Agile BioFoundry

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BIOENERGY TECHNOLOGIES OFFICE

DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

ABF Past Accomplishments - TEA/LCA

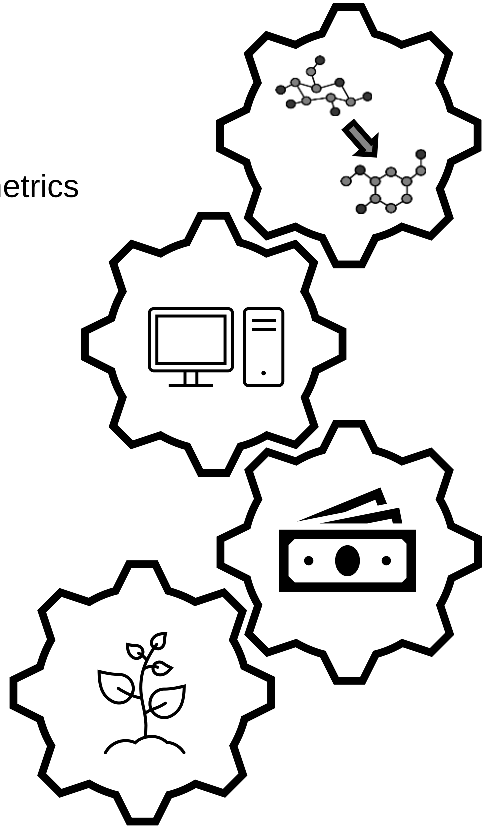
April 3rd, 2023
Agile BioFoundry

Bruno Klein, Pahola Thathiana Benavides
NREL, ANL

Project overview: TEA/LCA

Project history

- This task (Integrated Analysis) initiated at the inception of the Agile BioFoundry
- Purpose of supplying other ABF tasks with insights towards economic and environmental metrics
- Initial focus on target/host pairs, later pivoted to beachhead/exemplar molecules



Project goals

- Scan the metabolic space of interest to ABF for process simulation targets
- Develop process models for relevant production pathways within the consortium
- **Specific goal:** Carry out techno-economic and life cycle assessments (TEA/LCA) to quantify the economic and environmental performance of selected fermentative routes
- Provide guidelines to the experimental teams for further bioproduct development
- Act as a liaison between ABF and other BETO consortia (i.e. Separations Consortium)

Relevance

- Benchmarking the performance of current ABF bioconversion routes, setting the path forward for future experimental directions, and helping to pave the path to decarbonize the chemical industry

Approach: risks and mitigation strategies

Risks

- **Timely availability of experimental data** for designing process models and carrying out TEA/LCA
- Uncertainty in **downstream processing and upgrading** of fermentation products
- Uncertainty in **capital cost** of novel technologies
- Gaps in **life cycle inventories** for new products

➡

Mitigation strategies

- Pivoting to sensitivity analyses when experimental data is not at hand
- Ensuring data are provided in **consistent framework/quality**
- **Connecting with multiple DOE consortia** (SepCon, ChemCatBio, etc.) to harmonize processes and integrate assessments
- Leveraging robust models that have been initially developed and utilized elsewhere under the BETO portfolio
- Certifying the **rigor of process modeling, TEA, and LCA** efforts

Approach: challenges and critical success factors

Challenges

- Developing process models for **novel bioconversion routes and bioproducts**
- **Identifying relevant baselines** (i.e., most representative conventional or fossil-based products to which biobased molecules are compared)
- **Identifying exemplar molecules** to carry out TEA/LCA of beachhead molecules
- **Scaling up fermentative processes** in biorefineries employing ABF experimental data
- **Quality of data** for process design and analysis

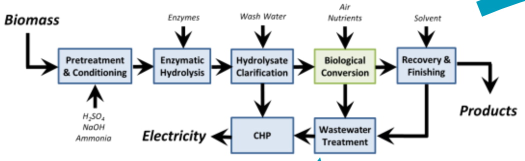
Critical success factors for this project

- Building consistent TEA/LCA models with **reliable and reproducible methods**
- Providing TEA/LCA findings to **support R&D efforts needed to enable ABF goals**
- Working closely with the DBTL team to **adopt learnings and improve process models**
- **Disseminating TEA/LCA results** to the team and to the general public

Approach: task workflow

Iterative process for developing process models and deriving the associated economic/ environmental performance metrics

1. Formulated or refined process based on current research



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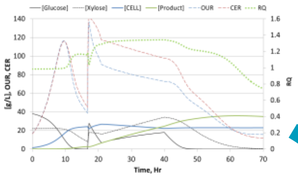
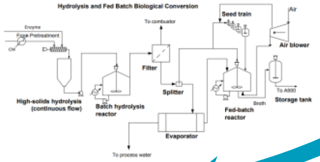


2. Modeled unit operations using experimental data.

3b. Identify the major cost drivers.

Main metrics to measure progress

TEA
Process outputs
Minimum selling price

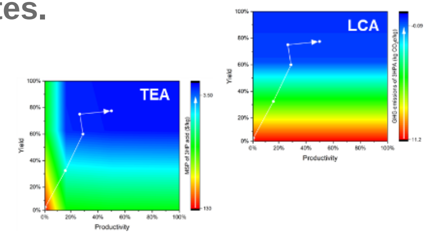


LCA
GHG emissions
Fossil fuel use
Water use

GREET LIFE-CYCLE MODEL

3b. Identify the major sustainability drivers.

