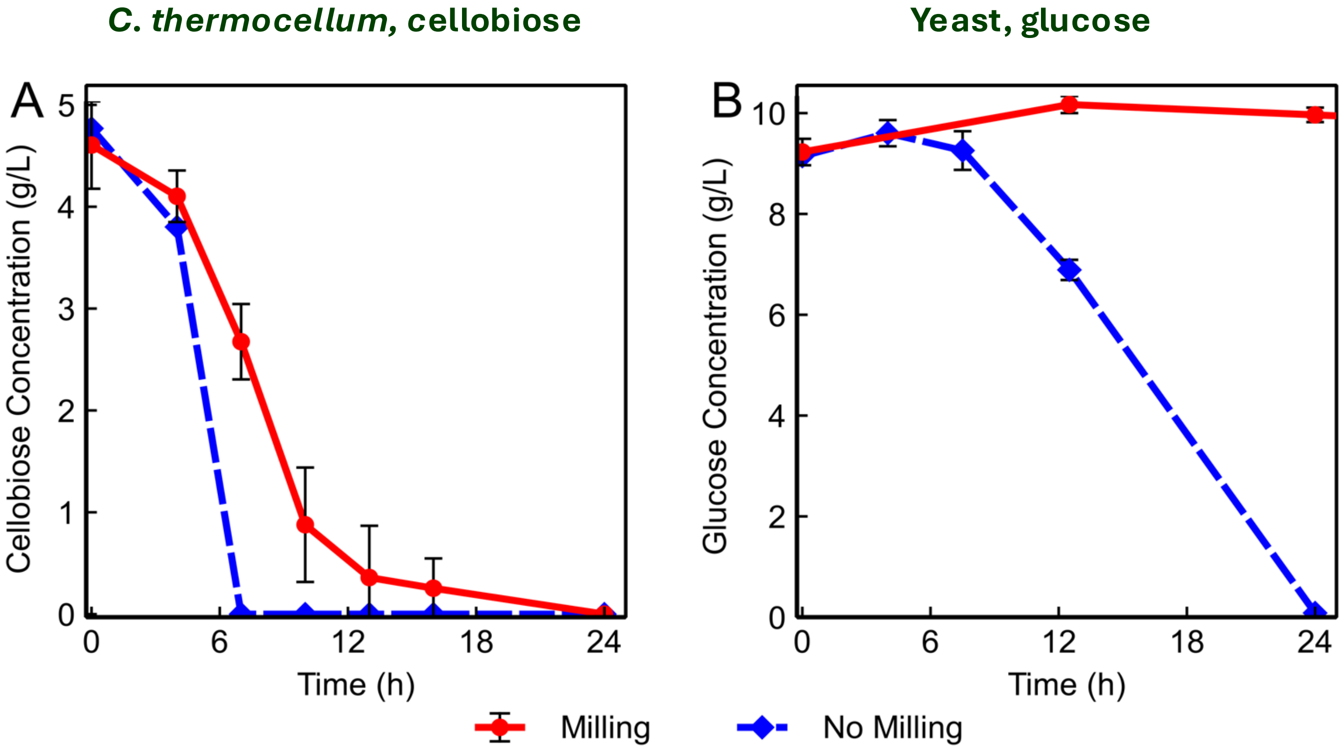
Rethinking biological deconstruction & biocatalysts invites rethinking augmentation strategy

	Chemical Inhibition	Mechanical Disruption
Yeast	Among the most resistant cellular life forms	Sensitive
Cellulolytic anaerobes (Gram positive)	Sensitive	Among the most resistant cellular life forms

Cotreatment: Mechanical feedstock disruption *during* fermentation in lieu of thermochemical disruption *before* biological processing

How best can biological deconstruction of cellulosic biomass be augmented?

Model (not industrial) system to investigate impact of milling on microbial fermentation & biomass solubilization: **Ball mill fermentor**

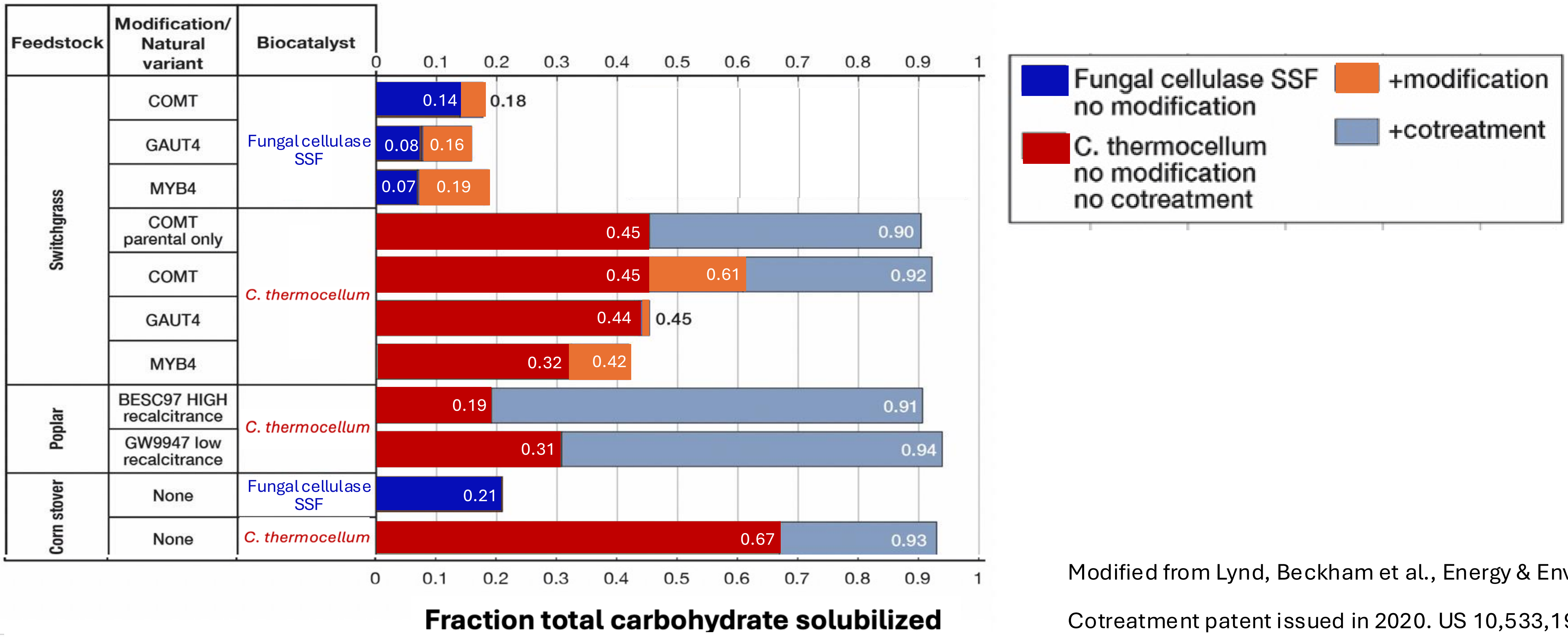


C. thermocellum fermentation readily proceeds with aggressive milling

Yeast fermentation does not

Balch et al., EES, 2017

Mechanical disruption during fermentation (Cotreatment) allows near-complete solubilization without thermochemical pretreatment



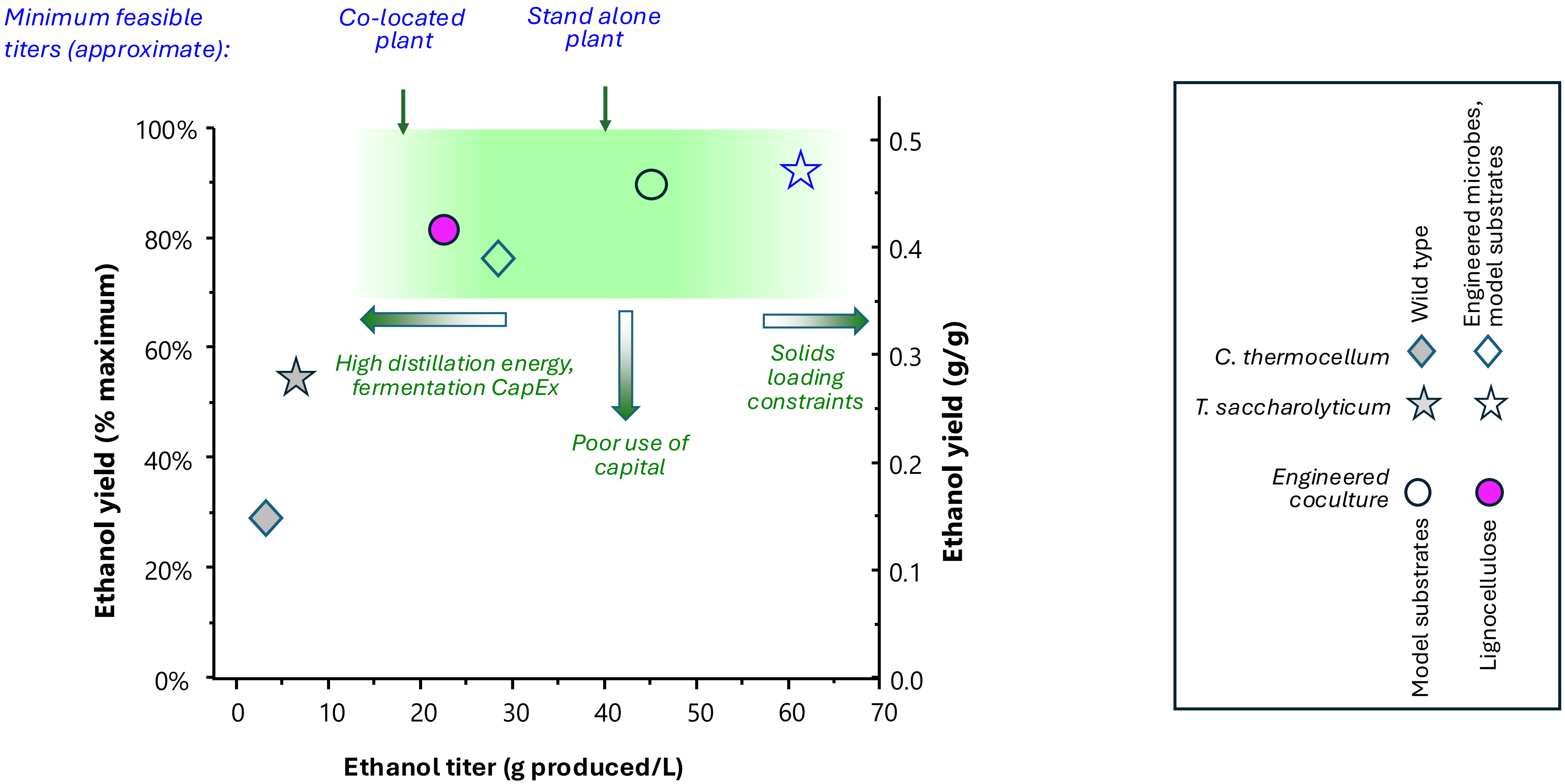
Modified from Lynd, Beckham et al., Energy & Env. Sci., 2022.

