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

Bioprocessing Separations Consortium

Bioenergy Technologies Office Peer Review

March 4-8, 2019

Denver, Colorado

BIOPROCESSING SEPARATIONS CONSORTIUM

Consortium Steering Committee:

Jennifer B. Dunn, Argonne National Laboratory

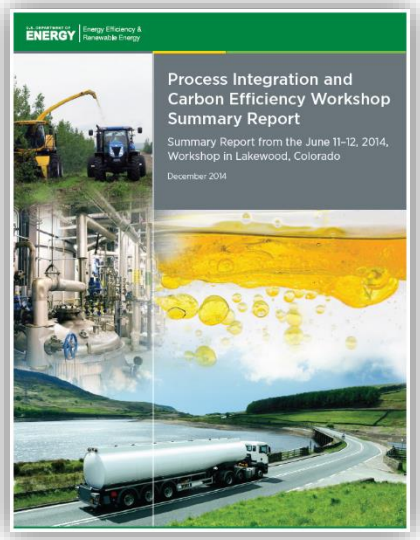
Todd Pray, Lawrence Berkeley National Laboratory

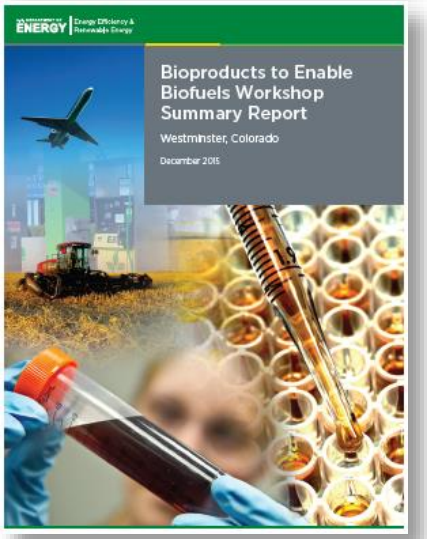
Taraka Dale, Los Alamos National Laboratory

Section 1: Project Overview

1 - Bioprocessing Separations Consortium Rationale

- Overall, industrial separations could constitute up to 15% of total energy consumption in the United States.[1]
- Significantly less mature than current industrial separations, bioprocessing separations are universally costly and complex regardless of conversion pathway.
- Separations costs, technology challenges are barriers to realizing the bioeconomy.
- BETO stakeholders have highlighted upstream and downstream separations and purification challenges as near-term challenges.[2,3]





1. Sholl and Lively. "Seven chemical separations to change the world," *Nature*, 532: 425-437.
2. EERE. 2015. Bioproducts to Enable Biofuels Workshop Summary Report. Workshop held in Westminster, Colorado.
3. EERE. 2014. Process Integration and Carbon Efficiency Workshop Summary Report. Workshop held in Lakewood, Colorado.

1- Bioprocessing Separations Consortium Rationale

The consortium formed in FY17 to address stakeholder feedback that separations challenges impede the cost-competitive production of biofuels and bioproducts. Furthermore, BETO analyses identified separations challenges that, if resolved, could reduce minimum fuel selling price of biofuels by up to 50%.

All biomass conversion pathways require cost-effective, molecularly-efficient separations.

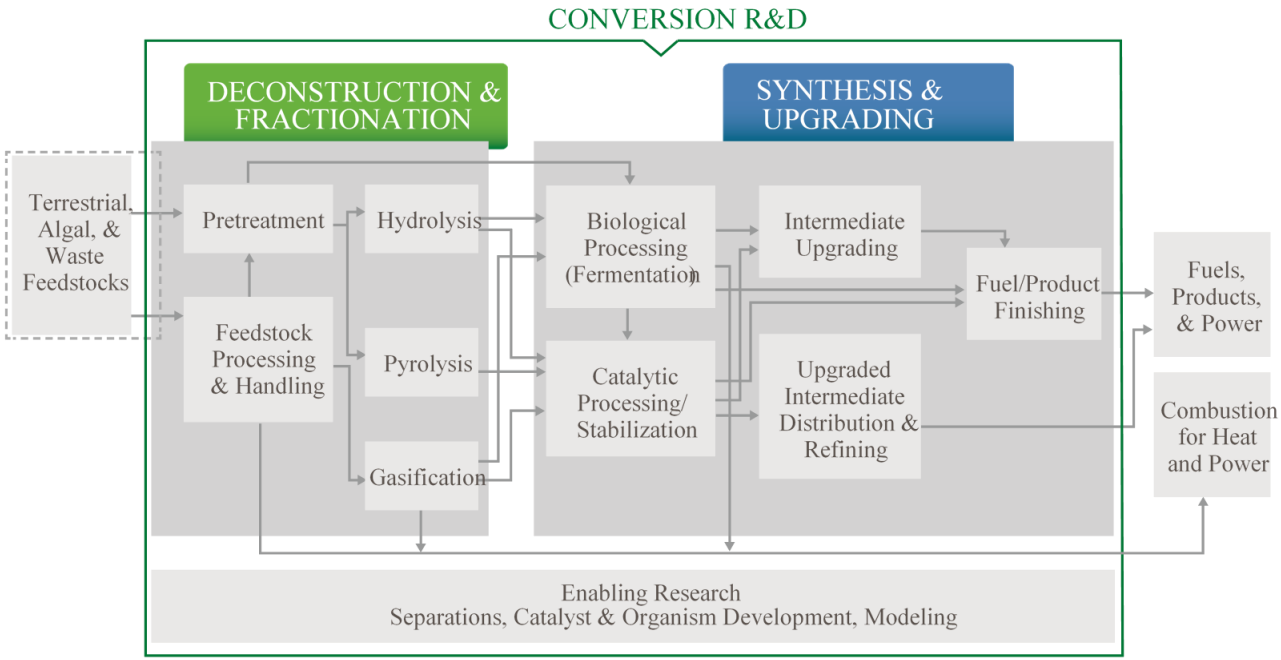


Figure 2-5: Conversion pathways from feedstock to products

1 - Bioprocessing Separations Consortium Overview

Goal: Develop cost-effective, high-performing separations technologies through coordinated separations research that targets industry-relevant bioprocessing separations challenges.

Outcome: Biofuels and bioproducts industries will have new, high-performing, low-cost separations technologies available to them.

Relevance to Industry: BETO industrial stakeholders have long raised separations challenges as a major barrier to cost competitive biofuels and bioproducts. BETO analyses indicate that separations steps can constitute up to 50% of processing costs.

Consortium approach coordinates and brings to bear breadth and depth of national laboratory expertise, capabilities, and resources on this foundational challenge.

