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DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

1.3.4.100 HTL Model Development

MARCH 24, 2015
ALGAE

Sue Jones
Yunhua Zhu, Lesley Snowden-Swan, Dan Anderson, Rich Hallen, Karl Albrecht, Doug Elliott, Andy Schmidt
Pacific Northwest National Laboratory

Goal Statement for HTL Model

GOAL: Enable **R&D** to produce **sustainable, economic liquid fuels** through **targeted research** coupled with techno-economic analysis **(TEA)** leading to **optimized algal conversion processes.**

- **This project directly supports BETO's goals to:**
  - "*Enable **sustainable**, nationwide **production of biofuels** that are **compatible with** today's **transportation infrastructure**, can **reduce greenhouse gas emissions** relative to petroleum-derived fuels, and can **displace a share of petroleum-derived fuels** to reduce U.S. dependence on foreign oil.*
  - *Encourage the creation of a new domestic bioenergy and bioproduct industry.*" (Nov. 2014 MYPP)

Quad Chart Overview

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Timeline

- Start: October 1, 2013
- End: September 30, 2017
- Percent complete: 30%

Budget

	Total Costs FY 10–FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding FY 15-FY17
DOE Funded	$0	$239K	$317K	$1,888K

Barriers

- Barriers addressed
  - **At-A**: Comparable, transparent and reproducible analysis
  - **St-C**: Sustainability data across the supply chain
  - **Aft-I**: Algal Feedstock Preprocessing

Partners*

- Partners:
  - **WSU**: water treatment (5% FY15)
- Interactions/Collaborations:
  - **ANL:** life-cycle analysis
  - **NREL:** farm model TEA
  - **INL:** related analysis
  - **CSU:** fuel quality analysis
  - External reviewers for design case

* See additional slides sections for all abbreviations & acronyms used in this presentation

Project Overview

- **History** Project includes **experimental** and **TEA** aspects
  - **FY13**: Project started & **design case** (2022 projection) completed
  - **FY14**: 2014 State of Technology (**SOT**) baseline completed
  - **FY15**: Setting **technical targets** for 2015 and beyond

- **Context** **Economic** and **sustainable** algal based biofuel production - **HTL well suited** for **processing wet feeds** to produce intermediate oils with **higher yields than solvent extraction** baseline from NAABB

- **Key Objective** Use **consistent assumptions** and **experimental data** to estimate projected commercial scale mature plant costs, and **establish research targets** for HTL, oil upgrading, water treatment and nutrient recycle

Approach (Technical)

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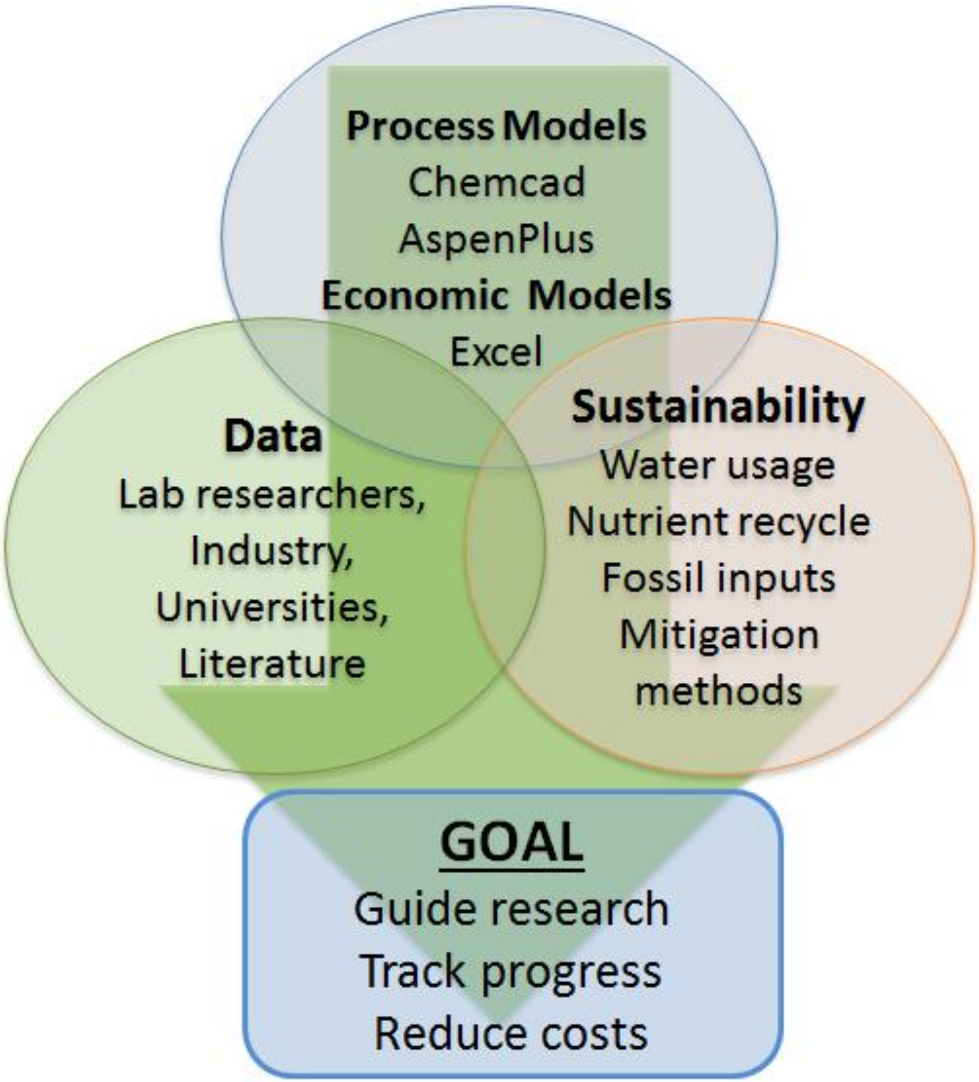
Approach structure