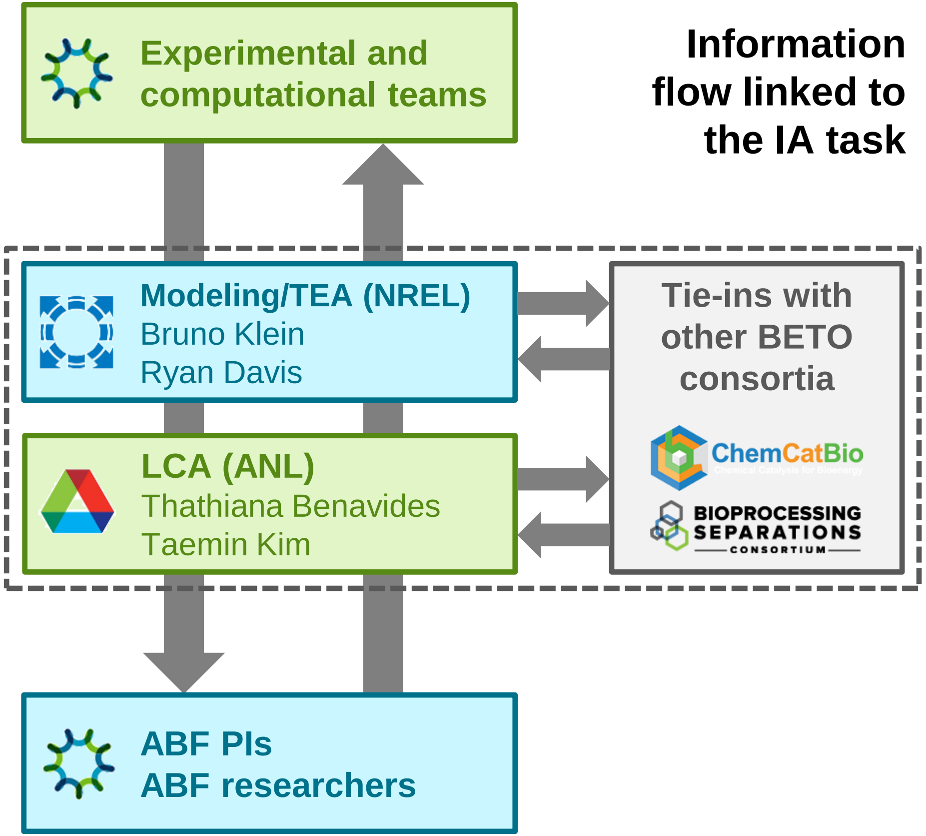
4. Fed back results into step (1) and the process iterates.



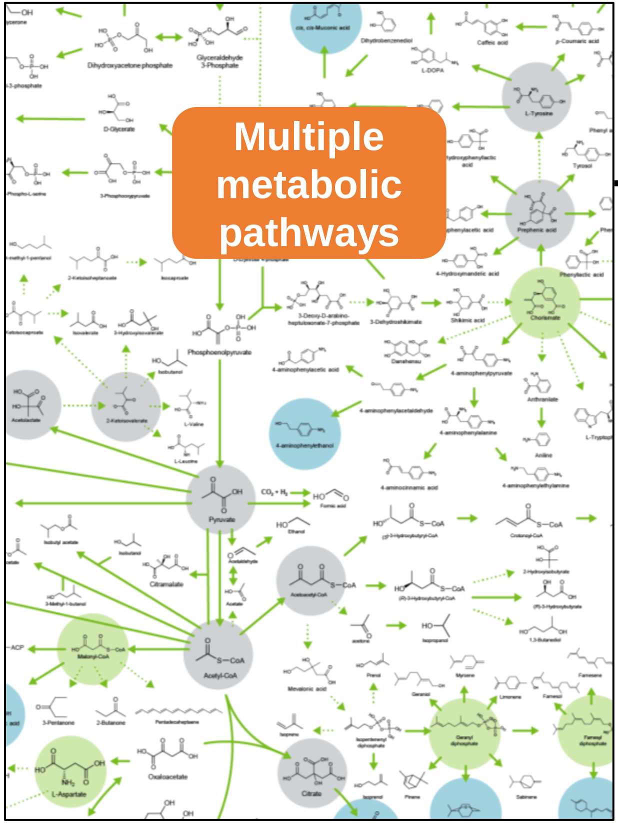
Approach: management and communication

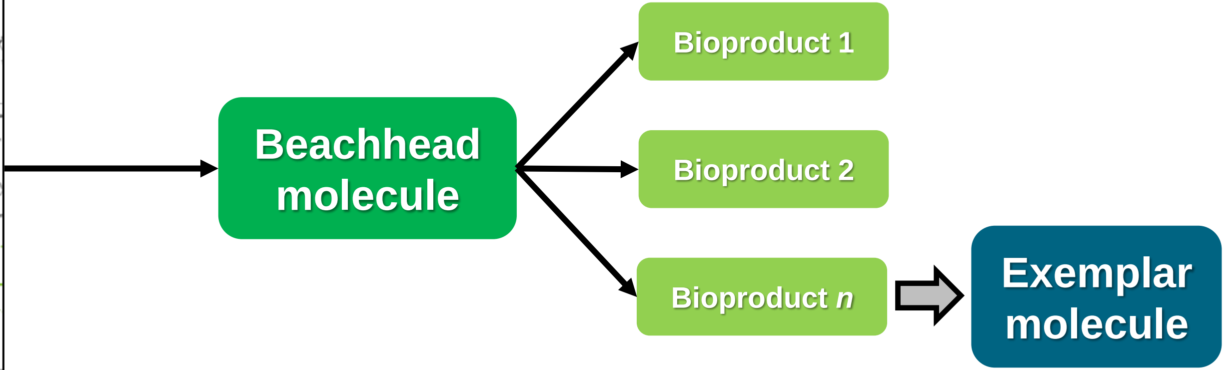
IA team's main activities

- Participate in ABF **bi-weekly meeting calls**
- Engage with the Industrial Advisory Board to **review approaches and results**, adopting new guidance in the process
- **Report progress on results** in meetings, task lead calls, BETO webinars
- **Interact with researchers from other BETO-consortia** (SepCon, PABP, ChemCatBio, etc.) to align goals and assessment assumptions
- Complete periodic deliverables to **support the development of TEA/LCA of new bioprocesses** and update prior analyses with latest details