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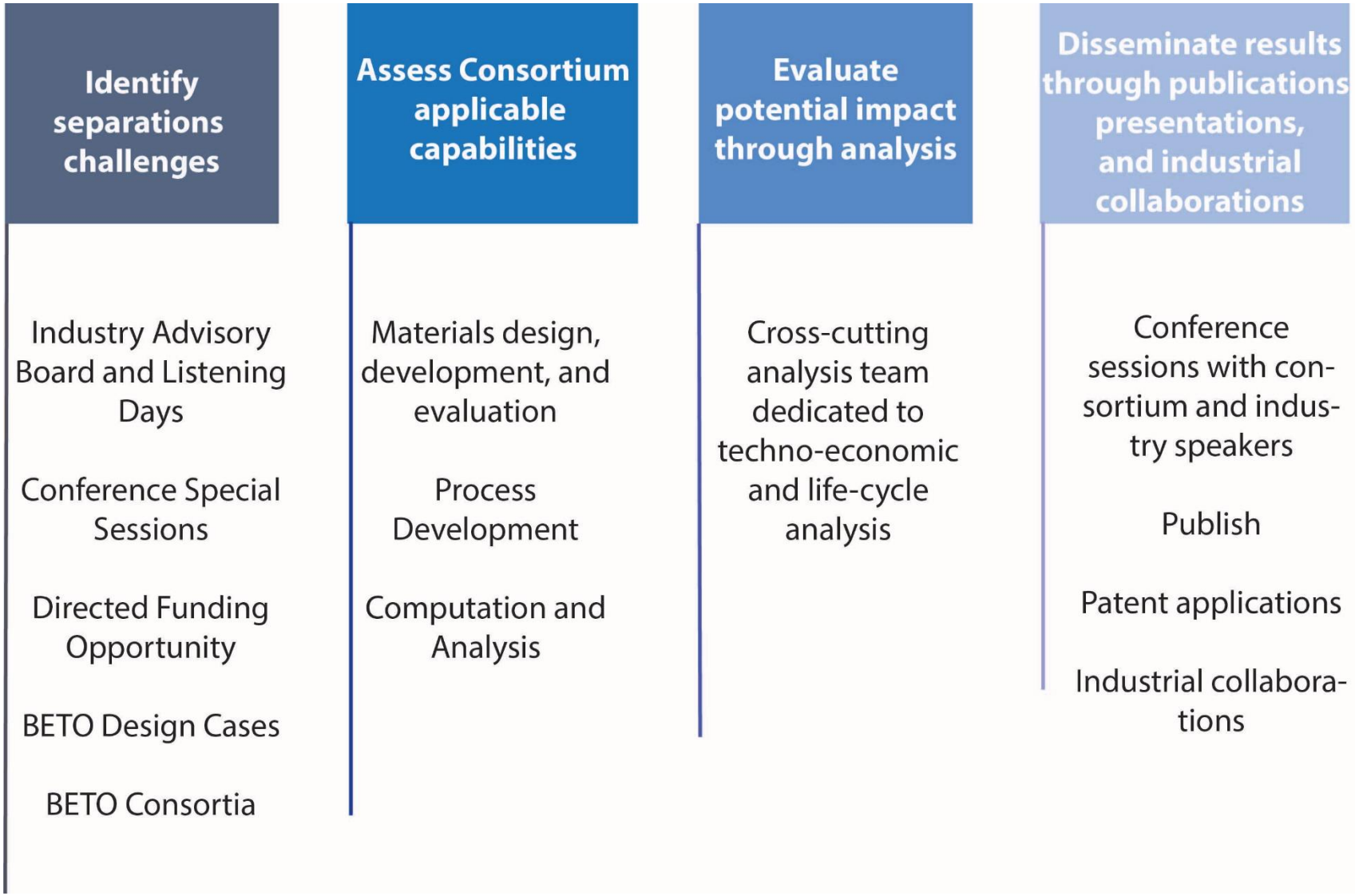
1 - How does the Consortium choose projects?



1 - Major challenges addressed within Consortium

Remove catalyst poisons from feedstocks and fermentation broth	Poisons and foulants like carbonyls, furfural limit the lifetimes of upgrading catalysts and biocatalysts. Selective removal strategies to eliminate them will extend catalyst life and decrease processing costs.
Recover carbon from dilute aqueous streams	Increasing carbon efficiency of processes from recovery of valuable co-products can lead to improved process economics.
Lignin fractionation and valorization	Lignin fractionation enables conversion to valuable co-products that can enhance process economics and sustainability.
Process integration	Reducing the number of processing steps associated with separations, including through reactive fermentation and in-situ product recovery, reduce process energy intensity and costs.

Quad chart overview

Timeline

- Start date: October 2016
- End date: September 2019
- Percent complete: 75%

	Total Costs Pre FY17	FY 17 Costs Total/ Steering Committee	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE funded	$500,000	$3,010,000/ $205,000	$3,485,000/ $90,000	$3,475,000/ $90,000
Labs' Share		ANL: 23%/20% INL: 6%/10% LANL: 7%/17% LBNL: 5%/15% NREL: 25%/10% ORNL: 20%/10% PNNL: 8%/10% SNL: 6%/10%	ANL: 29%/44% LANL: 6%/39% LBNL: 3%/17% NREL: 27%/0% ORNL: 29%/0% PNNL: 7%/0%	ANL: 29%/33% LANL: 6%/33% LBNL: 3%/33% NREL: 26%/0% ORNL: 30%/0% PNNL: 6%/0%

Barriers addressed

- **Ot-B: Cost of Production. Advanced and robust separations and molecular efficiency are required to reduce the up to 50% share of separations costs in bioprocesses.**

Objective

Develop cost-effective, high-performing separations technologies through coordinated separations research that targets challenges relevant to industry and BETO.