- **Approach Consistent** use of **BETO** technical and financial **assumptions** (detailed later)
- **Critical Success Factors**
  - Identify **cost reduction** strategies
  - Help **set research goals**
  - Quantify **sustainability impacts**
- **Potential Challenges – risk and uncertainty:**
  - **Sensitivity** studies to **assess uncertainties**
  - Conclusion uncertainties **Risk management**:
    - Peer review
    - Interaction with industry
    - Multi-lab collaborations
    - Make assumptions transparent

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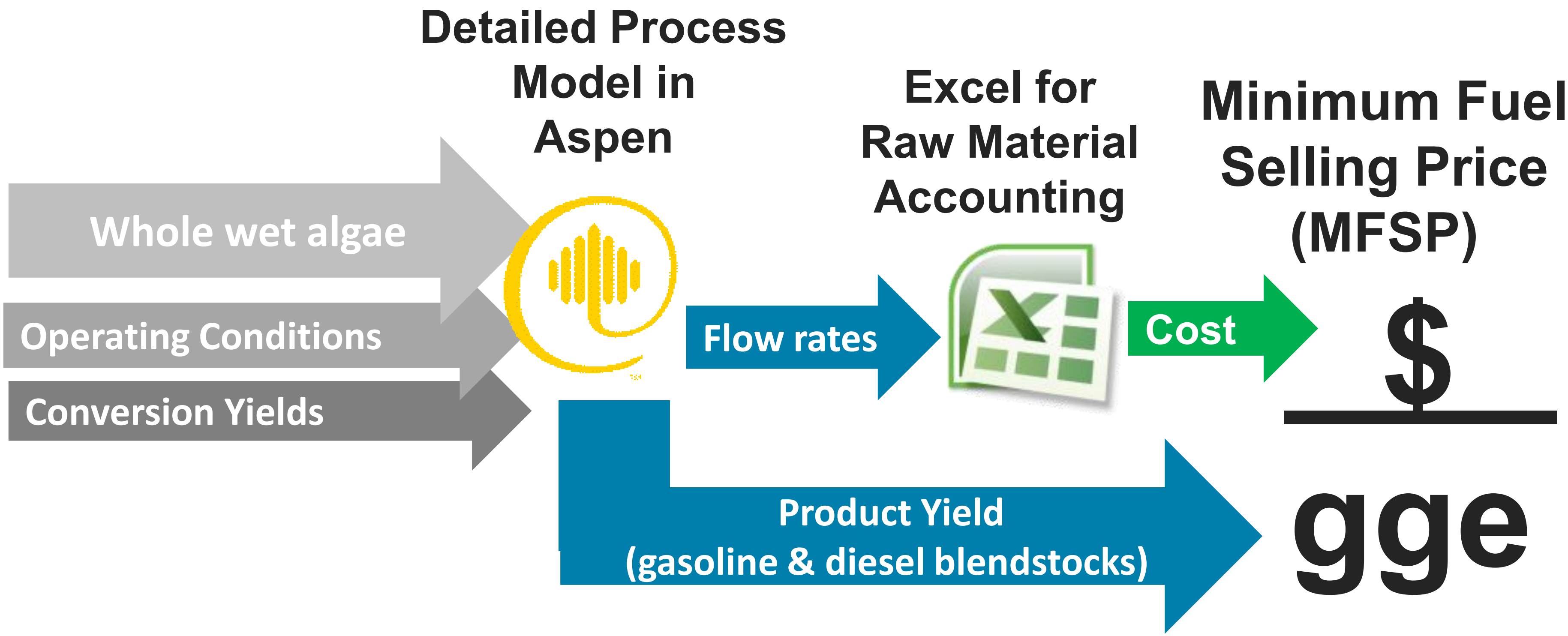
Approach for Conversion Analysis