Approach: assessing beachhead intermediates





– Since carrying out TEA/LCA for all possible bioproducts is a time-consuming effort, the IA team downselects bioproducts to a single “exemplar” molecule per beachhead molecule of interest

  - *“Exemplar” molecules represent all bioproducts with similar characteristics and processing conditions that could be obtained from a given metabolic pathway*

Progress and outcomes: milestones

Completion?

- **FY21** – Conduct **TEA/LCA modeling for at least 4 new beachhead/exemplar molecule cases**. Outcomes: new process models developed for 2,3-butanediol (BDO), malic acid, aconitic acid, and polyhydroxyalkanoates (PHA). ✔
- **FY22** – In-depth **TEA/LCA modeling to highlight target-host specific characteristics** applicable to bioreactor operation. Outcomes: identified theoretical yield as the main parameter when choosing hosts for sugar conversion. ✔
- **FY22** – Demonstrate at least one representative target of a beachhead at a TRY that can achieve **within 20% of the fossil feedstock incumbent MSP** (*DBTL milestone with IA support*). Outcomes: target achieved for biosourced β-ketoadipic acid. ✔
- **FY22** – Report delivered in manuscript format for journal publication that **compiles at least 7 separate beachhead and exemplar product molecules**. Outcomes: full details of 8 different pathways included in the manuscript. ✔

Milestones are the starting points to provide TEA- and LCA-based guidelines to the experimental team to advance the development of different biosynthesis pathways in an effective way

Progress and outcomes: metabolic map coverage

IA team provided an overview of economic and environmental metrics using detailed TEA/LCA for the following pathways:

✓ FY22 Milestone

Beachhead molecule	Exemplar molecule	Molecules that could be derived from the same beachhead molecule	Host
Protocatechuate	**Adipic acid *** from muconic acid	*Catechol, β-ketoadipic acid, vanillin*	*Pseudomonas putida*
Pyruvate **	**1,3-butadiene *** from 2,3-butanediol Methyl ethyl ketone from 2,3-butanediol Malic acid	*Citramalate, malic aid, lactic acid, ethanol, acetic acid, acetolactate*	*Zymomonas mobilis* *Lipomyces starkeyi*
L-aspartate	Acrylic acid from **3-hydroxypropionic acid ***	*Malonic acid, 1,3-diaminopropane*	*Aspergillus pseudoterreus*
Geranyl diphosphate	**1,8-cineole ***	*Other monoterpenes*	*Rhodosporidium toruloides*
Citrate	Aconitic acid	*Itaconic acid, oxalic acid*	*Aspergillus pseudoterreus*
Acetoacetyl-CoA	Polyhydroxyalkanoates (PHA)	*Isopropanol, 1,3-butanediol, octanoic acid*	*Pseudomonas putida*

** In this presentation, TEA/LCA results are shown for these exemplar molecules*

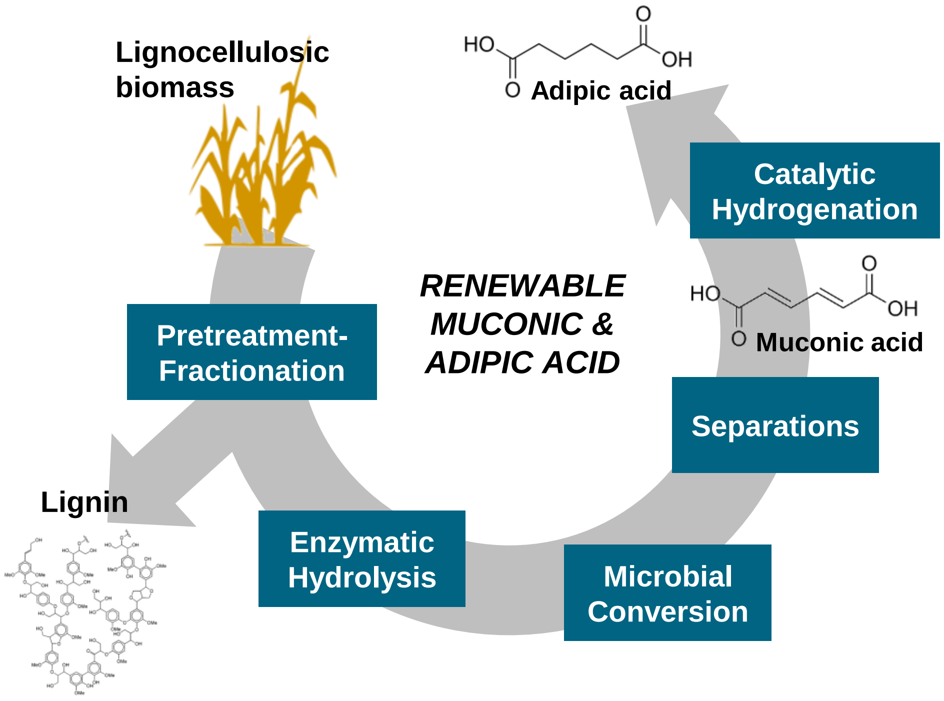
*** Pyruvate defines a very large metabolic space, hence warranting expanding the rational to three exemplar molecules for detailed TEA/LCA*