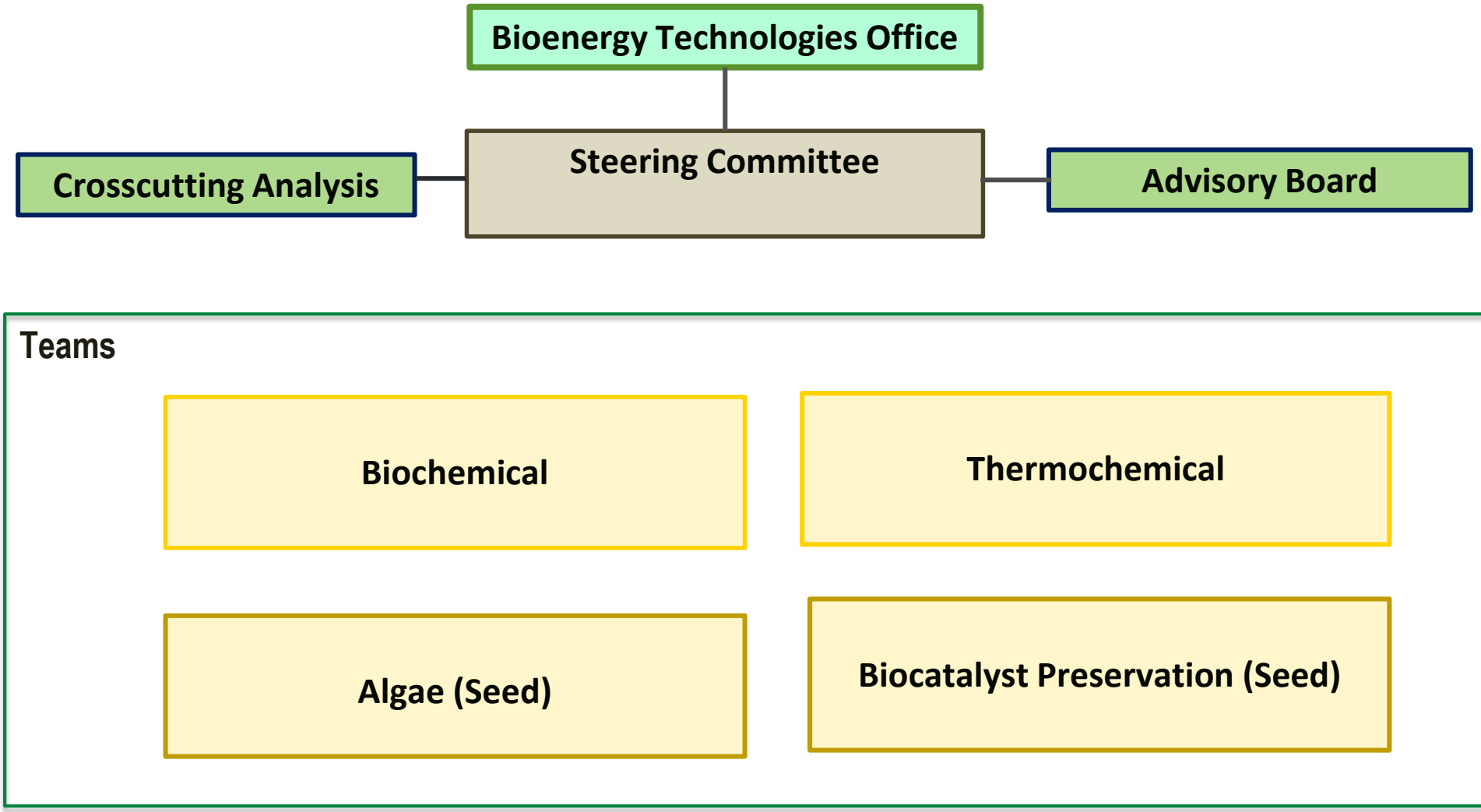
End of Project Goal

Technical goals will be covered in each team's presentation.

Demonstrate the consortium's value to BETO and the biofuel and bioproduct communities through documentation of technical advances, influence on process economics, and potential industrial applications of consortium technologies.

Section 2: Management Approach

2 - Original Separations Consortium Structure FY17



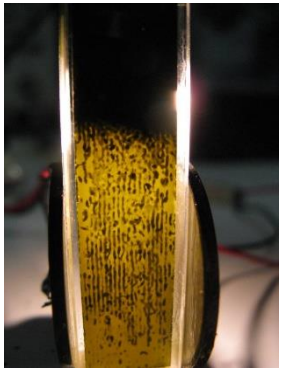
- Seed projects met go/no-go targets.
- Seed structure not a good fit with planning process and was discontinued.

2 - Go/No-Go decision for algae seed project

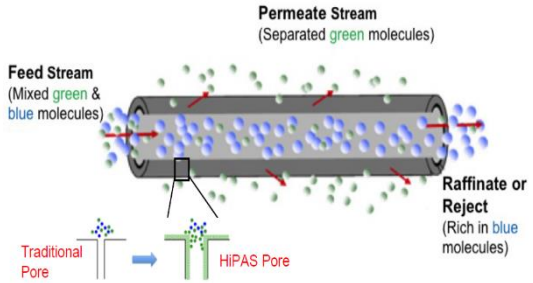
Background: Algae dewatering is a cost driver in algal biofuel pathways. Concentration must increase from ~0.5 g/L to 200 g/L in some cases.

Hypothesis: Advanced membrane technologies and ultrasonic separations can concentrate microalgae to ≥10 g/L and >50 g/L, respectively.

(Step 1) Ultrasonic Separation



(Step 2) Crossflow Membrane



Result: Advanced membrane technologies and ultrasonic separations achieved microalgae concentrations of 70-100 g/L and 79 g/L, respectively.

Outcome: Technical targets exceeded, algae team briefed on results.

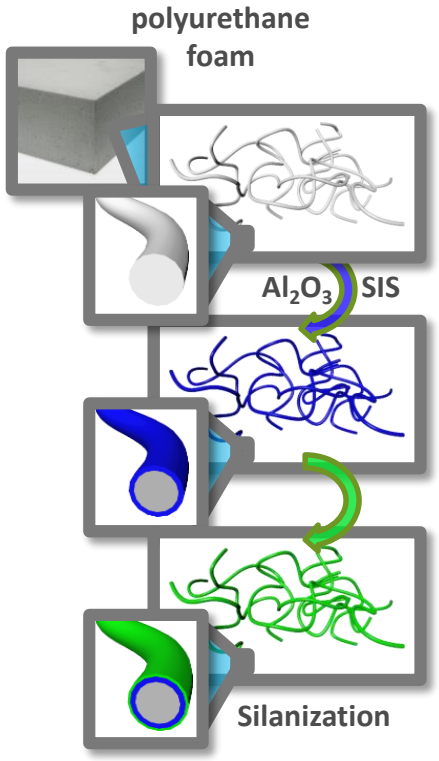
2 - Go/No-Go decision for biocatalyst preservation seed project

Background: The use of tailored nanostructured adsorbents with specificity for removal of toxins and inhibitors could drive down the costs of bioconversion of lignocellulosics to biofuels and bioproducts.