Same methodology used across all labs



Approach (Management)

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- **Approach structure**
  - **Project Management Plan** (PMPs) in place indicating scope, budget and schedule
  - **Annual Operating Plans** (AOPS) prepared prior to each fiscal year: Details quarterly **milestones** and **deliverables**
  - **Quarterly reporting** to BETO (written & regularly scheduled calls)
- **Potential challenges and Risk Mitigation**
  - **Data availability**: timely and frequent communication with researchers
  - **Researcher proximity**: scheduled calls & data exchanges with NREL and ANL for collaborative work
- **Critical success factors**
  - Make **results public** (MYPP and published reports)
  - Deliver quality work **on-time**, **on-budget**

Technical Accomplishments since 2013 Review (Overview)

- **Algal conversion to diesel via hydrothermal liquefaction and bio-crude upgrading**
  - Completed **biocrude hydrotreating** and **waste water treatment** experimental work for input into models
  - **Design report** published with **2022 target**: externally peer reviewed
  - **2014 SOT report** published providing a **baseline** from which technical progress can be measured
  - 2014 SOT and 2022 targets **published in MYPP**
  - Completed “Harmonization” analysis with ANL, NREL, PNNL to couple **resource assessment** with **TEA** and **LCA**
  - Developing multiple **sensitivity scenarios** for experimentalists leading to out-year cost targets
  - Supported ANL’s Supply Chain Sustainability Analysis (**SCSA**) LCA for this conversion process

Technical Accomplishments: Whole Algae Conversion Design Report – 2022

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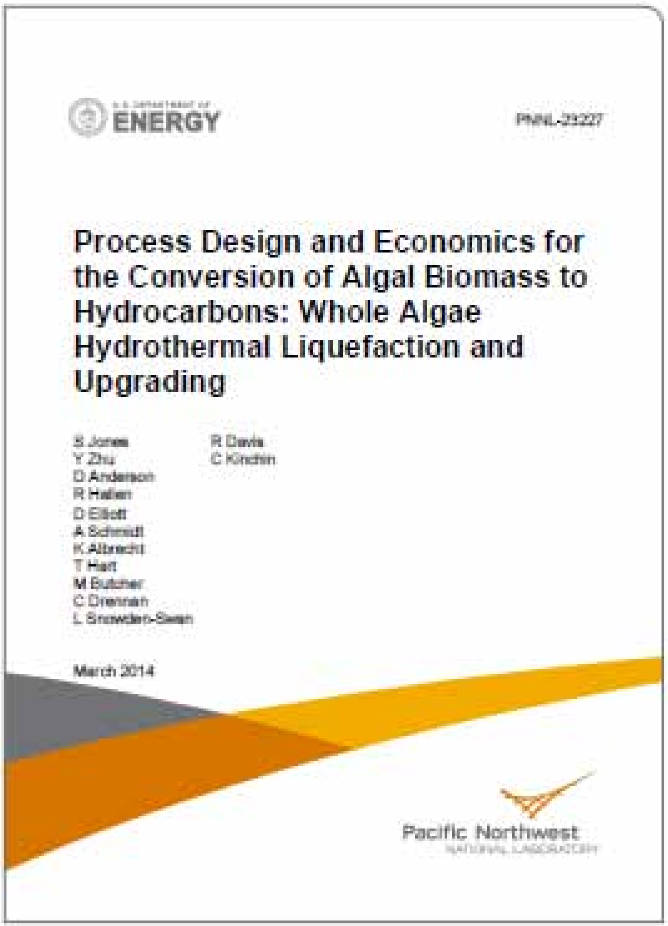
- **Published March 2014***
- Farm costs from NREL