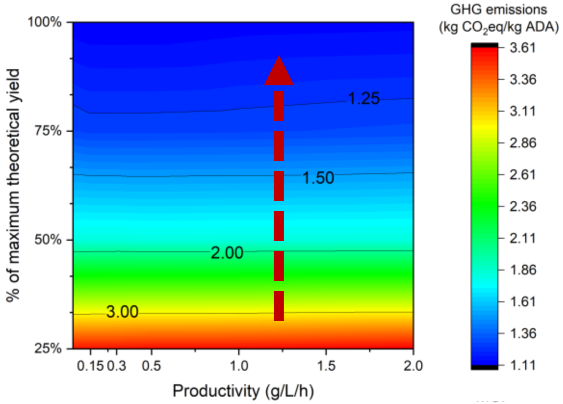
All details and results will be made public: Klein, Benavides et al. Techno-economic and environmental assessment of bioproducts across a large metabolic space (2023)

Progress and outcomes: TEA/LCA of adipic acid

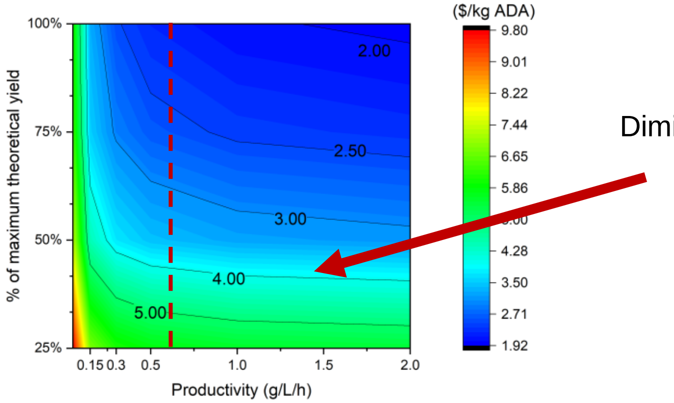
Case study: aerobic production of muconic acid, followed by upgrading to adipic acid

✓ FY21 Milestone



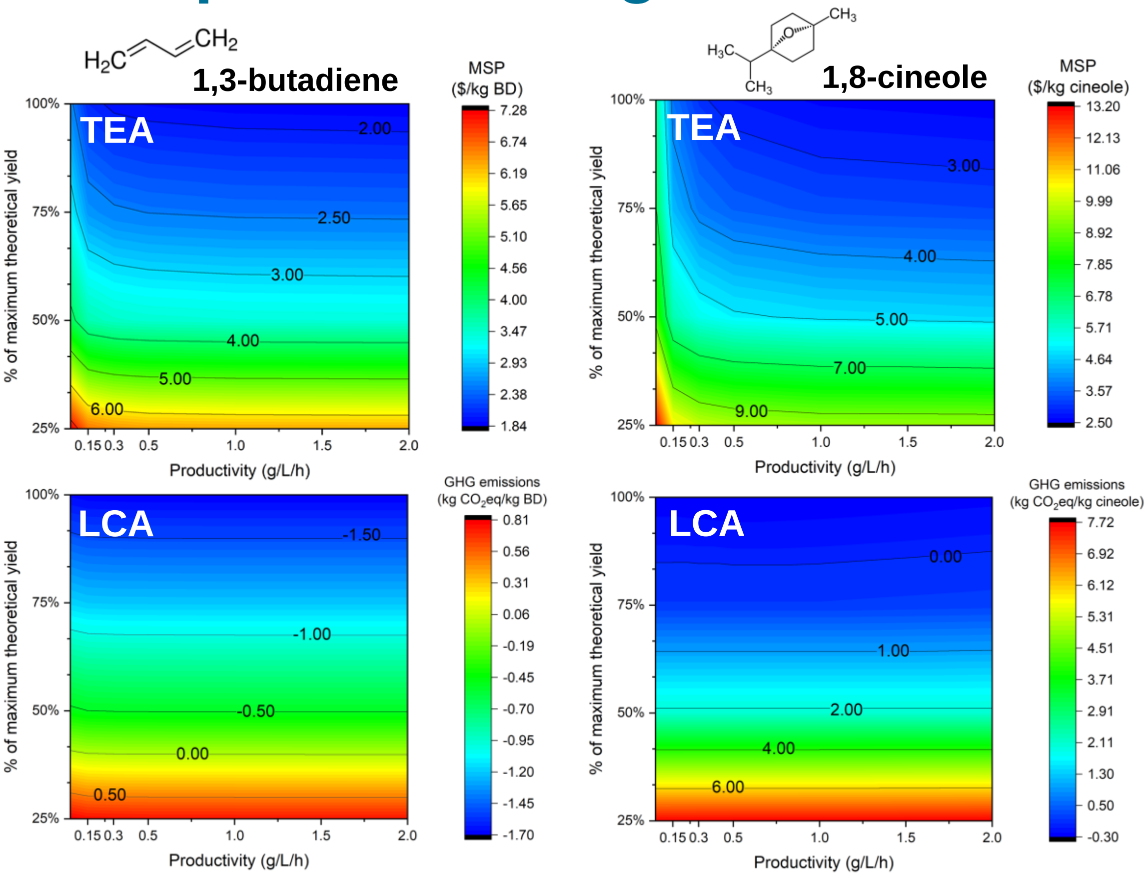


Yield as the main driver of environmental performance



Diminishing returns upon further productivity enhancements

Impact: covering the ABF metabolic space



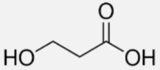
- TEA and LCA as tools to **probe the economic and environmental performance** of industrially-relevant bioproducts
- Early-stage TEA and LCA to provide **insights into barriers and opportunities for prioritization of R&D efforts** in ABF

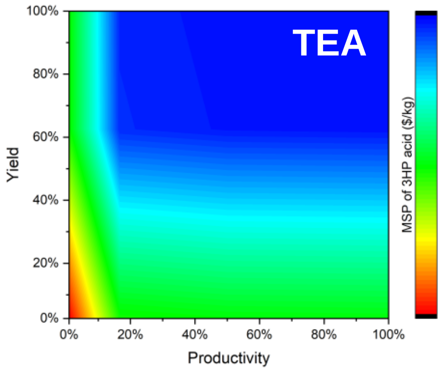
Full set of details and results will be published soon: Klein, Benavides et al. *Techno-economic and environmental assessment of bioproducts across a large metabolic space* (2023). In preparation.