Cotreatment patent issued in 2020. US 10,533,194.

Implies barrier to solubilization is physical not chemical

Modified feedstocks → much smaller impact than milling

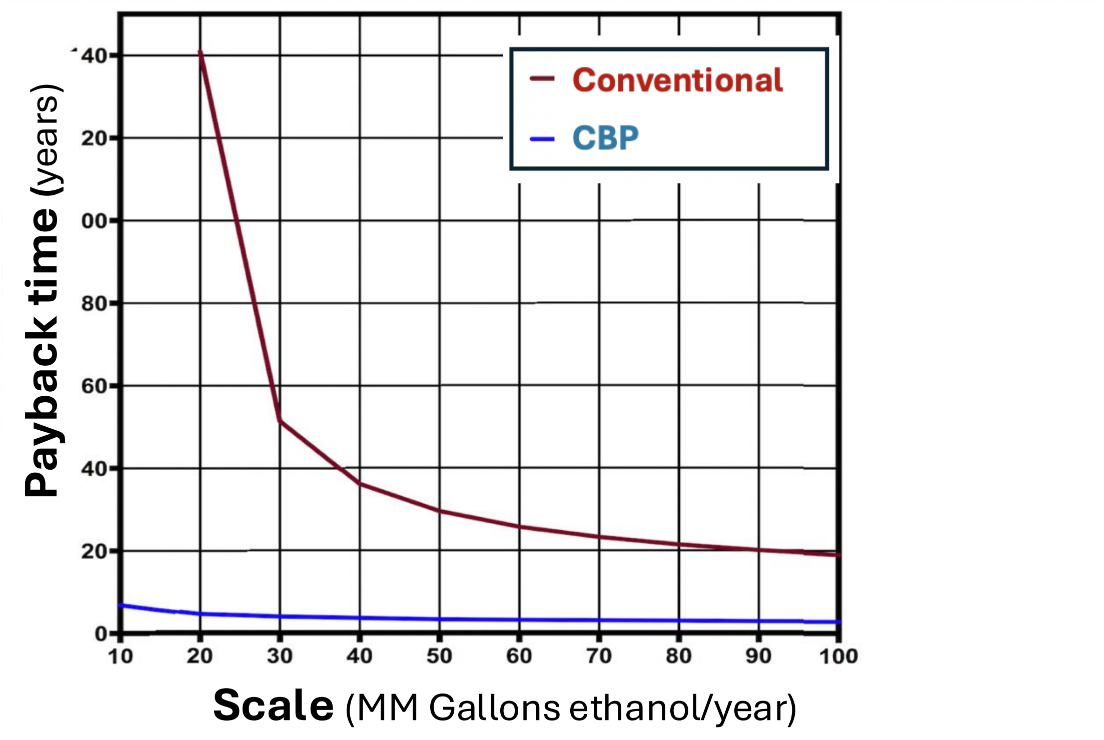
Strain development progress



* Co-location of a small CBP plant processing stillage or lignocellulose at a large 1G host plant incurs a negligeable distillation OpEx penalty. Details available upon request.

Long-Term TEA for Corn Stover to Ethanol via CBP

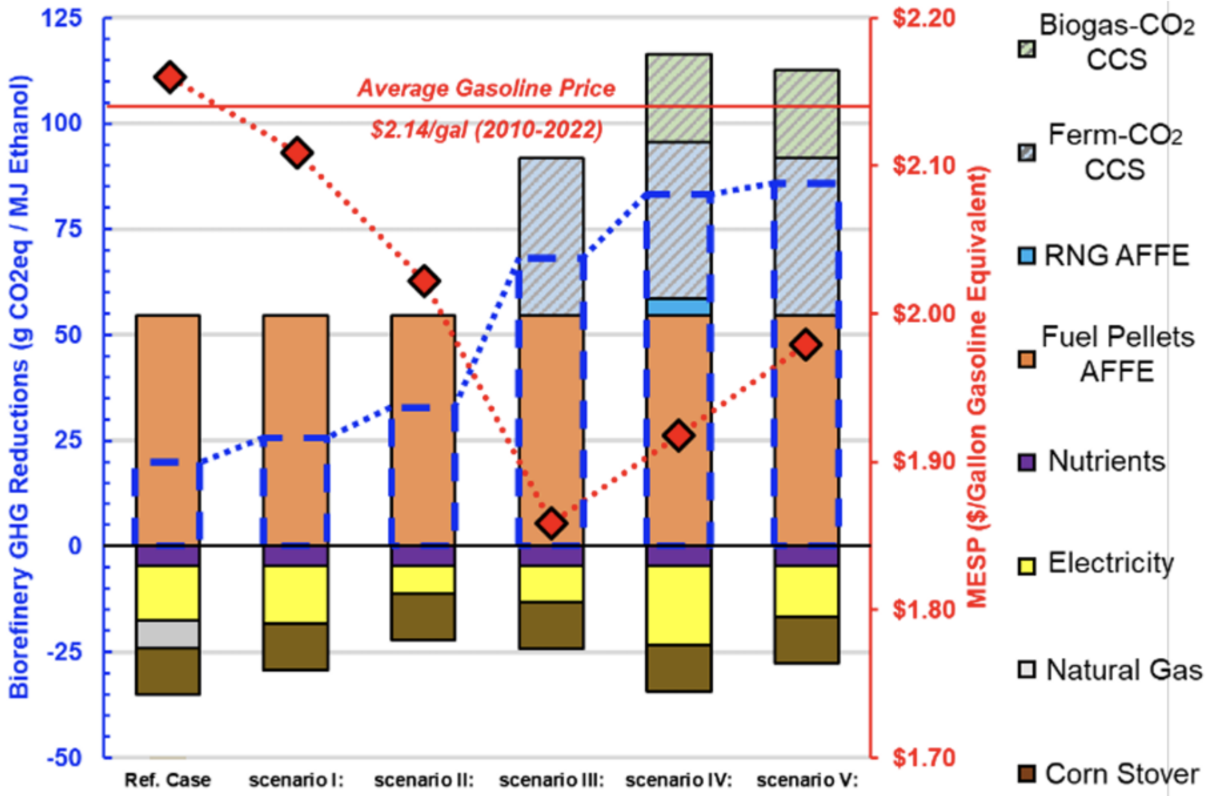
With cotreatment, no pretreatment or added enzymes



Compared to conventional paradigm specified by NREL coauthors

- 8-fold shorter payback time (CapEx/annual profit)
- Economic feasibility at 10-X smaller scale

Lynd et al, Current Opinions in Biotechnology, 2017



Process modifications that increase negative GHG emissions

Cost competitive with gasoline @ recent prices

Process modifications that increase CO_2 recovery improve economics

Kubis and Lynd, Sustainable Energy & Fuels, 2023

terragia

Incorporated: October 2022

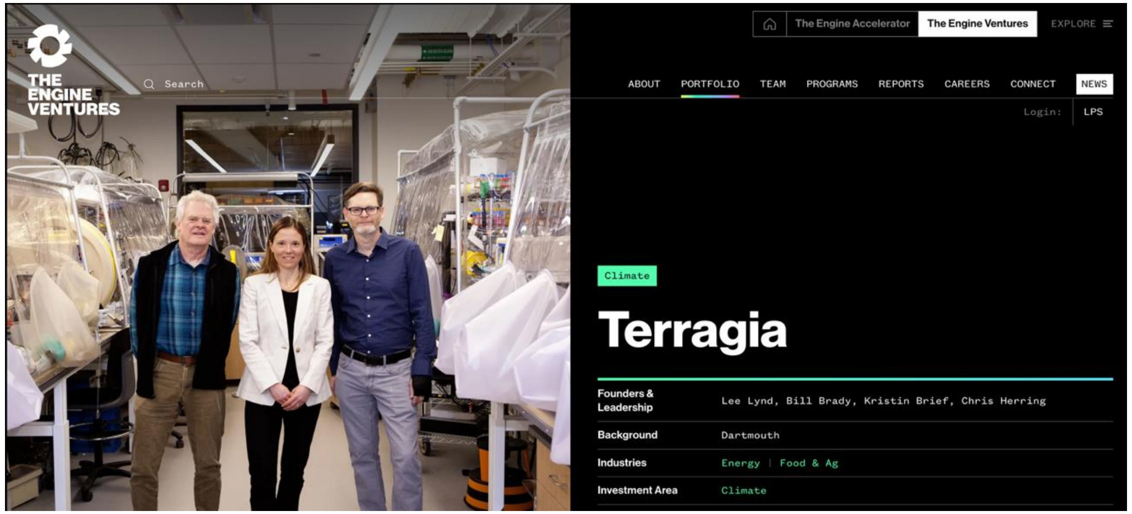
JDA with a major US biofuel producer. January 2024

$6 million seed funding from VCs. March 2024

24 Employees

IP Agreements with Dartmouth & Unicamp

Technology, business strategy different from cellulosic biofuels 1.0



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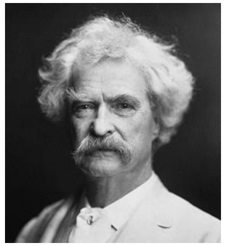
Terragia Secures $6M to Develop Cost-Competitive, Low-Carbon Biofuel Technology

March 28, 2024 12:00 PM Eastern Daylight Time

HANOVER, N.H.--(BUSINESS WIRE)--Terragia Biofuel, a technology startup aiming to drive the next generation of biofuels, today announced it has raised a $6 million seed round led by Engine Ventures and Energy Impact Partners (EIP). The company will use the capital to commercialize its novel biology-based approach to converting cellulosic biomass into ethanol and other products, expand its employee headcount and initiate partnerships with major biofuel producers.

"Terragia has an opportunity to succeed where others in the cellulosic biofuel industry have not. The company's technology provides a radically different approach that uses biology to reduce the high costs and scale of conventional cellulosic biofuel production."

It ain't what you don't know that gets you in trouble.
It's what you know for sure that just ain't so.