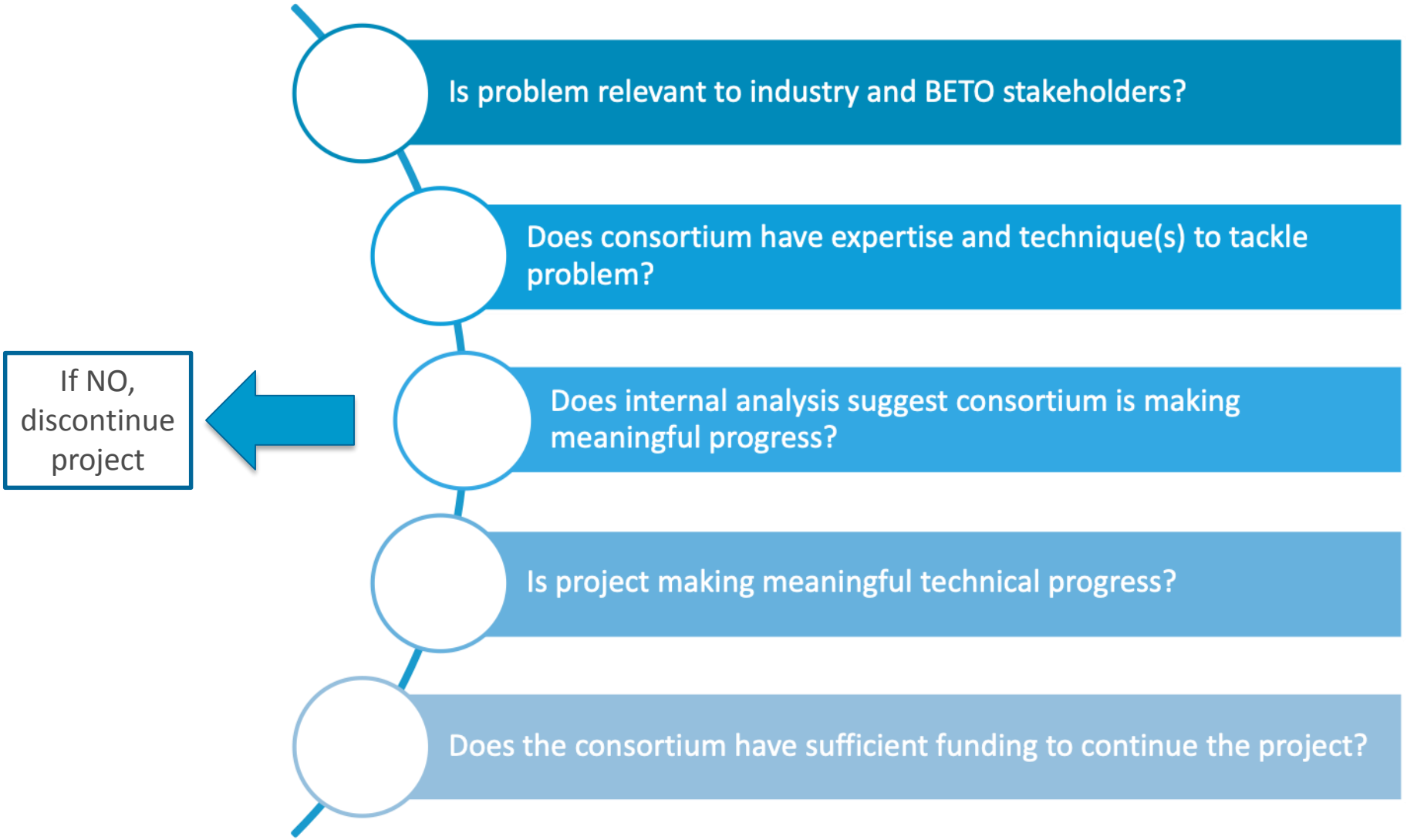
Hypothesis: Nanostructured adsorbents can exhibit a specificity of 4:1 for one feedstock contaminant and one inhibitor.

Result: Specificity exceeded 4:1 for several compounds including feedstock-based inhibitor furfural (>10) and fermentation-based inhibitor methylglyoxal (>15).

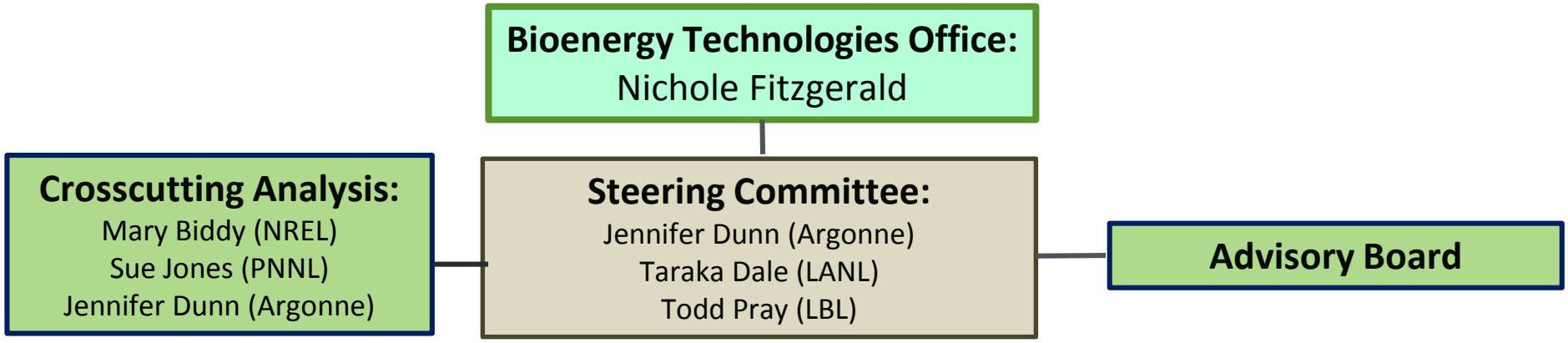
Outcome: Technical targets exceeded. Elements of this work now rolled into biochemical conversion team.



2 - Go-No Go decisions determine if a project is no longer appropriate for the Separations Consortium



2 - Separations Consortium Structure FY18 and FY19

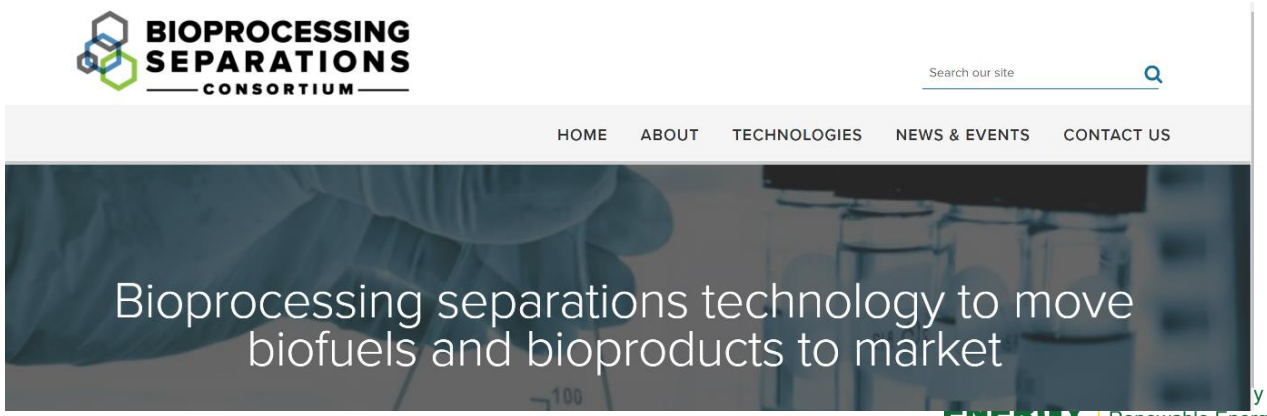


2- Approach (Management)