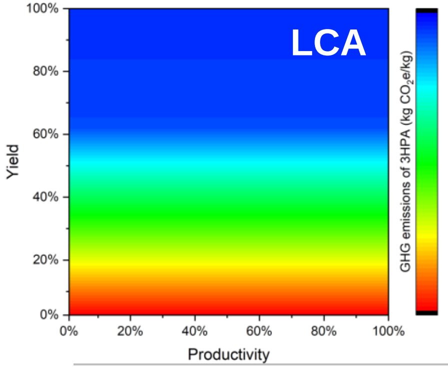
Impact: tracking titer/productivity/yield evolution

Translating technical performance to economic and environmental impacts, showcasing the **actual** evolution of fermentation metrics achieved under ABF

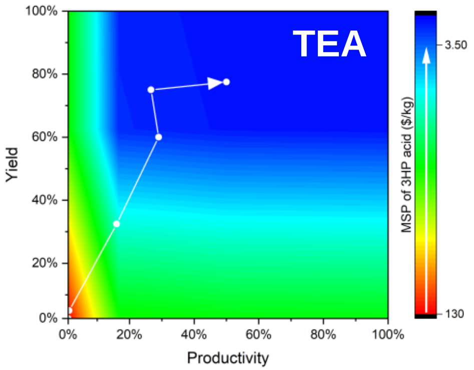
3-Hydroxypropionic (3HP) acid

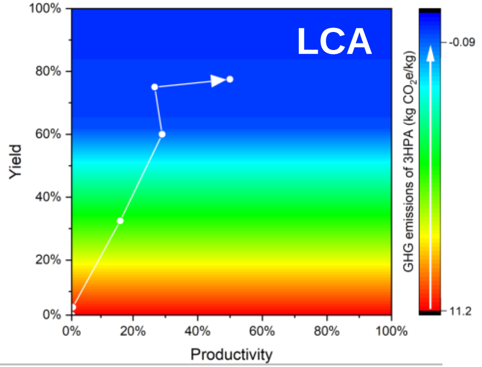






A priori assessment → *A posteriori* assessment





Informing the ABF team of the impact of experimental achievements through:

Scaling up fermentative processes in integrated biorefineries **employing ABF experimental data**

Understanding **critical factors** in large-scale fermentations

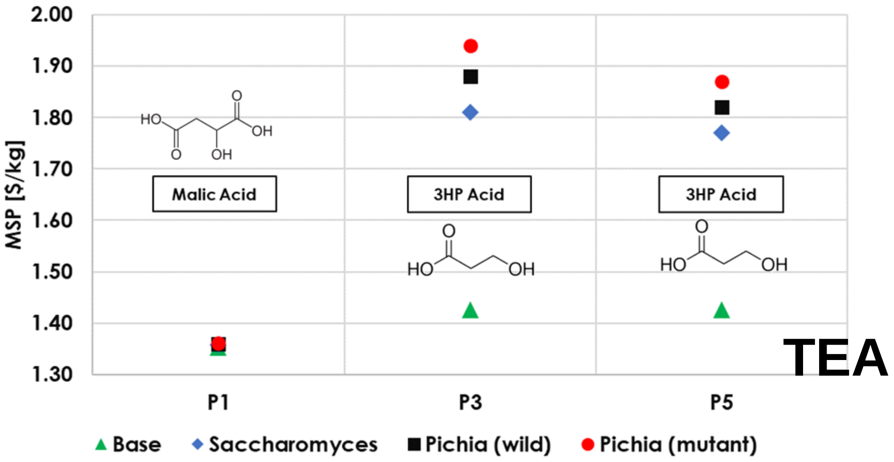
Defining **future experimental directions** based on TEA/LCA guidance

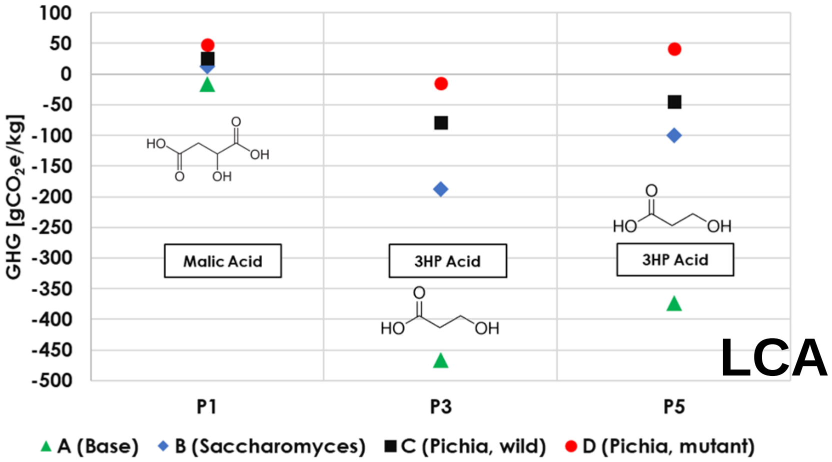
Impact: alternative biosynthesis pathways