U.S. DEPARTMENT OF ENERGY

PNNL-23227

Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading

S Jones, Y Zhu, D Anderson, R Hallen, D Elliott, A Schmidt, K Albrecht, T Hart, M Butcher, C Drennan, L Snowden-Swan, R Davis, C Kinchin

March 2014

Pacific Northwest
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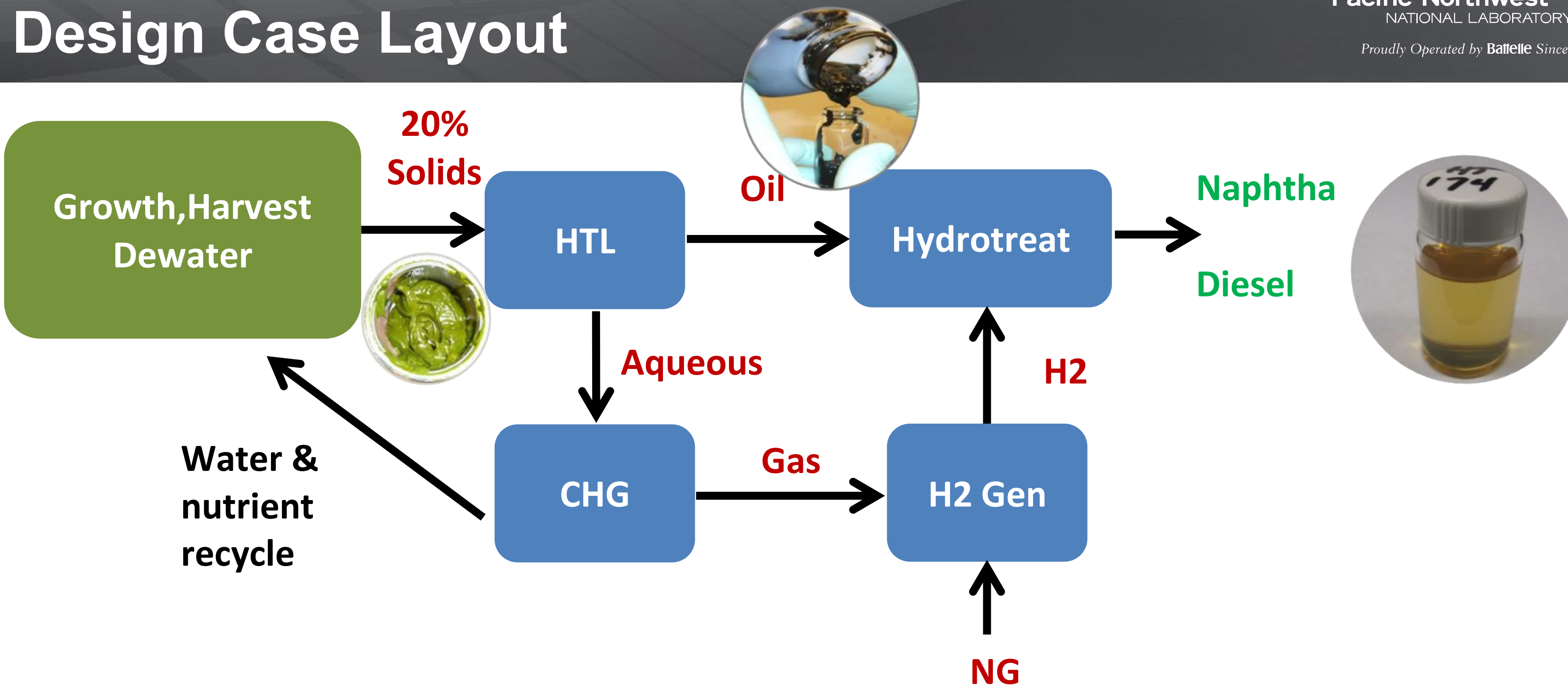
- Purpose: **Establish technical and economic targets for 2022 timeframe**
- **Key assumptions**:
  - Conversion only: 1340 dry metric tonnes per day algae (AFDW)
  - Algae delivered at 20 wt% solids (AFDW basis)
  - $430/dry ton feedstock (from the MYPP)
  - 40% equity financing, 10% IRR
  - 60% debt financed at 8% for 10 years
  - Costs in 2011 $ for a mature n^{th} plant
- **Externally peer reviewed** by 11 experts from 9 institutions (industry & university). Reviewers and review comments provided to BETO and NREL
  - Overall approach sound
  - **HTL makes sense for high water content feeds**