Common biofuel claims	Contrary observations
We can do without biofuels	• Large biomass role in low-C scenarios • Fermentation → lowest cost CO_2 removal option • About half of transport energy difficult to electrify
Better options for BECCS	• Total mitigation per ton feedstock can be comparable to electricity, H_2
Impractically large land requirements	• Widespread agreement that at least 100 EJ biomass available for energy • Large potential for pasture intensification, crop residues • Global geographic potential of agave 600 EJ, ~ equal to energy use of humanity, all sectors
Flawed climate change mitigation logic	• Key arguments rebutted (iLUC, carbon debt, opportunity cost)
Unfavorable energy balance	• Zero fossil process inputs for sugarcane, bagasse, corn ethanol today (Brazil)
Inevitably compete with food	• Strong potential for cellulosic biofuels to benefit food & feed production
Using crop residues → loss of soil C	• Not so for AD if process residues returned to the field • Likely also the case for liquid cellulosic biofuels
Corn ethanol unsustainable	• Current practice in Brazil offers outstanding sustainability benefits • US industry CI decreasing in response to incentivizes
Ethanol is passe	• Lowest cost biologically-derived fuel molecule today, likely always • Promising intermediate for SAF, other difficult-to-electrify transport modes
Cellulosic biofuels too expensive	• $/GJ feedstock purchase price less than petroleum • Commercial plants being replicated now (Brazil) • Documented potential to be cost competitive with gasoline
Cellulosic business case not promising	• Terragia, investors and partners aim to show otherwise

Feeding the bioeconomy
UK biomass availability

Adrian Higson, Director & Principal Consultant

BBNet Conference 2025

Alder BioInsights

Thirteen years ago

2 November 2012

Dear Adrian

CONTRACT R2-B3-10 – INDUSTRIAL ENGAGEMENT COORDINATOR FOR THE IBTI CLUB

AMENDMENT

The RCUK SSC Ltd, on behalf of the Biotechnology & Biological Sciences Research Council ('BBSRC') wishes to amend the above Contract to include a scope of services for the support for the BBSRC Networks in Industrial Biotechnology & Bioenergy (NIBB) Call.

The scope of services is as per your proposal dated 19th October 2012. The additional cost of this

25 Jan 2013

The Biotechnology and Biological Sciences Research Council, in association with the Engineering and Physical Sciences Research Council, the Technology Strategy Board and the BioKTN, CIKTN and HealthKTN, invites applications for its networks in industrial biotechnology and bioenergy (NIBB).

Alder BioInsights

Bioenergy | Biofuel | Biorefining | Bio-based Products | Feedstocks

A specialist strategic business consultancy with over 20 years of bioeconomy experience

Business Planning

Collaborative Research

Feedstock Supply & Sustainability

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Market Analysis & Strategy

Policy & Strategy

Regulations & Compliance

Investment Support

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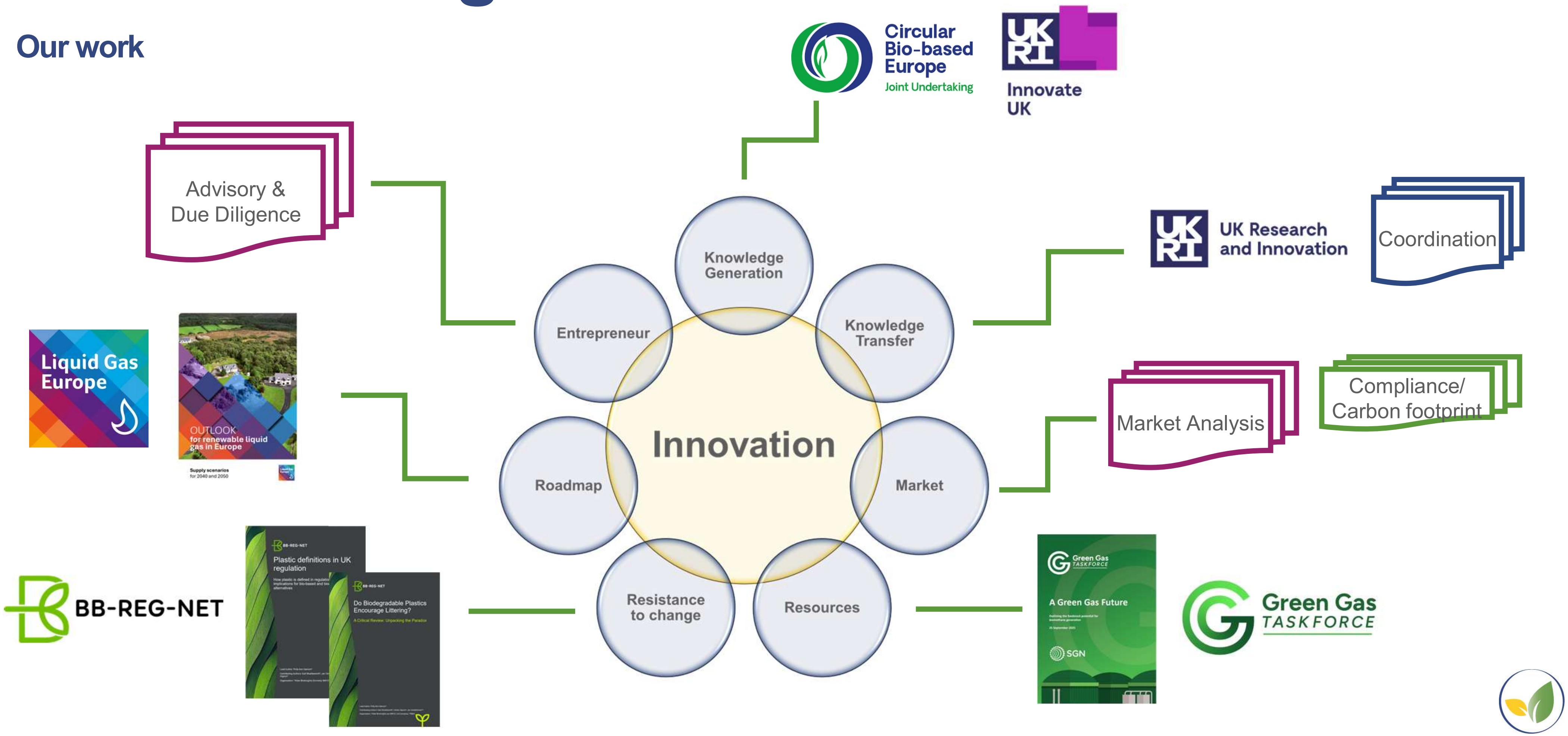
Our work

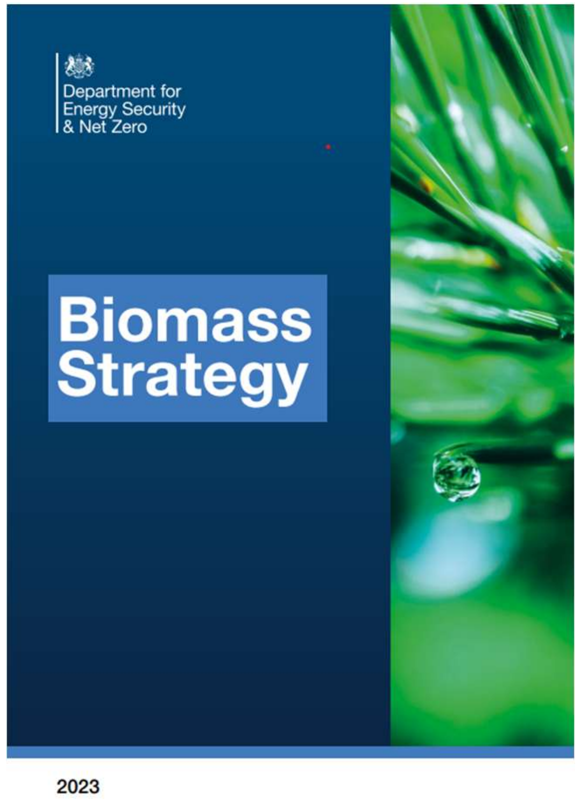


Int biomass brilliant!

UK Biomass Strategy

Principles of biomass use

- **Sustainability**, ensuring that biomass used in the UK is sustainable and is in line with our climate and environmental goals.
- **Air quality**, minimising any public health impacts from the use of biomass.
- **Net zero**, ensuring that biomass uses contributes towards the UK's net zero target.
- **Circular economy & resource efficiency**, to ensure that these wider benefits from biomass use to the UK economy are realised wherever possible, in line with government goals.

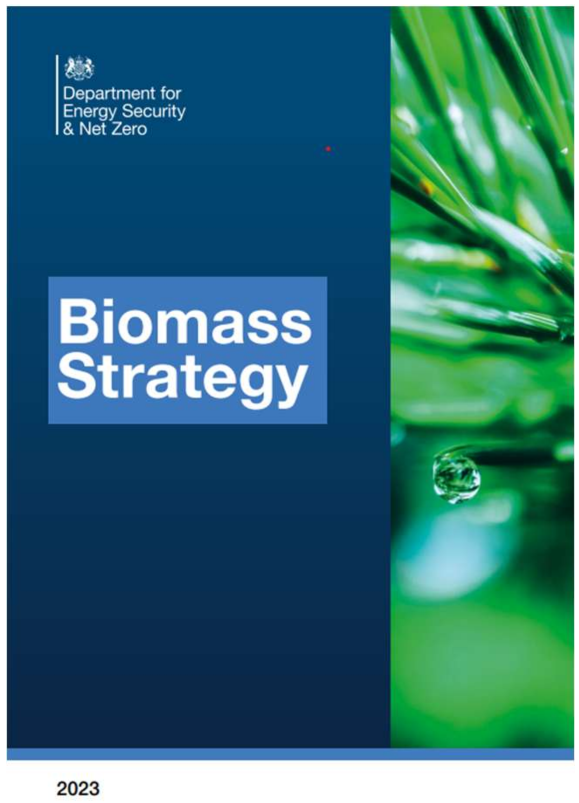


https://assets.publishing.service.gov.uk/media/64dc8d3960d123000d32c602/biomass-strategy-2023.pdf