- Assessing the effect of yield, O_2 requirements, and nutrient demand in selected fermenting microorganisms

- TEA/LCA results showed that, at a fixed productivity, **yield to product is the strongest driver** of both economic and environmental impacts, superseding parameters such as nutrient consumption

Biosynthesis pathway code	**P1**	**P3**	**P5**
Beachhead molecule	Pyruvate	Acetyl-CoA	Acetyl-CoA
Exemplar molecule	Malic acid	3HP acid	3HP acid
Baseline microorganism	*Lipomyces starkeyi*	*Aspergillus pseudoterreus*	
Alternative microorganism #1	*Saccharomyces cerevisiae*		
Alternative microorganism #2	*Pichia kudriavzevii* (wild strain)		
Alternative microorganism #3	*Pichia kudriavzevii* PDC PDH knockout (mutant strain)		





Impact: other aspects

Dissemination of results

- Participation in both internal DOE/BETO calls and external BETO webinars; supply of data for public-facing reports; and preparation of comprehensive manuscripts that detail the work around beachhead molecules

Go/No-Go decision point

- N/A for the Integrated Analysis task, but regular interaction with other ABF tasks to support their own Go/No-Go milestones

Economic and technical metrics

- TEA: process yields, minimum selling price (MSP, $/kg)
- LCA: greenhouse gases emissions (kg CO_2e/kg), water consumption (L/kg)

Related BETO projects

- Bioprocessing Separations Consortium (SepCon), Performance-Advantaged Bioproducts (PABP) and Chemical Catalysis for Bioenergy Consortium (ChemCatBio) → often consulted for inputs to develop process simulations of bioconversion pathways in ABF

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Summary

Overview	TEA and LCA tools use to quantify the economic and environmental sustainability potential for bioproducts synthesized with hosts pertinent to the ABF consortium
Technical approach	• Incorporate key scientific and technical parameters (T/R/Y) around product synthesis/ recovery steps into integrated process models and associated TEA/LCA • Developed methodology for selection of beachhead molecules for further characterization • Work closely with other ABF tasks to coordinate data needs, provide guidance to further improve economic and environmental metrics, and leverage insights from other BETO consortia

Progress	• Present comprehensive multi-variable TEA/LCA scans to quantify the economic performance and environmental sustainability potential for several bioproducts of industrial interest
	• Identify key drivers and trends over a range of values for bioconversion metrics: fermentation yield and productivity
	  • *TEA metrics: productivity takes precedent over product yield for aerobic fermentations, while the opposite is true for anaerobic/micro-aerophilic systems*
	  • *LCA metrics: essentially a function of fermentation yield*

Impact	Integrated TEA/LCA tools can point the best way forward for product development purposes
Future work	Continue supporting the ABF consortium within the revised/updated scientific directions, namely the synthesis of sustainable aviation fuels (SAF) and selected bioproducts

Quad Chart Overview

Timeline
- *October 1, 2019*
- *September 30, 2022*

	FY23 Costed	Total Award
DOE Funding	*(10/01/2021 – 9/30/2022)*	*$15M*
Project Cost Share *		

TRL Range: 2-4

Project Goal
Enable biorefineries to achieve 50% reductions in time to bioprocess scale-up as compared to the current average of around 10 years.

End of Project Milestone
- One representative target at a TRY within 20% of the fossil feedstock incumbent MSP demonstrated, from DMR-EH hydrolysate or mock hydrolysate
- At least 10 of the ABF beachheads across onboarded hosts achieve titer metrics
- Adapt baseline metabolic models for at least 3 ABF hosts to calculate theoretical yield. Calculate the minimum selling price of chemicals to benchmark realistic target chemical markets.
- Bring a total of at least 15 microbial hosts to at least Tier 1 capability, provide corresponding information, resources, and tools via publicly-accessible ABF HObT website

Funding Mechanism
AOP

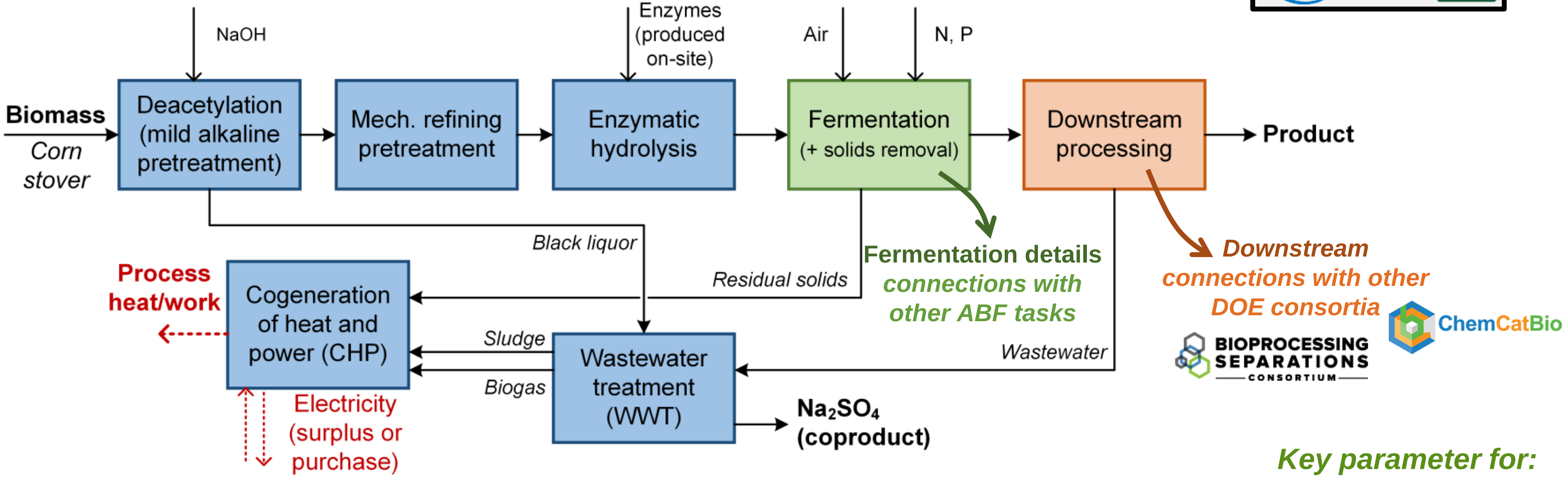
Project Partners*
LBNL (23%), SNL (20%), NREL (18%), PNNL (17%), LANL (8%), ORNL (8%), ANL (6%)