Consortium Management

- Monthly full-consortium calls to update on business and technical accomplishments; each team has regularly scheduled calls
- **Cross-team interactions** leverage results and information
- **Cross-cutting analysis team** engages with each R&D team to inform technical targets, economic impact of projects
- Stream stewards produce commonly-used, **exemplary streams** for separations experiments within different teams
- Internal sharepoint for file management
- **External website** established to disseminate information about the consortium and provide stakeholders information about current project portfolio and how to interact with the consortium.

http://bioesep.org/

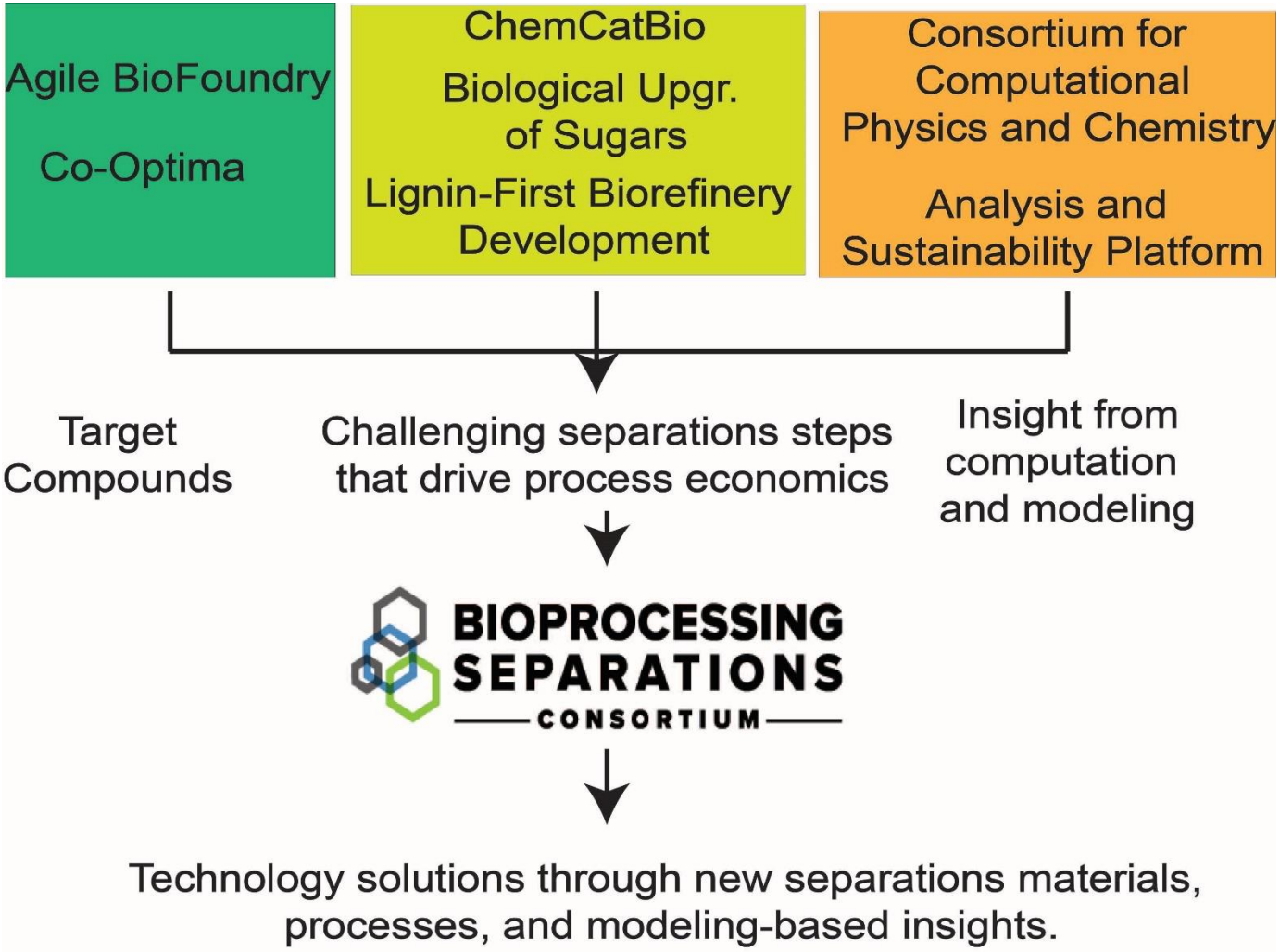


2 - Industrial Advisory Board

- Industrial Advisory Board Interactions
  - Consortium holds biannual face-to-face meetings with IAB
  - IAB receives quarterly reports, publications as pre-reading and presentations regarding technical progress and future plans
  - Feedback is delivered to consortium steering committee and team leads after a closed-door session.

- Industrial Advisory Board Charter
  - Help the consortium maintain an industry-relevant focus and knowledge of recent technology advances and challenges.
  - Provide advice, review results and progress in comparison with work plans, provide feedback regarding prioritization of research projects (experimental and analytical), and inform development of the consortium's strategy for out years.

2 - Interactions with BETO Consortia and Projects



Section 2, continued: Technical Approach

2 - Technical Approach

Biochemical Team

- Enable recovery of target products from fermentation
- Enable separations relevant to lignin valorization

Thermochemical Team

- Remove bio oil feed contaminants to preserve upgrading catalyst performance in catalytic fast pyrolysis
- Valorize carbon from bio oil process streams
- Intensify separation processes

Analysis Team

- Quantify and document technical advances, influence on process economics and sustainability, and potential industrial applications of consortium technologies.

2 - Steering Committee Objectives and Achievements

Objectives

- **Consortium guidance**: Lead discussions on technical direction, external engagement
- **Progress and impact monitoring**: Evaluate milestone status, risks affecting projects in the portfolio
- **Coordinate external communications**: Interactions with Industrial Advisory Board, establish and maintain website
- **Manage consortium business**: Reporting, monthly conference calls

Achievements

- **Established Industrial Advisory Board and coordinate board communications and meetings**
- **Held industrial listening day**
- **Developed and expanded website to communicate consortium capabilities, progress**
- **Coordinated Directed Funding Opportunity**
- **Managed consortium reporting and monthly communications**

2 - Challenges and critical success factors

Challenges

- Characterizing baselines and potential impact for all projects holistically in the consortium
- Communicating within and external to consortium regarding separation technology advancements and needs
- From large potential project space, selecting most impactful projects