UK Biomass Strategy

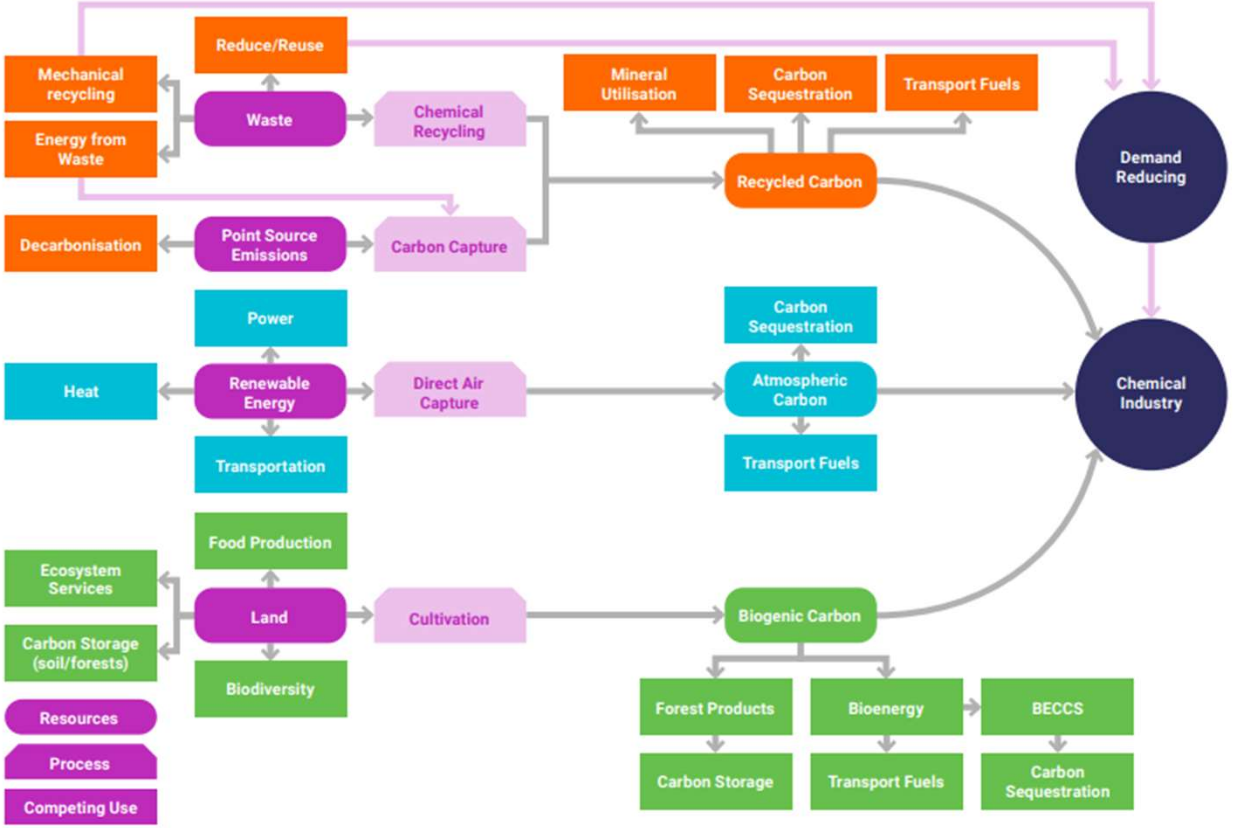
Priority use of biomass

- **Near term**, sustainable biomass deployment through a range of incentives and requirements covering power, heat and transport.
- **Medium term**, transition away from unabated emission uses of biomass *where possible* to uses such as Bioenergy with Carbon Capture and Storage (BECCS).
- **Long term**
  - Difficult to predict.
  - Modelling indicates that biomass use combined with BECCS for power, heat and transport contribute the most towards net zero.
  - Emerging bioeconomy products and markets beyond energy will continue to be reviewed.



https://assets.publishing.service.gov.uk/media/64dc8d3960d123000d32c602/biomass-strategy-2023.pdf

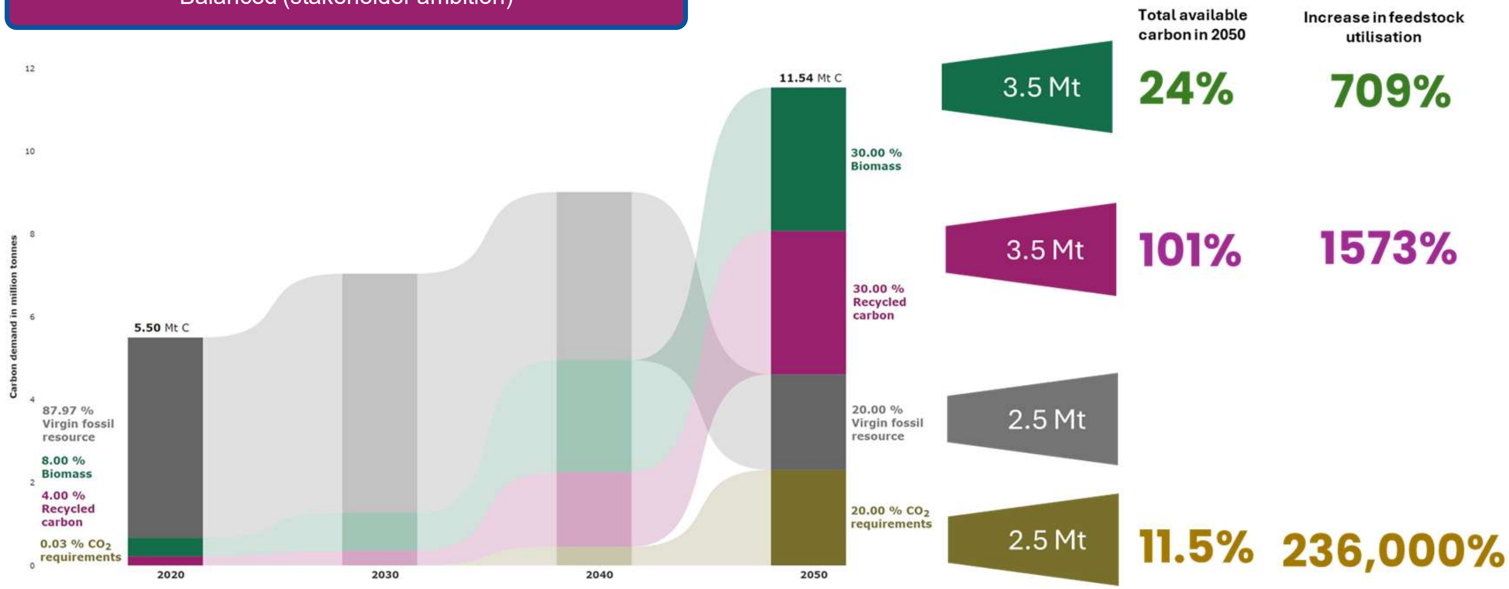
Defossilising chemical production



UK Chemical demand for carbon

Stakeholder rejected several scenarios as either unacceptable, unattractive or unachievable

Balanced (stakeholder ambition)



https://iuk-business-connect.org.uk/perspectives/sustainable-carbon-ambition-for-the-uk-chemicals-industry/

Feedstock limitations and challenges

Each carbon source has critical limitations

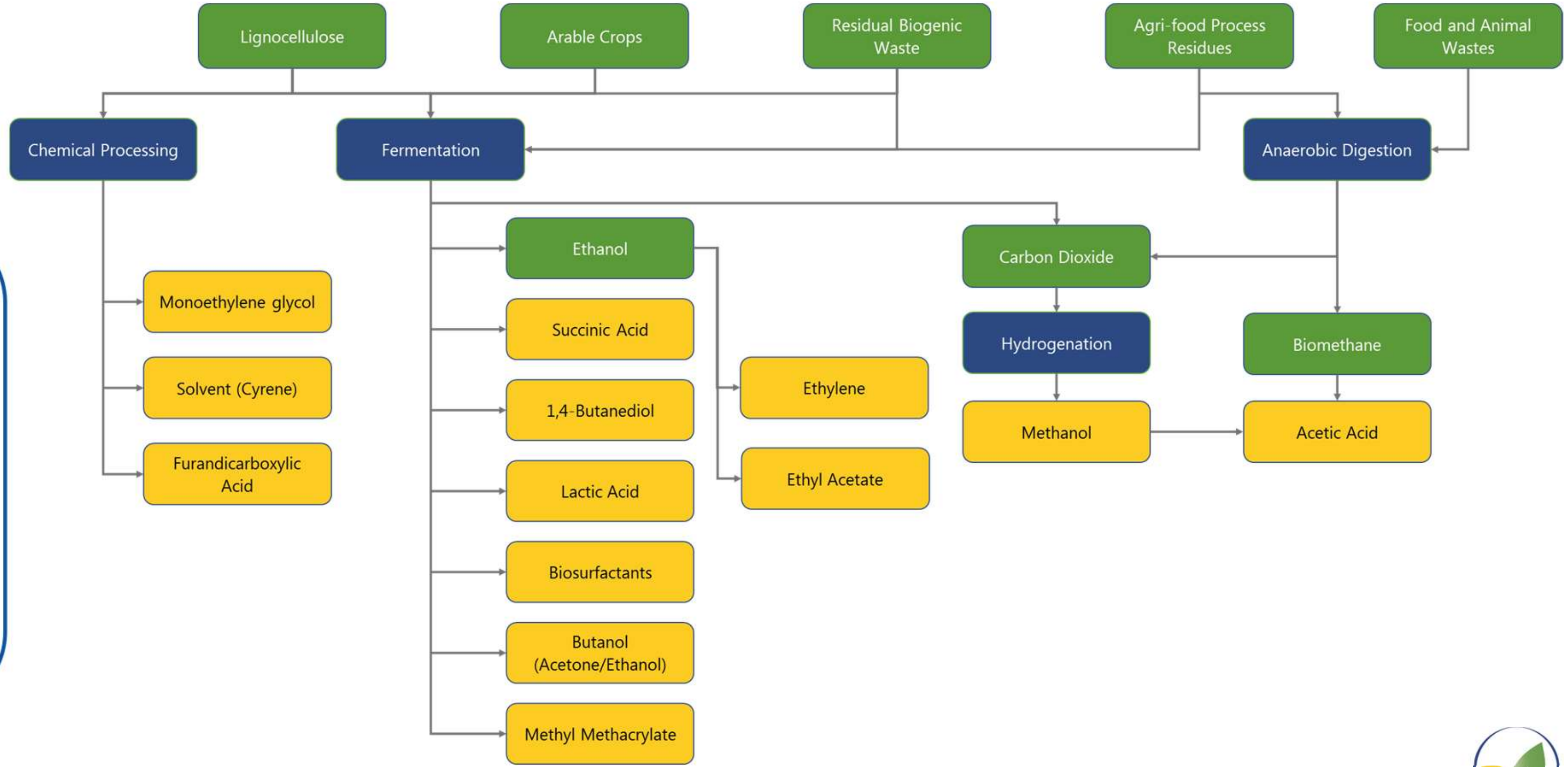
- Abated fossil carbon does not fully address end of life emissions.
- Biogenic carbon is limited by ecosystem and social impact concerns.
- Recycled carbon is limited by collection rates, and delays rather than eliminates fossil carbon emissions.
- Atmospheric carbon is limited by renewable energy requirements and extraction costs.

Achieving the stakeholder preferred scenario is challenging.

- Domestic recycling can only provide a fraction of the UK's carbon demand.
- Biomass is available, but significant demand from energy applications and in less attractive volumes compared to other global regions.
- CO_2 is available in significant quantifies but requires low-cost renewable energy for conversion.