Additional Slides

Approach: process simulation and TEA

Designing and assessing integrated biorefineries

Simulation and TEA



Main parameters and process configuration consistent with NREL's 2018 Biochemical Design Report: https://www.nrel.gov/docs/fy19osti/71949.pdf

Key parameter for:

Goal: Assess sensitivity drivers to key fermentation parameters (productivity, yield) over a range of achievable values towards impacts on MSP and GHG emissions

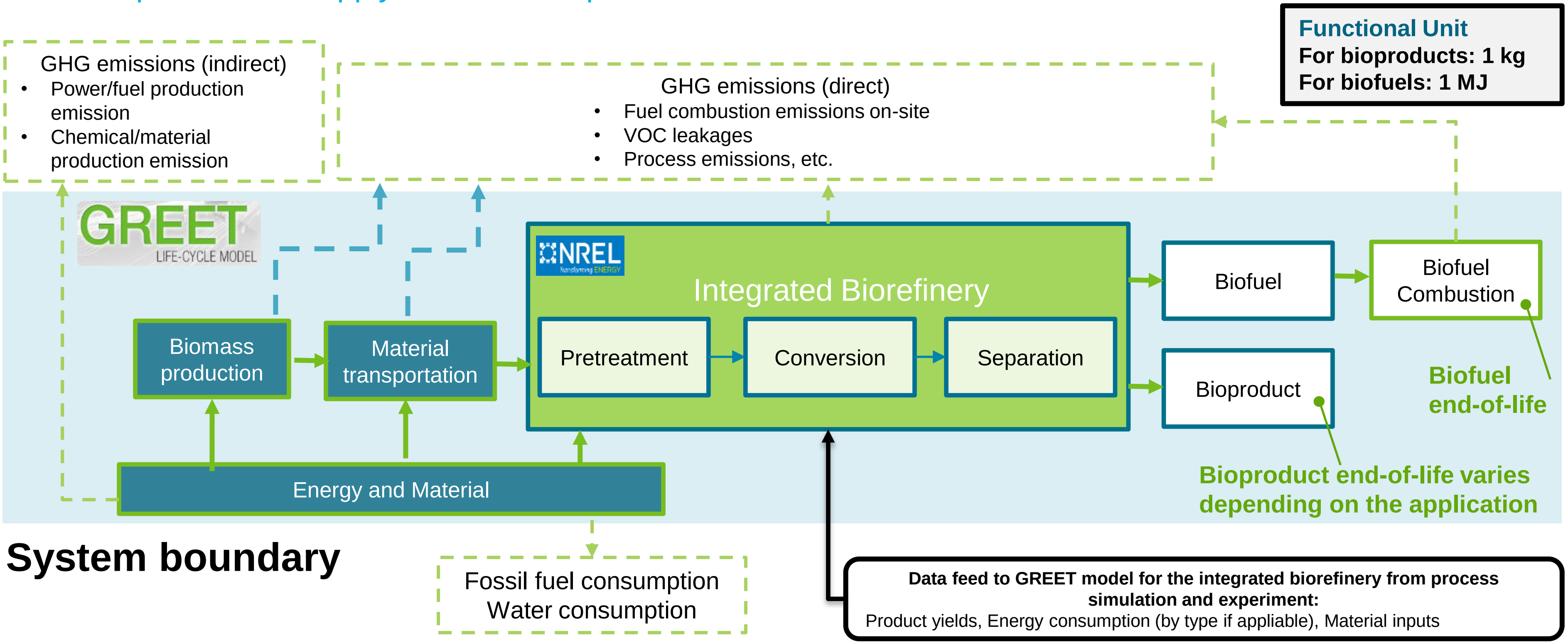
Productivity (g/L/h) →	TEA
Yield to product (%) →	TEA and LCA

Approach: LCA

Holistic approach to evaluate the environmental impacts of the supply chain of a bioproduct

Biorefinery LCI from process simulation by NREL

Upstream/downstream - leverage GREET inventory



Approach: selecting exemplar molecules

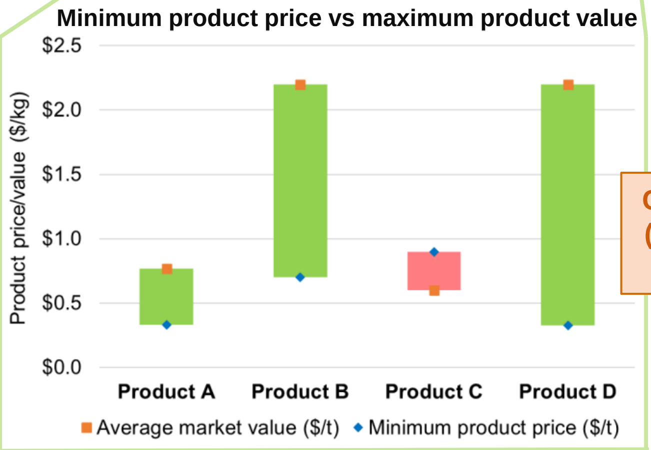
Rationale to choose a molecule that represents a given metabolic space of interest to ABF