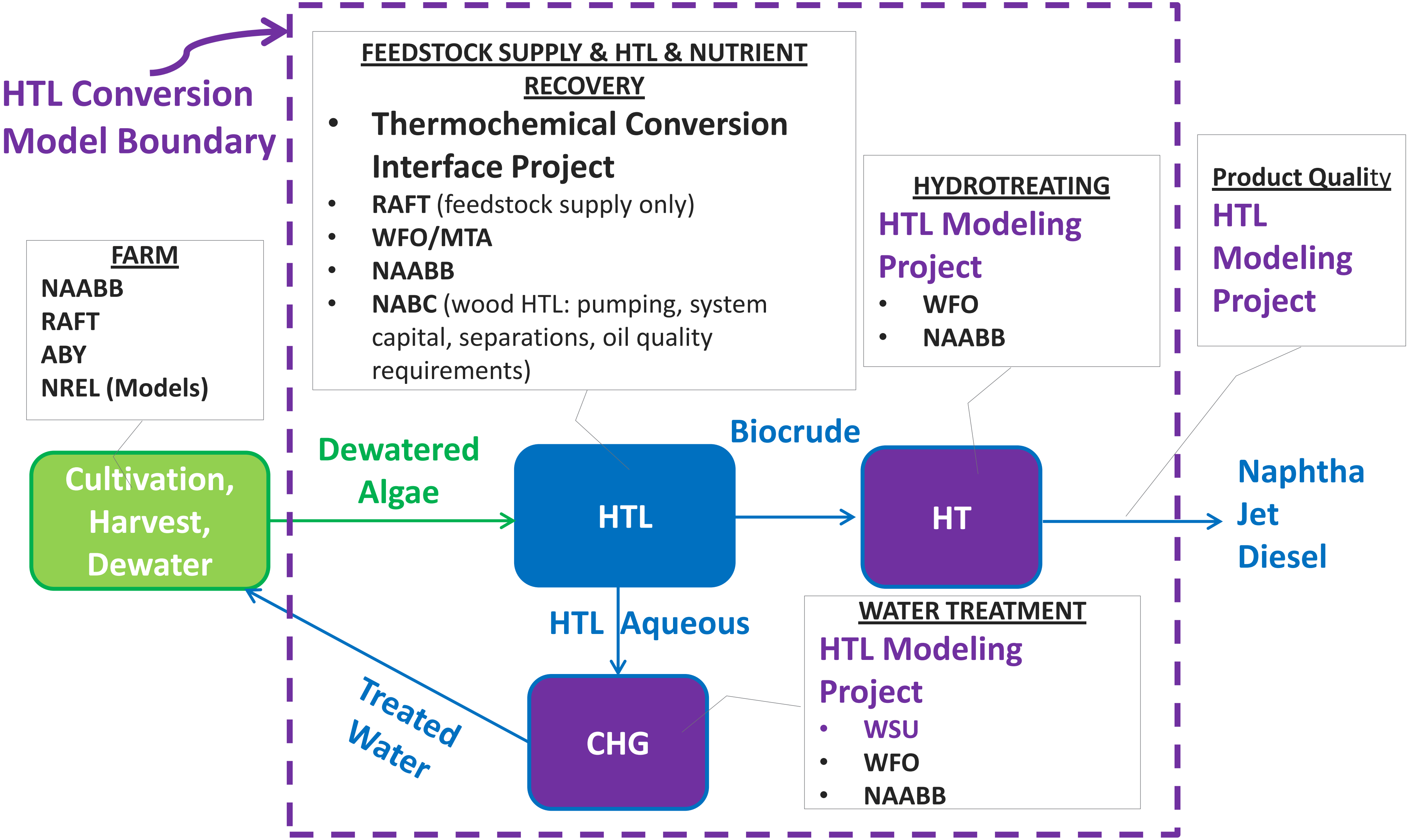
* http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf