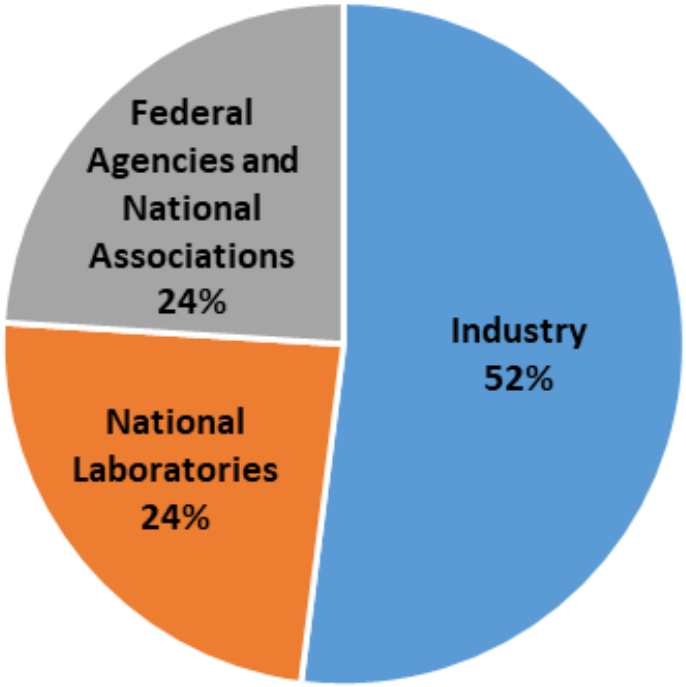
Critical success factors

- Strong analysis team with sufficient resources for baseline characterization, quantification of project impacts
- Scheduled strategic meetings for intra- and inter-consortium communications
- Intentional interaction with industrial stakeholders through listening days, conference sessions, funding opportunities
- Well-maintained and informative website to attract collaborators
- Clear definition of project selection criteria and adherence to these criteria during project selection

Section 3: Technical Accomplishments

3 - Industry workshop in Collaboration with AltSep

- Breakout sessions covered industry-relevant separations issues and streamlining collaborations with the national laboratories
- Public report serves as reference for consortium planning



Summary of Bioprocessing Separations Consortium
Industrial Listening Day

Held
May 23, 2017 at BWI Sheraton

Report v1 dated: June 30, 2017

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https://bit.ly/2CS9hVo

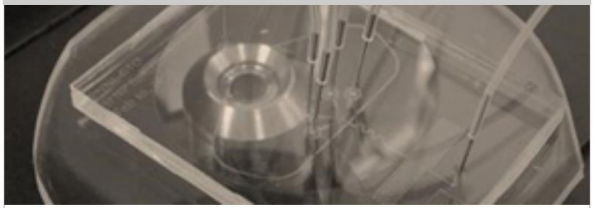
3 - Special Sessions at Targeted Conferences

- The Bioprocessing Separations Consortium held special sessions at two conferences in 2018 with invited speakers from industry to highlight bioprocessing separations challenges and disseminate information about the consortium and its technical progress.
- 40th Symposium on Biotechnology for Fuels and Chemicals
  - Genomatica
  - Clemson
  - Delft University of Technology
  - Food Research Institute, Japan
  - NREL
  - University of Minnesota

- BIO World Congress on Industrial Biotechnology (Philadelphia, PA in July) – attended by 60 people
  - ProSim
  - LanzaTech
  - Bioprocessing Separations Consortium

3 - Website showcases capabilities

Capabilities



Separations Materials Development & Evaluation

The Bioprocessing Separations Consortium has the capability to develop separations materials including functionalized membranes, adsorbent materials with unique physical properties, biosorbents, polymer resins and to develop advanced solvents.Furthermore, advanced materials characterization capabilities lend insight into how material development conditions, material composition, and other factors influence structure that drives performance.

Membrane Materials

Consortium members develop tailored membranes for different separations applications. Membrane technologies include high-throughput membranes, seeding and growth systems applied to inorganic

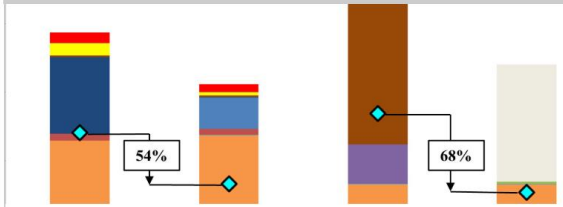
Separations Process Development

The Bioprocessing Separations Consortium tests separations strategies employing new materials, process intensification, and other strategies with techniques involving membranes, advanced sorbents, catalytic filtration, and other methods.

Process Evaluation at Multiple Scales

Consortium members have equipment and expertise to assess different separations approaches from membrane separation to liquid-liquid extraction at multiple scales.

- Advanced Biofuels and Bioproducts Process Development Unit: Lawrence Berkeley National Laboratory's ABPDU hosts many different types of equipment to evaluate approaches to separations challenges: centrifuges, tangential flow filtration units, liquid-liquid extraction columns, wiped film



Analysis & Computation

The Bioprocessing Separations Consortium evaluates the economic viability of separations approaches and the influence of separations approach on overall process energy and environmental impact. Furthermore, the Consortium partners with the Computational Chemistry and Physics Consortium to apply computational approaches to separations challenges.

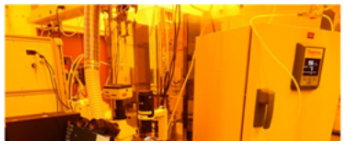
Techno-economic and Sustainability Analysis

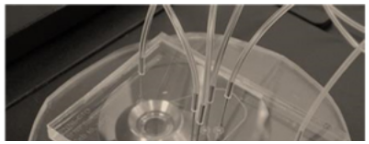
- Techno-economic and Sustainability Analysis: The National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratory team together to carry out techno-economic and sustainability assessments of integrating new separations approaches into bioprocesses

www.bioesep.org/capabilities

Advanced Sorbent Development and Scaleup

Capability Title	Advanced Sorbent Development and Scaleup
Laboratory	Pacific Northwest National Laboratory (PNNL)
Capability experts	Pete McGrail and Radha Motkuri
Description	PNNL has both batch and continuous processing technologies for producing test quantities of new advanced sorbent materials, including advanced zeolites and custom MOF (Metal Organic Framework) compositions. PNNL's capabilities also include the associated compositional and performance characterization equipment for wide range of gases and vapors. PNNL has licensed a continuous particle growth technology for sorbent scale-up technology to Innaventure LLC, whose business is focused on providing industrial quantities of advanced sorbents. Another continuous system that has been developed is based on using microfluidic cells produced with photolithographic manufacturing, leveraging the capabilities in PNNL's EMSL user facility.
Limitations	The continuous sorbent scale-up system is currently limited to the homogeneous liquid reaction conditions and addition of a slurry injection system which allows heterogeneous liquids or solid/liquid systems is in progress.
Unique aspects	PNNL's continuous sorbent development systems enable larger-scale, higher quality, and more diverse production of MOFs, while cutting costs for commercial applications while also reducing process energy use and greenhouse gas emissions. PNNL's unique analytical capabilities include *in situ* Flow Cell TEM and High Temp/ High Pressure AFM for analyzing growth characteristics for sorbent precursors and products at nanometer and sub-nanometer scales. An *in situ* XRD Flow Cell has also been developed to characterize bulk crystals during formation.
Availability	Capabilities are available for consideration to new clients
Citations/references	https://www.pnnl.gov/news/release.aspx?id=4387 Jambovane S R, Nune S K, Kelly R T, McGrail B P, Wang Z , Nandasiri M I, Katipamula S , Trader C D, Schaef H T 2016. "Continuous, One-pot Synthesis and Post-Synthetic Modification of NanoMOFs Using Droplet Nanoreactors." Scientific Reports. 6, (36657). DOI:10.1038/srep36657