Chemical potential

Targets and Feedstock

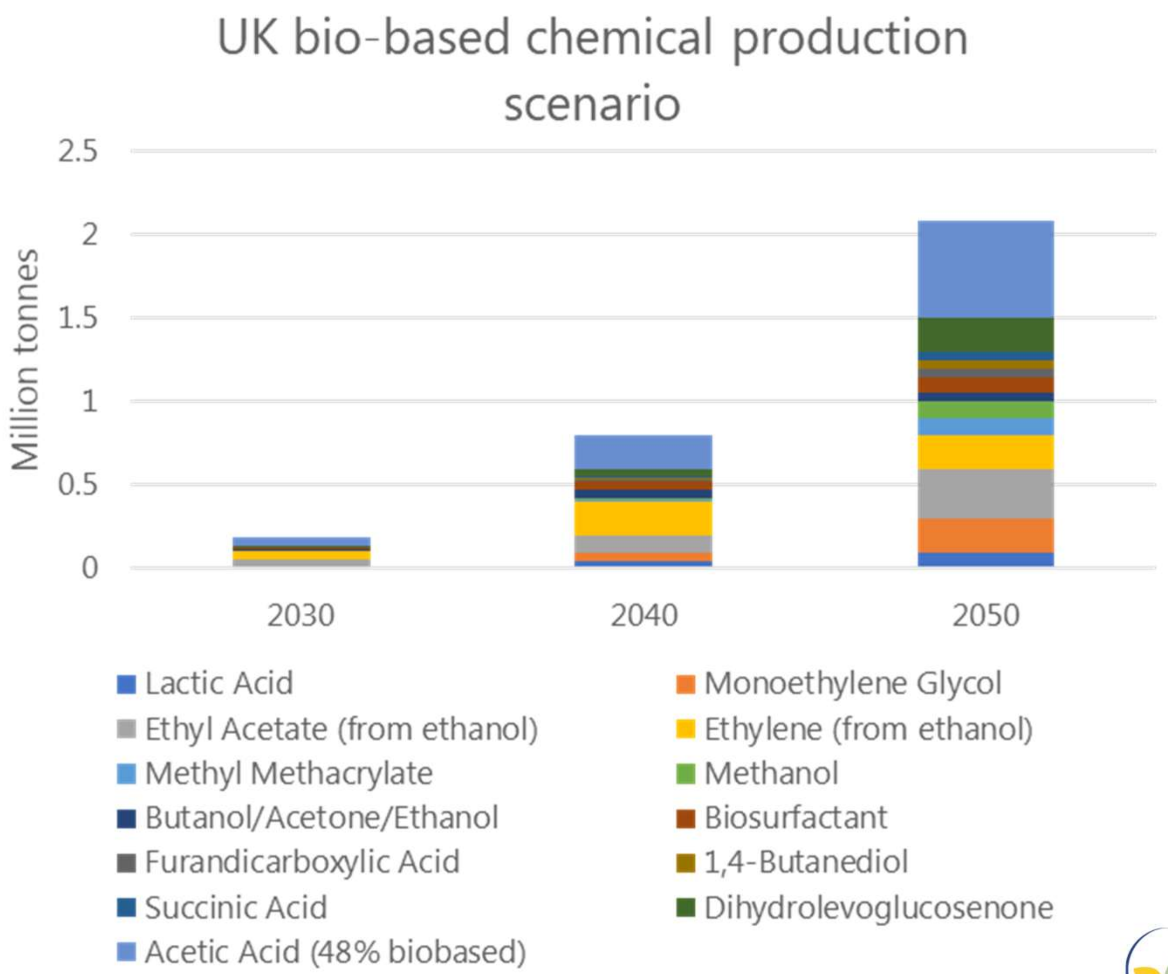


Chemical potential

By **2050**, the UK bio-based chemicals industry has the potential to significantly grow, producing over

2 million tonnes of bio-based chemicals, contributing to

5.2 million tonnes CO_2eq GHG savings and **£1.6bn** in value to the UK economy

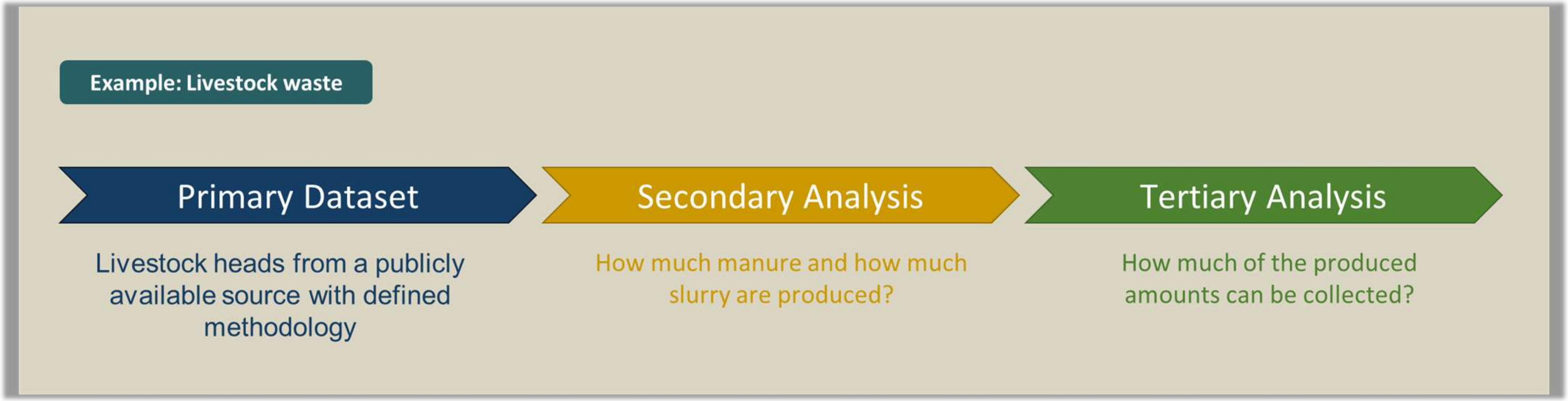


Assessing current availability

Data bases developed to support investor due diligence requirements

Feedstock Database

- **How much** biomass is available**?**
- **Where** are these **untapped resources** located**?**
- What is their **composition?**
- What could they be **used** for**?**
- What use **restrictions** are there**?** What are the **competing markets?**



Feedstock Database

Select both filter parameters from dropdown list (or type in the box) for a summary of production and collection figures on some crops residues. For a more granular breakdown, please refer to the table below.

Year	2024
Country	United Kingdom

Residues production (incl. straw) (odt)	
Wheat	
Barley	
Oat	
Sugar beet	
Potatoes	
Beans and peas	
Oilseed rape	
Maize	
Total	

Residues production (incl. straw) (fresh we	
Wheat	
Barley	
Oat	
Sugar beet	
Potatoes	
Beans and peas	
Oilseed rape	
Maize	
Total	

				Arable crops (ha)									
Country	Region	County / Unitary Authority	Year	Wheat (ha)	Winter barley (ha)	Spring barley (ha)	Oats (ha)	Other cereals (ha)	Total cereals (ha)	Potatoes (ha)	Sugar beet (2) (ha)	Field beans (ha)	Peas f harves
England	Yorkshire and The Humber	York	2021	4,803	1,409	2,034	383	115	8,744	556	149	461	
England	Yorkshire and The Humber	York	2016	4,238	1,565								
England	Yorkshire and The Humber	York	2013	3,124	1,079								
England	Yorkshire and The Humber	York	2010	4,495	1,539								
England	West Midlands (England)	Worcestershire	2021	22,795	3,221								
England	West Midlands (England)	Worcestershire	2016	22,522	3,289								
England	West Midlands (England)	Worcestershire	2013	18,282	1,938								
England	West Midlands (England)	Worcestershire	2010	23,456	2,864								
England	West Midlands (England)	Wolverhampton	2021	#	#	#							
England	North West (England)	Wirral	2021	627	#								
England	North West (England)	Wirral	2016	667	233								
England	North West (England)	Wirral	2013	370	#								
England	North West (England)	Wirral	2010	570	165								
England	South West (England)	Wiltshire CC	2013	37,908	6,000								
England	South West (England)	Wiltshire	2021	41,767	9,841								
England	South West (England)	Wiltshire	2016	41,213	9,597								
England	South East (England)	Westminster	2021	#									
England	South East (England)	West Sussex (South West)	2021	10,825	1,424								
England	South East (England)	West Sussex (North East)	2021	3,988	773								
England	South East (England)	West Sussex	2016	15,248	2,002								
England	South East (England)	West Sussex	2013	14,235	1,308								
England	South East (England)	West Surrey	2021	1,727	202								
England	East Midlands (England)	West Northamptonshire	2021	29,233	5,169								

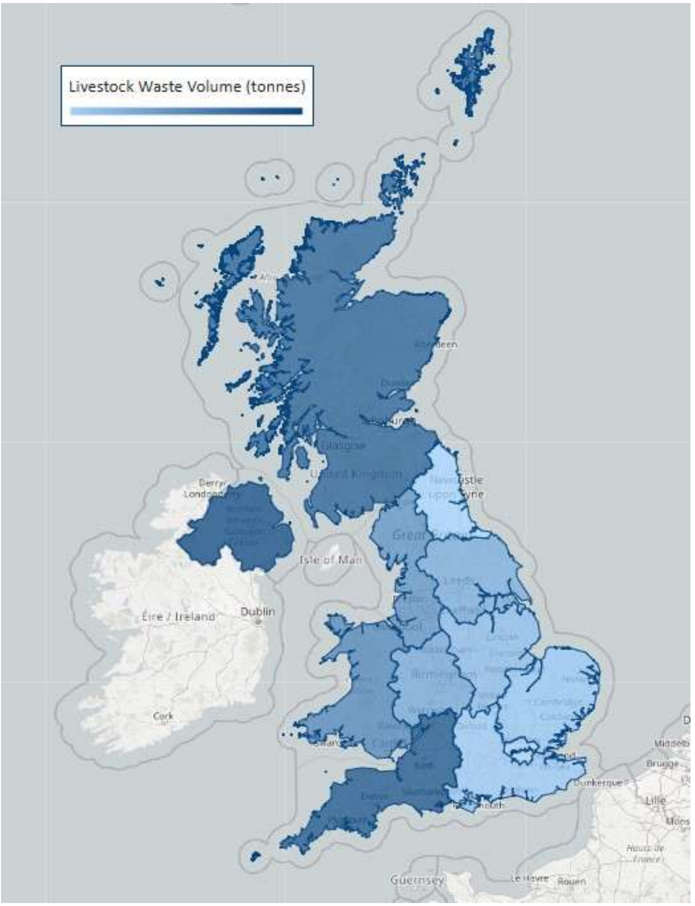
Introduction | Master Sheet | Crops Production 2010-2023 | Crop Residues | Assumptions | Version History | Region and Countie