Technical Accomplishments: Design Case Layout



- **Hydrothermal Liquefaction (HTL)** ~3000 psia, 350 C, no catalyst
- **Bio-crude Hydrotreating (HT)** fixed bed reactor ~1500 psia, hydrogen in excess of chemical consumption
- **Catalytic Hydrothermal Gasification (CHG)** ~3000 psia, 350 C, fixed bed
- **Seasonal variability** handled by drying and storing a portion of the excess summer production (30%) for later use in winter
- **Consistent** experimental data: **HT** and **CHG feeds** from same **HTL** run

Technical Accomplishments: Data Sources for Model



Technical Accomplishments: Data Sources for Design Report (2022 target)

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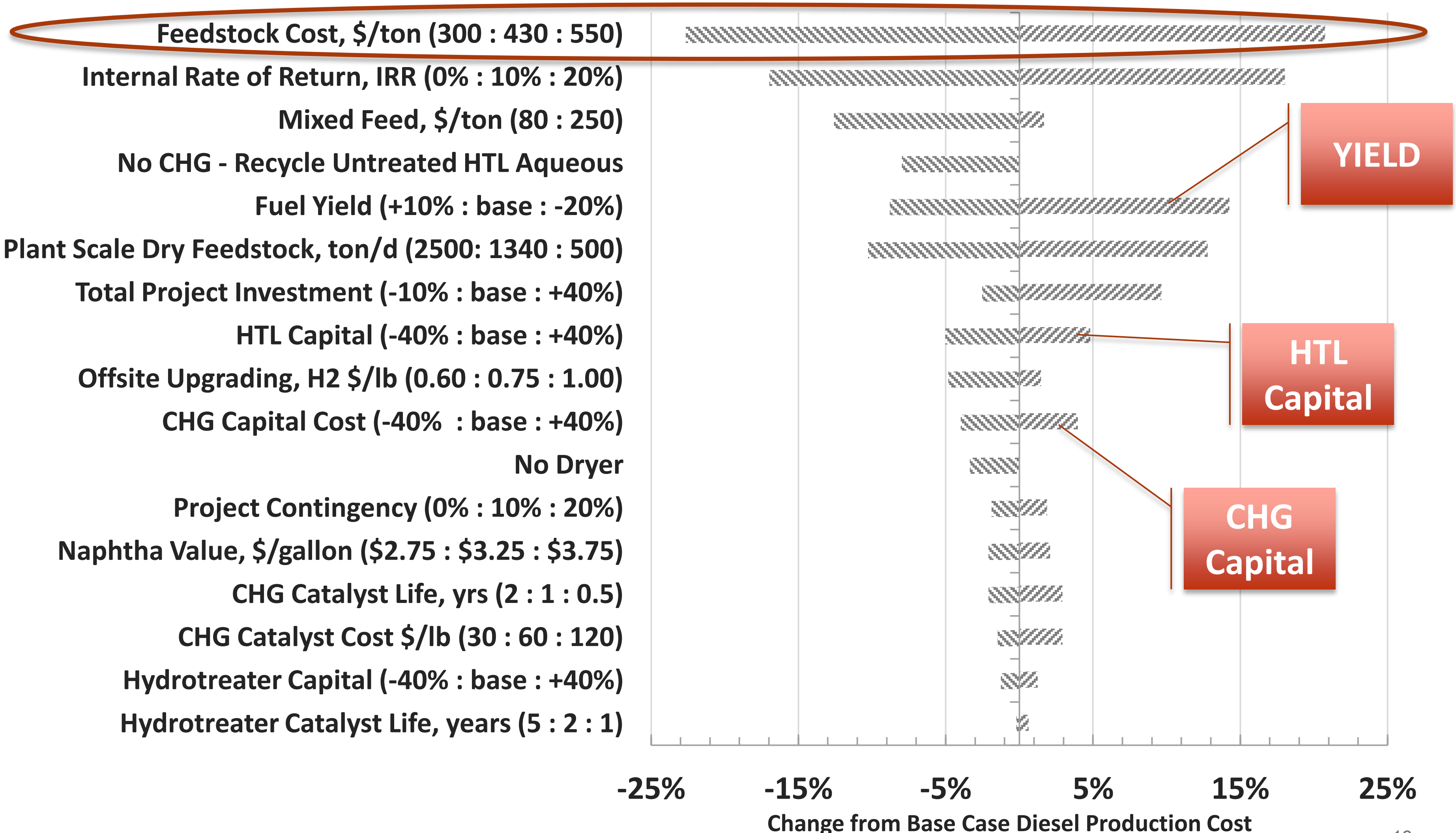
- Continuous flow **HTL**
  - Data from **PNNL experimental** work
  - Literature data from
    - NAABB publications
    - University of Sidney demo unit
  - **Batch HTL** – several dozen papers over last 2 decades
    - Residence time, temperature, feed concentration, recycle effects
    - Useful qualitative data
- Continuous flow **hydrotreating**
  - UOP data for NAABB confirmed ease of treatment, but details not published
  - Detailed data provided for model input by this project
- Continuous flow **catalytic hydrothermal gasification**: some super and sub-critical water treatment, but not specific to continuous HTL aqueous processing
  - Detailed data provided for model input by this project