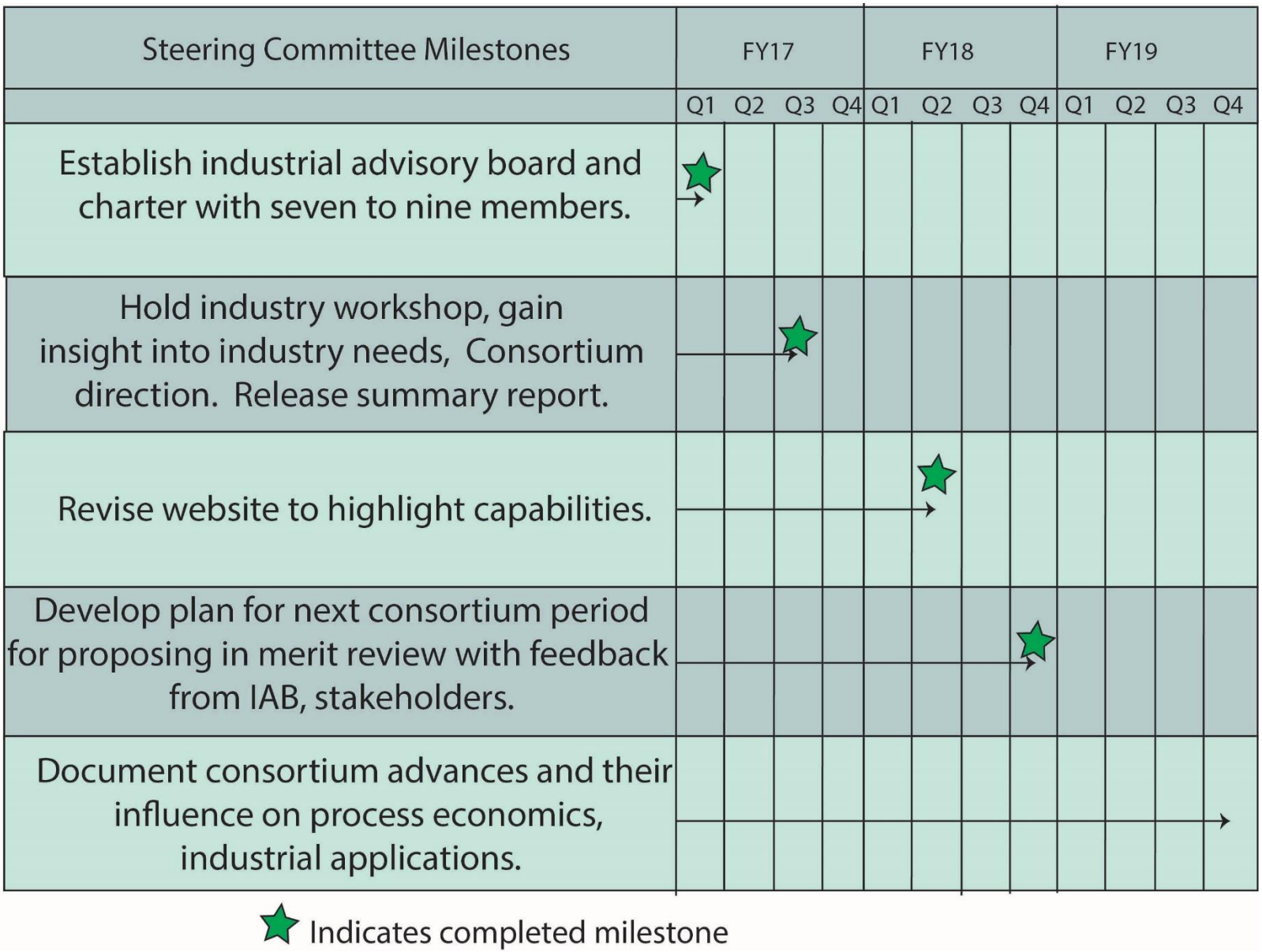


Capability descriptions provide additional information, including limitations on equipment operations, unique aspects of equipment.

3 - Separations Consortium Directed-Funding Opportunity

- **Goal:** Accelerate the development of separations technologies for the commercialization of biomass-derived fuels and chemicals through engaging with industry to overcome their most pressing bioprocessing separations challenges and leveraging Separations Consortium capabilities and expertise
- **Approach**: Conference calls with interested applicants to review industry needs, consortium capabilities and to identify partners
- **Result**: $2.4 million in federal funds requested (>2x over subscription). Five $200k federal fund projects awarded
- **Outcome:** Opportunity for industry to test BETO funded separations technologies/validate that these technologies have promise

3 - Milestone Chart



Section 4: Relevance

4- Relevance

Goal of the Bioprocessing Separations Consortium:

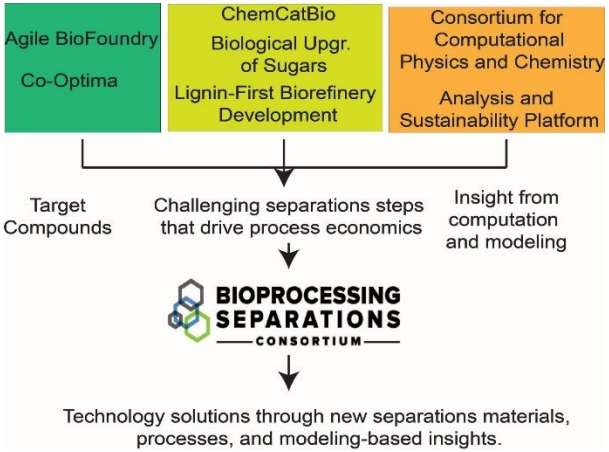
- Develop cost-effective, high-performing separations technologies through coordinated separations research that targets challenges relevant to industry and BETO.

Why is this project important and what is the relevance to BETO and bioenergy goals?

- Bioprocessing separations are challenging, expensive, and require coordinated resources and effort across the national laboratories to address
- It directly addresses BETO's mission to develop and transform renewable biomass resources into commercially viable biofuels
- It interfaces with BETO consortia and the conversion program to holistically address separation challenges

How does this project advance the State of Technology?

- Currently, separations costs can be 50% of total processing costs.
- The project develops new materials and processes to lower bioprocessing costs towards BETO targets as borne out by analysis.
- Success of the consortium will elevate and enable strategic incorporation of cost-effective, efficient separations in bioprocessing at the initial stages of process design.