Initial list of products from a given beachhead

Product A
Product B
Product C
Product D

Scan for commercial viability

Product A
Product B
~~Product C~~
Product D



Compare minimum product price (sugar costs + theoretical yields) vs market value

Identify promising economic margins

Evaluate candidate molecules

~~Product A~~
Product B
~~Product C~~
Product D

- Known TEA/LCA drivers
- Commercial interest
- ABF research relevance

Gather further data for comparison

~~Product A~~
Product B
~~Product C~~
~~Product D~~

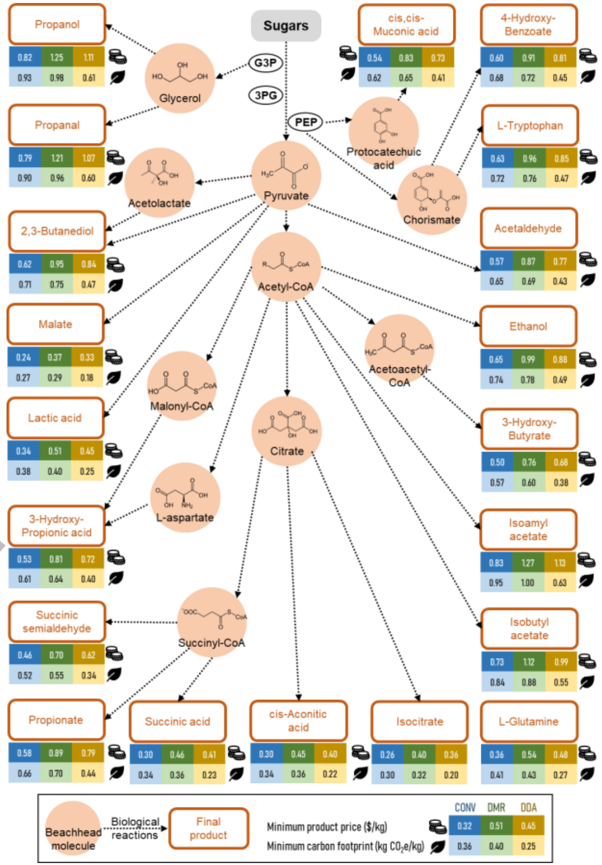
- Titer/productivity/yield
- Aeration requirements
- Fermentation mode
- Separation strategy

Process modeling and full TEA/LCA for the exemplar

GREET LIFE-CYCLE MODEL

Progress and outcomes: prospecting bioproducts

- Absolute-minimum product selling prices and carbon intensities were calculated for selected ABF molecules (diagram to the right)
- Same methodology as in the "exemplar molecule" screening process carried out in this three-year cycle: minimally-burdened production costs and GHG emissions tied to the bioconversion of sugars into different molecules
  - *This methodology purposefully disregards any other common process burdens, such as energy requirements, operational expenses, and capital expenses, to provide an agile way of identifying molecules with potential in achieving positive margins when produced in a biorefinery concept*
- Favored molecules with potential future assessment generally count with high yields from cellulosic sugars



Feedstock	Conventional sugar	Cellulosic sugars (DMR)	Cellulosic sugars (DA)
Cost ($/kg)	0.32	0.51	0.45
C intensity (kgCO_2e/kg)	0.36	0.40	0.25

DA: dilute acid pretreatment
DMR: deacetylation and mechanical refining pretreatment

Changes made since Peer Review 2021

The emphasis on TEA and LCA is one of the highlights of the ABF. **We have continued to use TEA and LCA as guiding tools for the whole consortium, providing guidelines for experimental development based on economic and environmental metrics.**

One question surrounds the selection and pursuit of beachheads. It is really good to see that the rationale for beachhead selection is backed up by case-specific TEA, process, modeling, and LCA, but it is unclear whether these selections are also vetted by potential industry partners. In fairness, some of the beachheads appear to be selected opportunistically based on projects already in flight (e.g., muconic acid). This bias is not intrinsically problematic, but it was not clearly presented, which gives the impression that the selection may be less data-driven than represented. **The process of exemplar molecule selection has been shared with ABF's IAB for comments. Ever since, it has been applied to several additional beachhead molecules and not necessarily bioproducts with direct development under ABF have been chosen (e.g. aconitic acid and polyhydroxyalkanoates [PHA]).**

The use of TEA/LCA to guide the choice of exemplars (and beachheads) is commendable, although as noted, it has some caveats. Some mention was made of including purification (post-fermentation) unit operations in the TEA, which is very important because sometimes the downstream processing costs represent a small fraction of the overall costs, and other times downstream processing accounts for up to 80% of the cost of production via fermentation; thus, it is critical to consider the likely or estimated downstream process when choosing molecule targets and setting TRY goals. **Although the costs of downstream processing for all molecules was already considered in our pre-Peer Review 2021 work, we have increased the interaction with other BETO consortia (such as the Bioprocessing Separations Consortium – SepCon) to ensure that the correct costs with purification are accounted for in the task's workflow.**

Publications, Patents, Presentations, Awards, and Commercialization

- Klein B., Benavides P.T., Kim T., Davis R. ***Agile BioFoundry Integrated Analysis: Techno-Economic and Life Cycle Assessment***. DOE webinar. May 2022 (virtual presentation)