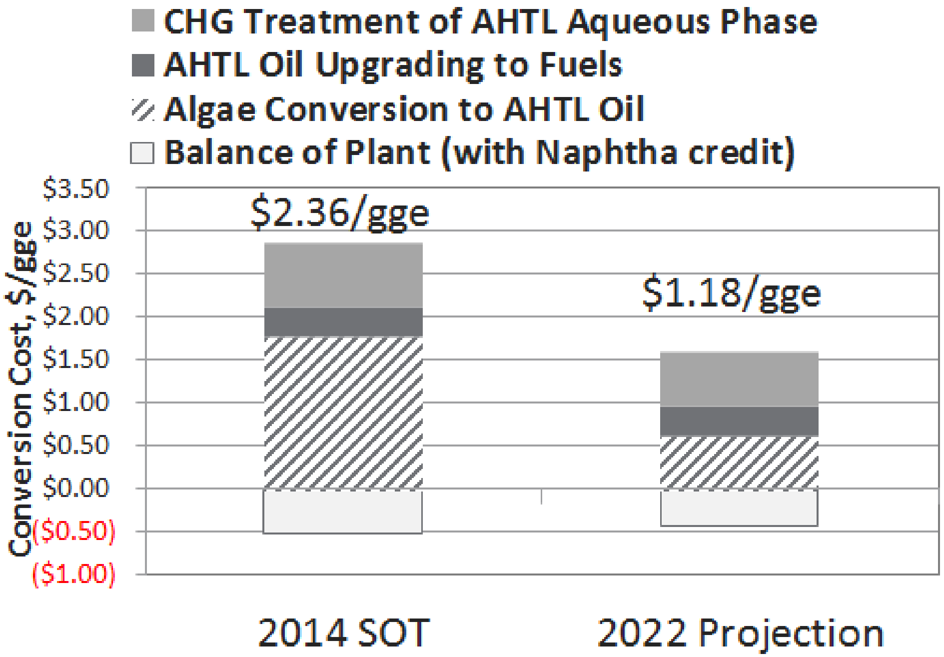
Technical Accomplishments: Design Case Sensitivities

- **Feedstock cost** for dewatered wet algae is **the major cost area**



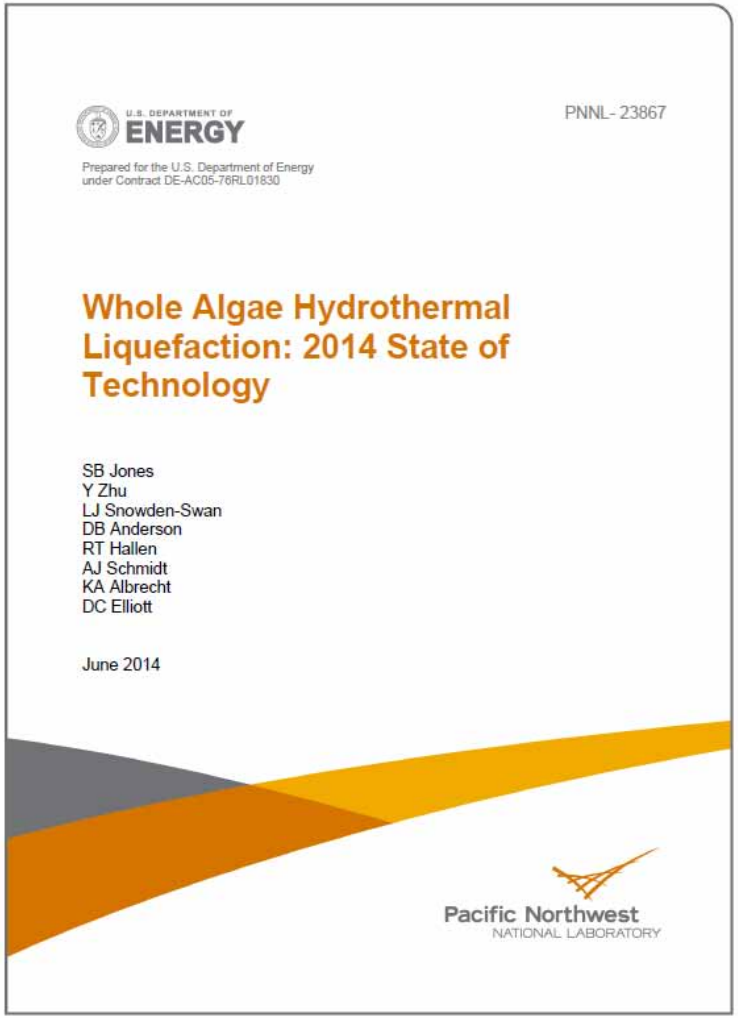
Technical Accomplishments: 2014 SOT and Progression to 2022