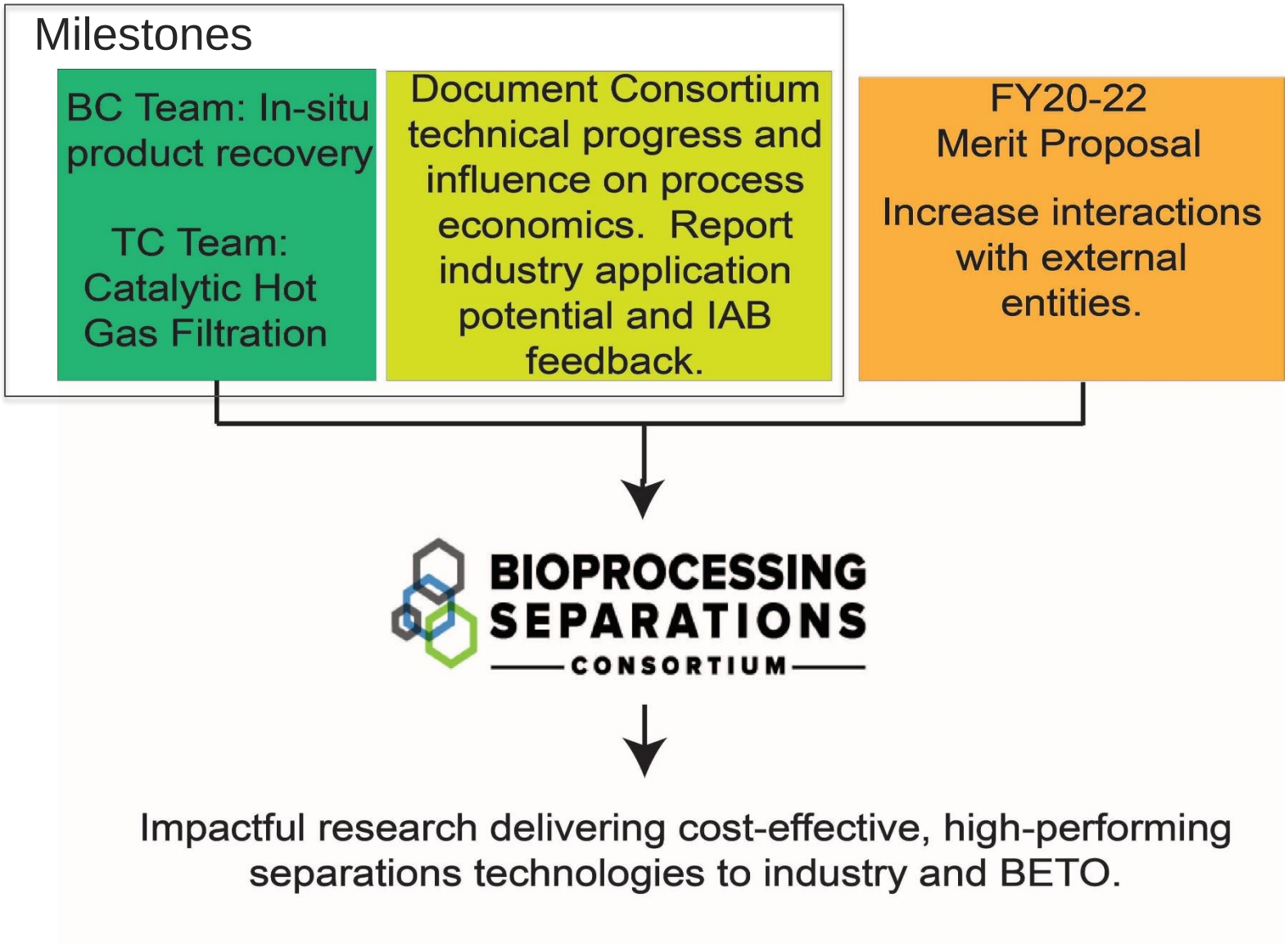


4 - Relevance to Industry

- The Consortium disseminates information to industry and gathers insight from industry regarding challenges and barriers to cost-effective, efficient separations through:
  - Engaging with a nine-member industrial advisory board that includes technology developers and companies working biochemical processing and thermochemical processing
  - Holding listening days with industry
  - Interacting with industry through special sessions at relevant conferences
  - Holding a directed funding opportunity that directly engages industry and national laboratory investigators in collaborative projects to advance the state of technology for industrial use
  - Maintaining a website that communicates national laboratory capabilities in developing separations technologies

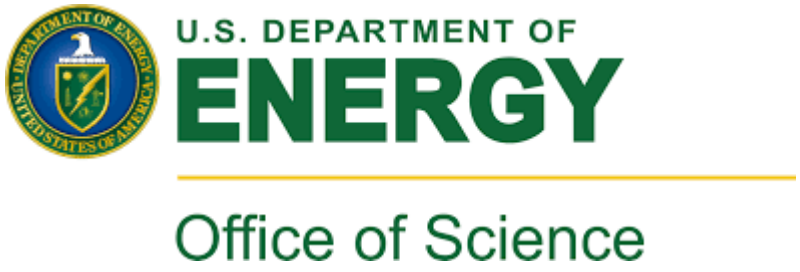
Section 5: Future Work

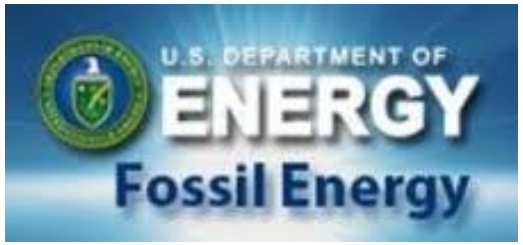
5 – Future Work



5- Future Work

The consortium will expand interactions with external entities to disseminate information about consortium capabilities and technical progress, identify collaboration opportunities.





Summary

Overview	**Develop cost-effective, high-performing separations technologies through coordinated separations research that targets challenges relevant to industry and BETO**
Approach	• Select consortium project based on understanding of BETO and industry needs • Use economic and sustainability analysis as guiding tools in project evaluation and selection • Interact with internal and external stakeholders to achieve impactful project portfolio, disseminate results
Progress	• **Industry interaction-** Held well-attended industry listening day, met with industrial advisory board biannually, organized two special sessions at strategic conferences to disseminatee progress and gain input, and conducted directed funding opportunity . • **Communications -** Redesigned website to highlight and provide detail concerning consortium capabilities • **Consortium organization –** coordinate intra-consortium planning, communications and reporting
Relevance	**Consortium develops new materials and processes to lower bioprocessing costs towards BETO targets and, more generally, for industrial stakeholders, as borne out by analysis**
Future Work	• Achieve technical targets for biochemical and thermochemical teams • Report on consortium success and progress • Plan for and propose a new three-year project period • Engage with additional external stakeholders

Additional Slides