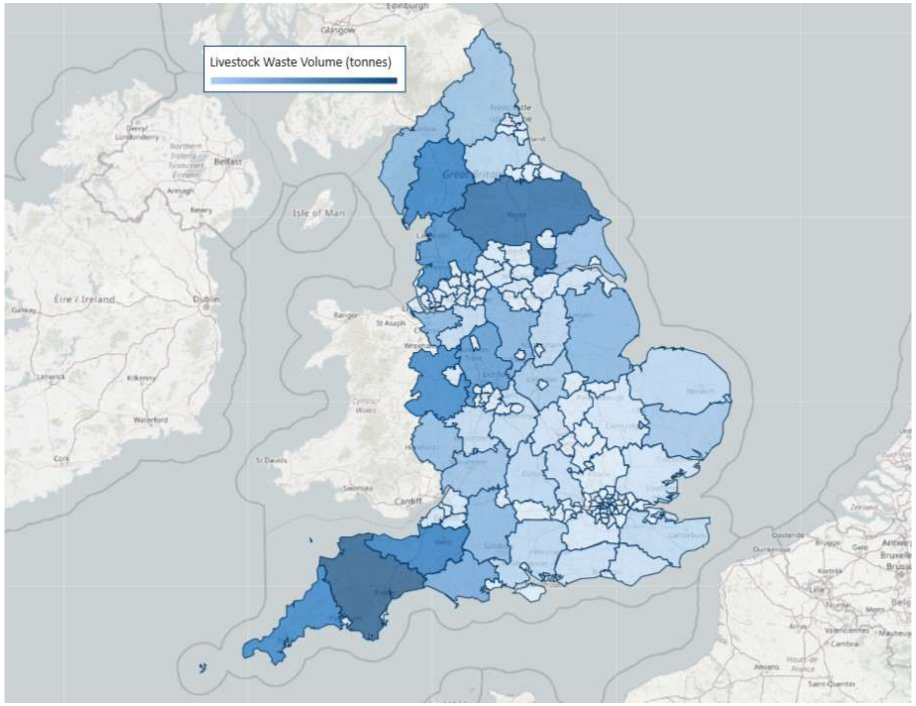
Residues production (oven dry tonnes) - incl. straw									
Spring barley Residues (oven	Oats Residues (dry weight)	Other cereals' Residues (dry	Total cereals Residues (oven	Potatoes leaves (oven dry weig	Sugar beet leaves (oven dry weig	Field beans Residues (oven	Peas Residues (oven dry weig	Oilseed Stalks (oven dry weig	Maize Residues (oven dry weig
8,967	1,566	570	48,942	3,543	1,231	2,003	299	3,353	1,538
5,875	-	-	41,911						
12,542	-	-	37,292						
4,430	484	33	41,748						
18,432	11,484	3,670	195,934						
14,004	9,663	2,621	184,327						
24,549	15,165	952	152,716						
7,133	10,451	1,761	175,334						
-		-							
593	-	-	4,616						
348	-	-	5,000						
2,303	-	-	3,956						
584	-	-	4,160						
116,890	20,966	2,766	386,446						
90,760	26,457	10,187	444,456						
91,243	17,016	3,802	417,703						
-	-	-	-						
14,135	8,995	2,890	102,591						
3,609	3,121	1,812	37,988						
20,802	11,599	3,475	143,812						
29,316	15,731	2,430	138,680						
1,066	2,385	689	16,232						
29,796	14,416	3,270	260,845						

		Straw (oven dried tonnes)				
Wheat straw (oven dried	Winter barley (oven dried	Spring barley straw (oven dri	Oat straw (oven dried tonnes)	Other cereals' straw (oven dri	Oilseed rape straw (oven dri	Total cereals straw (oven dri
15,604	3,547	4,835	1,352	288	2,192	25,626
13,843	4,396	3,167	-	-	3,695	21,406
9,544	2,982	6,762	-	-	4,777	19,288
14,522	4,103	2,389	418	17	5,451	21,448
74,062	8,106	9,937	9,912	1,857	9,929	103,874
71,637	8,350	7,550	8,339	1,327	21,216	97,203
51,268	5,444	13,235	13,088	482	29,286	83,516
71,280	7,670	3,846	9,019	891	23,669	92,706
-	-	-		-	-	
2,036	-	320	-	-	-	2,356
1,769	586	187	-	-	-	2,542
837	-	1,242	-	-	-	2,078
1,423	387	315	-	-	-	2,125
108,541	15,876	63,019	18,095	1,400	72,128	206,930
135,702	24,765	48,931	22,833	5,156	29,740	237,388
129,405	25,287	49,192	14,686	1,925	58,060	220,494
-	-	-	-	-	-	-
35,171	3,584	7,621	7,763	1,463	4,685	55,601
12,958	1,945	1,946	2,693	917	1,147	20,459
49,355	5,274	11,215	10,011	1,759	11,689	77,613
43,105	3,054	15,805	13,577	1,230	14,520	76,772
5,612	508	575	2,058	349	923	9,102
94,979	13,009	16,064	12,442	1,655	14,594	138,149

oduction 2010-2023 | Crop Residues | Assumptions | Version History | Region and Counties in the UK

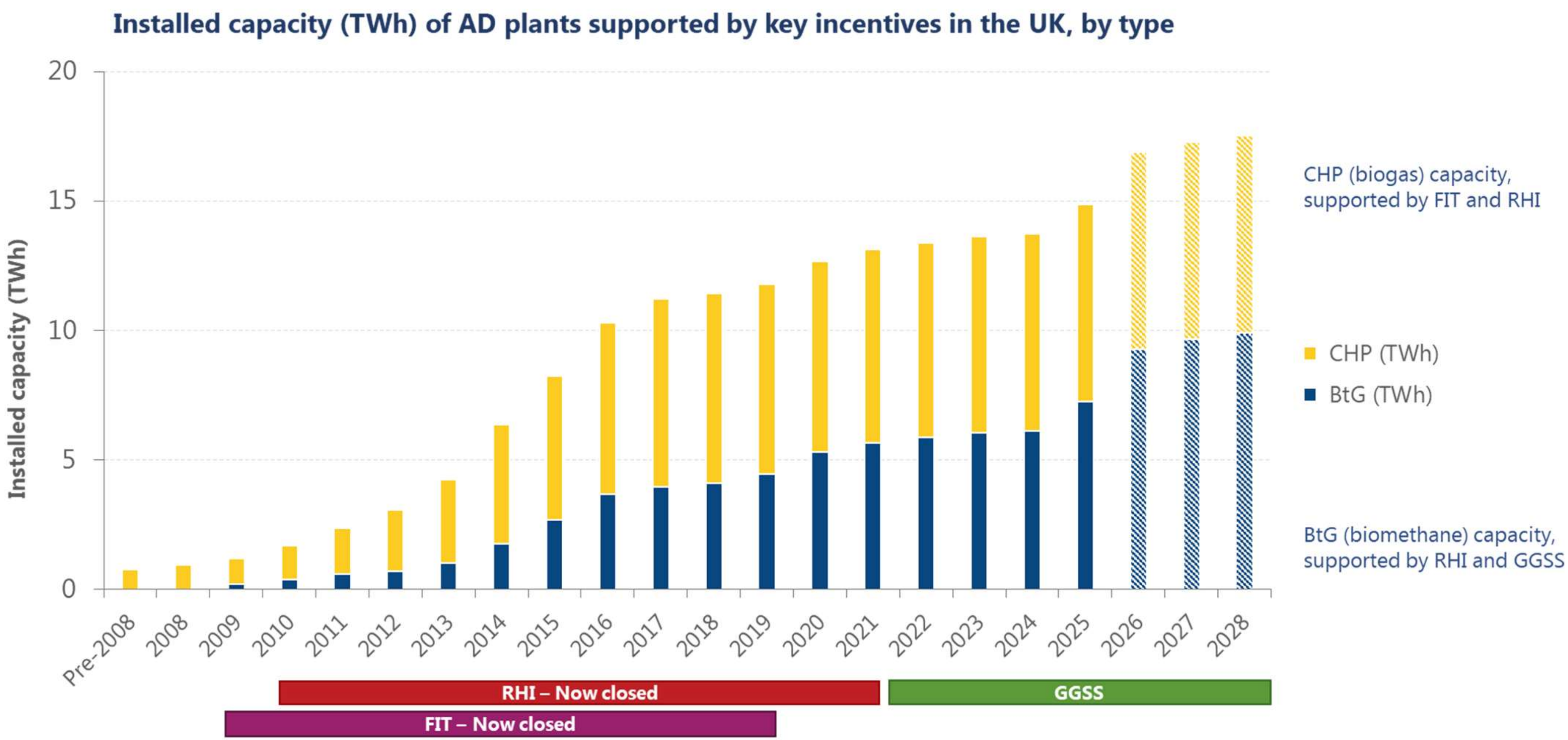
Feedstock Database





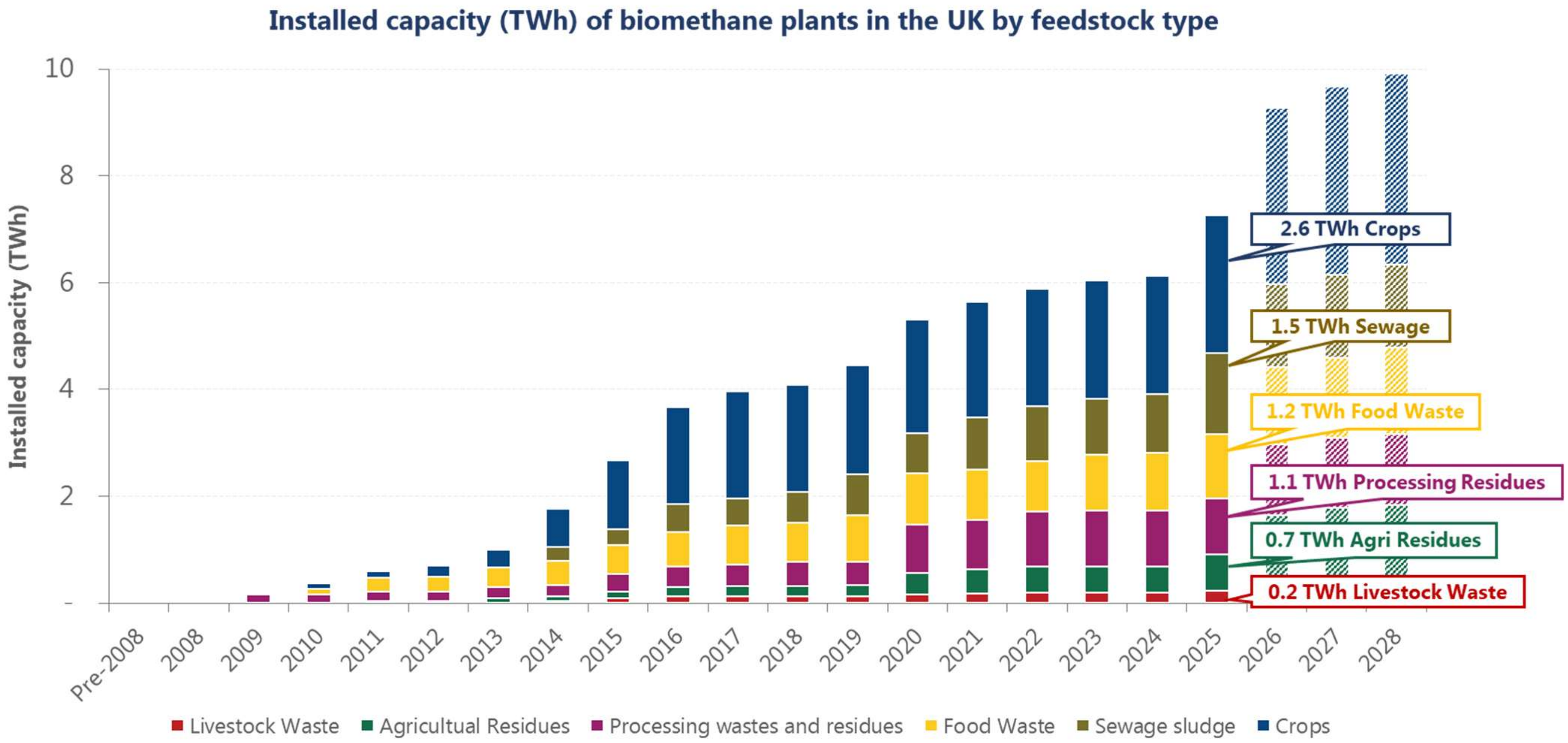
Biomethane in the UK

Capacity



Installed capacity (TWh) of AD plants supported by key incentives in the UK, by type
Installed capacity (TWh)
20
15
10
5
0
Pre-2008
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
CHP (biogas) capacity, supported by FIT and RHI
CHP (TWh)
BtG (TWh)
BtG (biomethane) capacity, supported by RHI and GGSS
RHI – Now closed
GGSS
FIT – Now closed

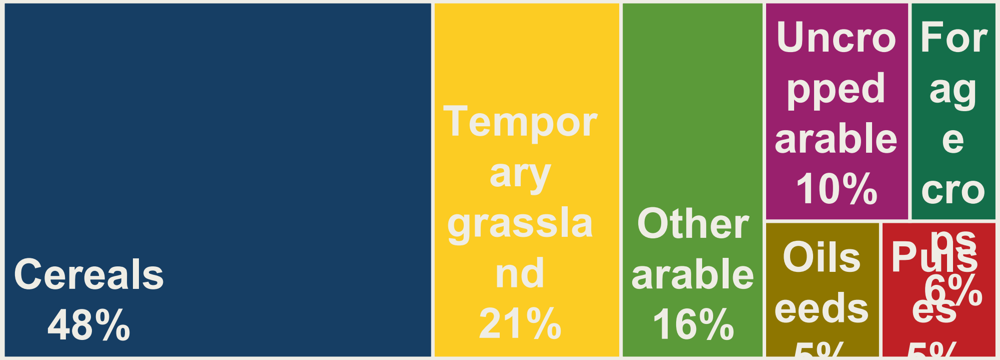
Current Feedstock



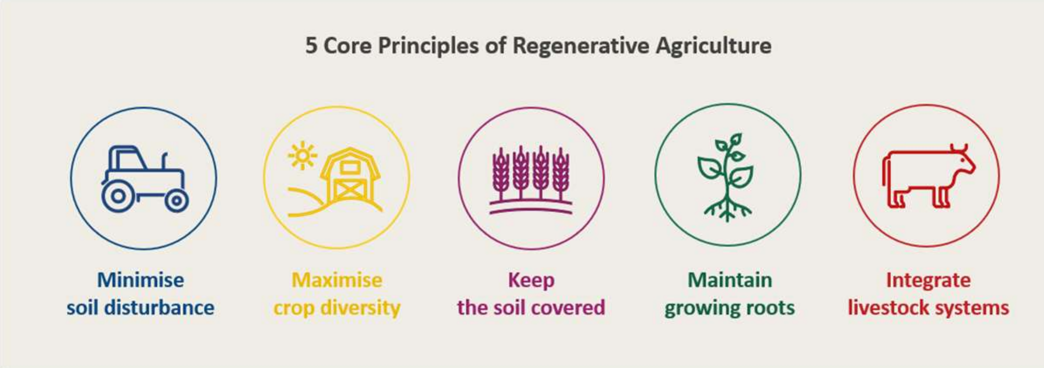
Agriculture

Food vs fuel – the debate you can't kill

UK Arable Land Use (2024)



Source: Defra June Census (2024): Land Use data



Considerations

Rotational crops (incl. main crop, cash crop, break crops): Alternating crops on a specific field (or fields) in a planned pattern or sequence in successive years. Rotations are typically 4-7 years.

A long, diverse rotation can support the delivery of multiple environmental and agronomic benefits, incl. improved soil fertility, increased soil carbon, enhanced crop yields, ground cover and soil protection, pest and disease control, diversified income.

Sequential crops (also termed intermediate, second or cover crops): two or more crops grown on the same field, one after the other, at different times in the year. Typically, this would involve a main (rotational) crop grown for commercial purposes, and another crop used as cover in the winter or summer months.

Sequential cropping is well aligned with the key principles of Regenerative Agriculture.

Regenerative Agriculture principles:

1. Minimise disturbance of the soil, physically and chemically
2. Keep the soil covered, to prevent damage and to restore nutrients
3. Maintain living roots in the soil for as much of the year as possible
4. Maintain plant diversity within the rotation and across the farm
5. Reintroduce livestock, or mimic the benefits of livestock grazing using organic manures

Intercropping (also referred to as undersowing): two crops grown on the same field at the same time, to increase the yield on any given field by choosing crops that will complement each other in terms of resource usage and nutrient input.

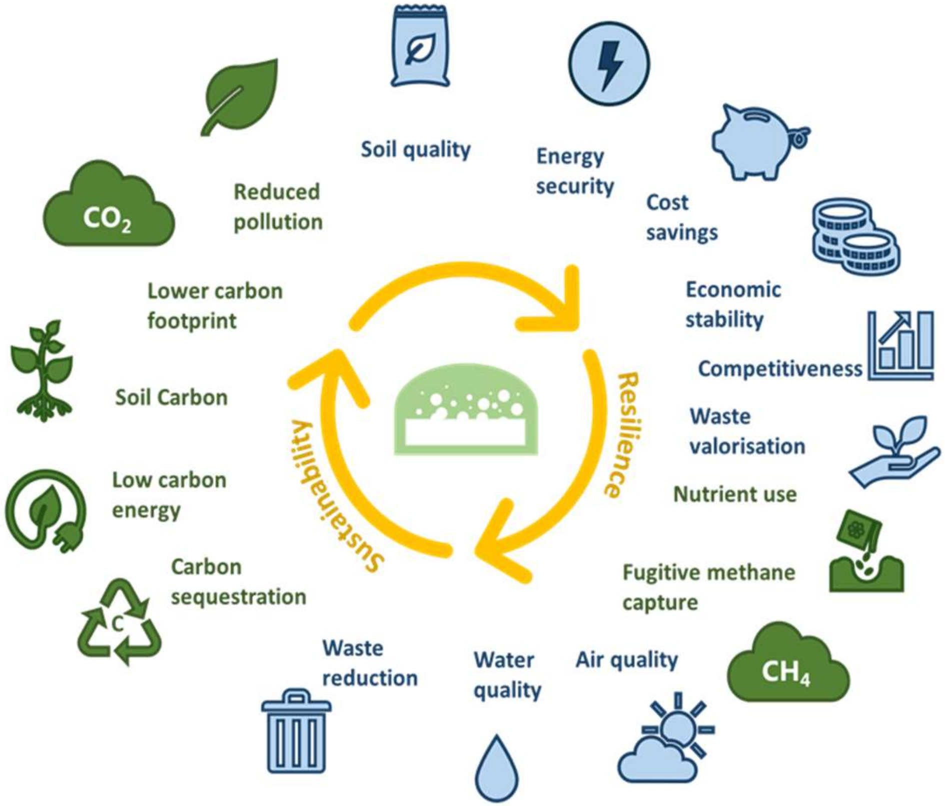
The main crop can be under-sown with a different species, so when the first (main) crop is harvested, the second grows providing cover and nutrition.

Agricultural residues: a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process, and the process has not been deliberately modified to produce it. An example agricultural residue is straw.

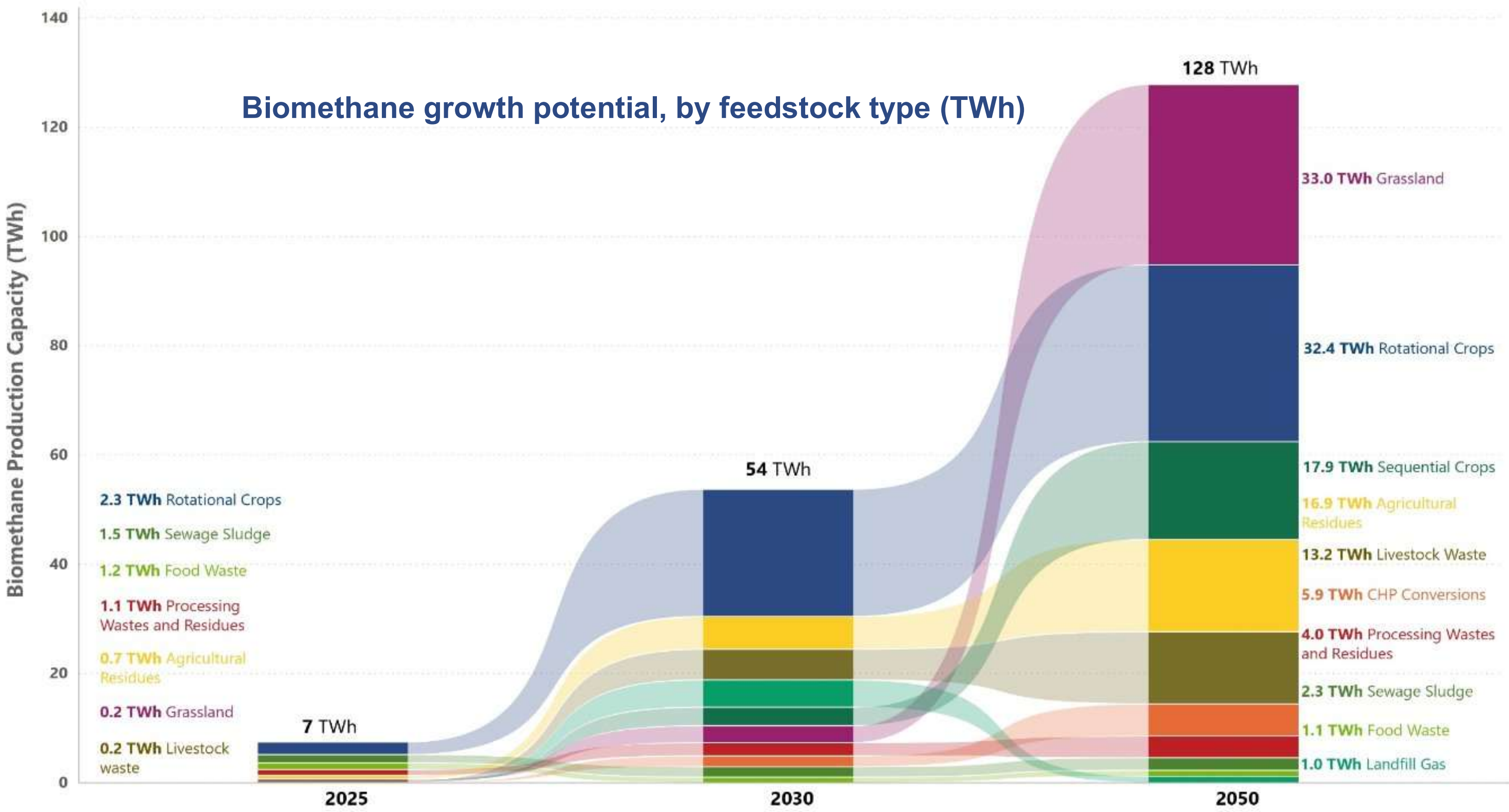
Energy crops: Often crops of a perennial nature, that are grown on lower grade or marginal land over a long-time period; typically, woody or lignocellulosic material, better suited to thermal or chemical conversion so targeted for power, heat or SAF production.

Recognising AD’s wider benefits

https://greengastaskforce.co.uk/key-reports/

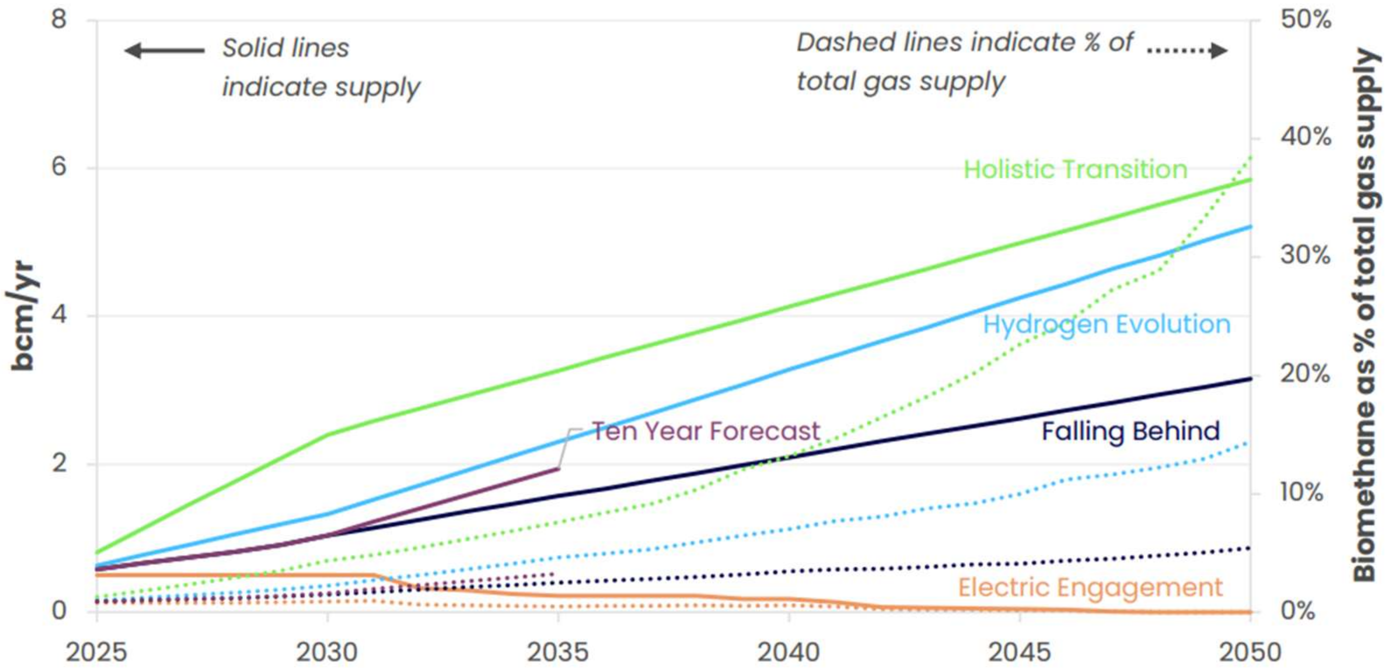


UK biomethane potential

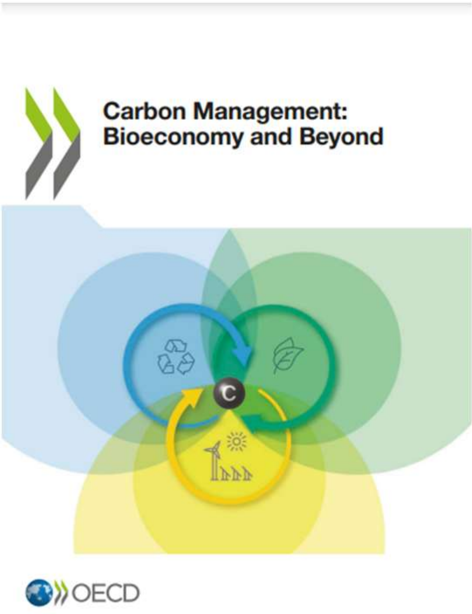


Implication

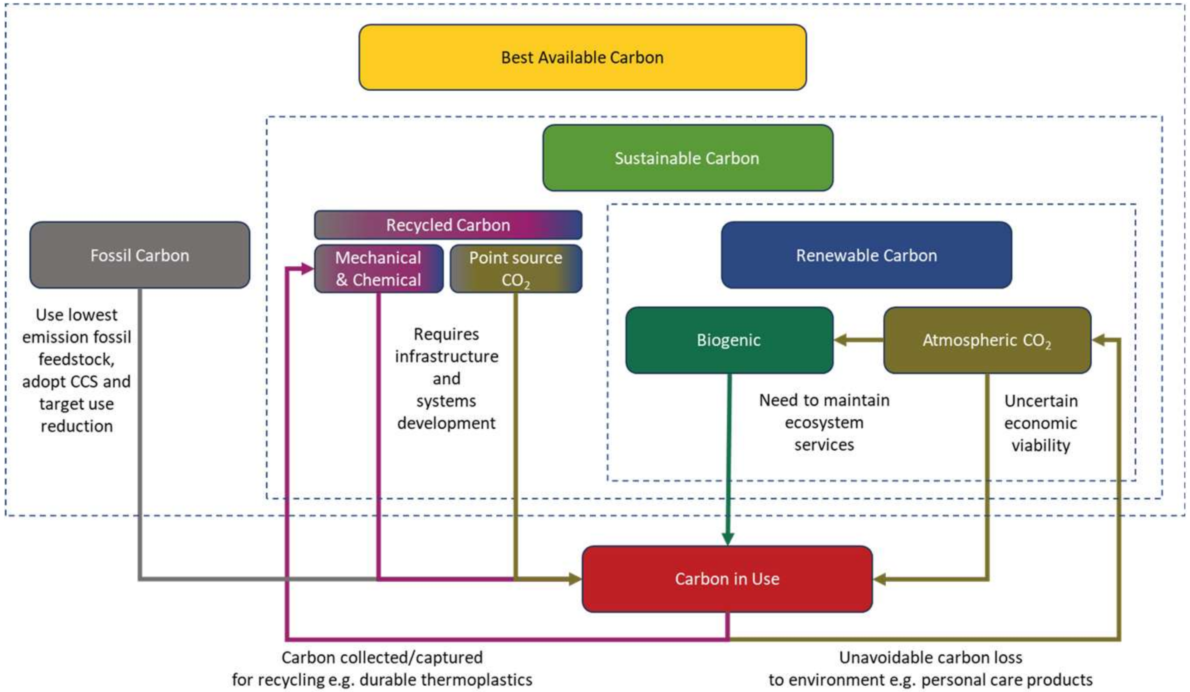
Biomethane in the GB energy mix



Carbon management



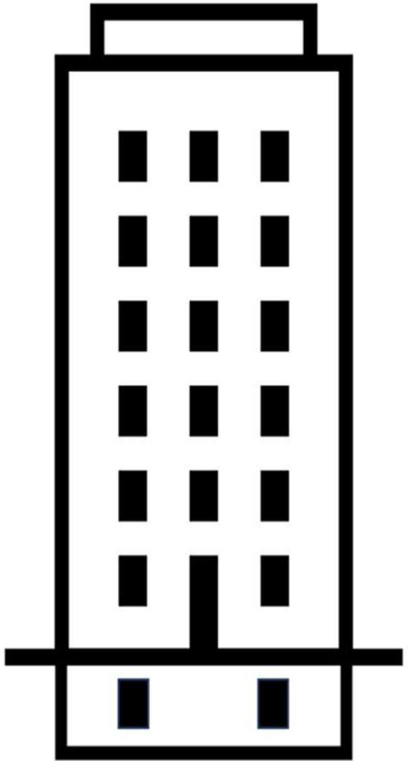
OECD (2023), *Carbon Management: Bioeconomy and Beyond*, OECD Publishing, Paris, https://doi.org/10.1787/b5ace135-en.



https://www.alderbioinsights.co.uk/news-and-insights/insights/a-perspective-on-best-available-carbon-bac-as-feedstock-for-the-chemical-industry/

A biomass hierarchy

BB-REG-NET



Basic needs and wellbeing requirements	Food; Ecosystem services; Carbon storage (natural); Maintain Biodiversity; Functional molecules (healthcare)
Wants and desires requiring natural products, polymers & materials	Structural material (timber); Fibre (paper/card); Fibre (textiles); Animal feed; Functional molecules (industrial and consumer)
Wants and desires requiring carbon molecules	Chemical feedstock (carbon); Aviation fuel; Marine fuel; Portable heat (as LPGeq); Portable stove fuel (as LPGeq)
Uses where limited alternatives exist	Industrial heat; Road transport fuel (heavy haulage); Dunkelflaute; Electricity generation with CCS
Uses where some alternatives exist	Chemical feedstock (hydrogen); Carbon storage (engineered); Emergency back-up power; Road transport fuel (light haulage)
Uses where alternatives are known and understood	Road transport fuel (domestic); Domestic heat (on grid as biomethane); Domestic heat (off grid as LPGeq)
Uses with limited merits and known alternatives	Electricity generation without CCS; Rail; Hydrogen with/without CCS (as fuel)

Summary

The ability for biomass to meet multiple demands complicates decisions on its immediate use and long-term strategic deployment

There is a strong desire to defossilise UK chemical production – however no cohesive policy framework exits

The potential to expand biomethane production is substantial providing a flexible low carbon fuel for heat, transport and power generation and chemical production

Need a cohesive policy framework - policy interests are dispersed across departments individually covering heat/power, transport, industry and environment.

Future policy should integrate agricultural, environmental, and economic benefits – thinking beyond energy and net zero

Thank you

A specialist strategic business consultancy with over 22 years of bioeconomy experience

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