- **SOT* baselines** where **research** is now relative to the 2022 design case
- **SOT published** in the **MYPP**
- Most **cost reduction opportunities** are associated with the **HTL system**



Gal/AFDW ton	2014	2022
Liquid Fuel	102	147

State of Technology (SOT)



* http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23867.pdf

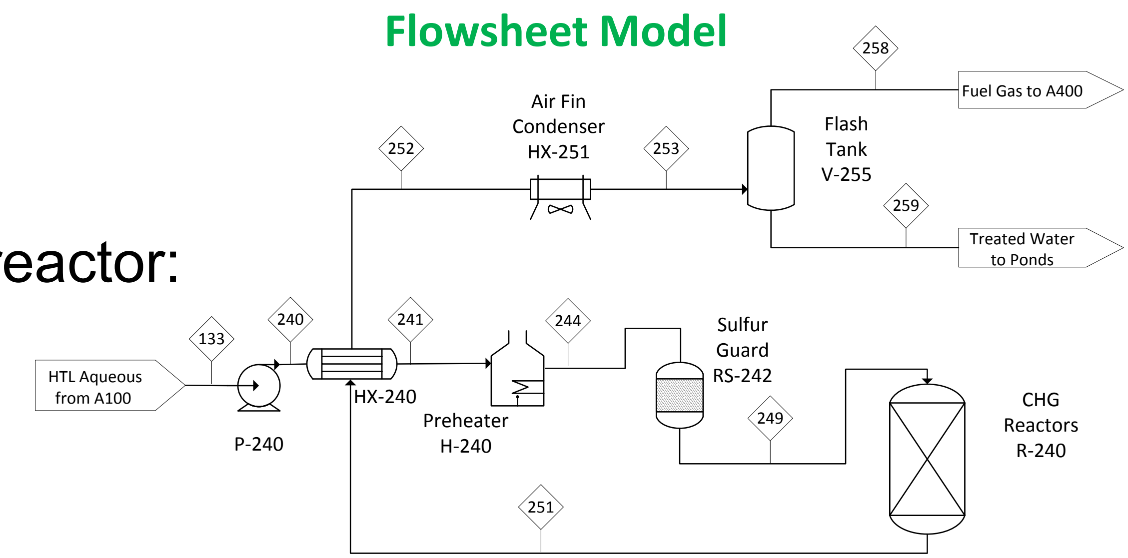
Technical Accomplishments: 2014 to 2022 Progression Research Needs

Parameter	Impact	Mitigation
Capex	HTL 60% in 2014 → 40% in 2022	Higher space velocity
Carbon recovery	59% carbon to final fuel(2014) 70% carbon to final fuel(2022)	Improved HTL separations; strain testing; multi-strains
Catalyst Maintenance	CHG catalyst expensive (Ru/C) Biocrude impacts on upgrading catalyst	Sulfur species removal options Biocrude washing
Nutrient recovery	Nitrogen, phosphorus disposition	Detailed analysis for all streams; recovery methods assessed
Fuel quality	Naphtha and Diesel meeting specs?	Detailed characterization
Seasonal Variations	Dry and store a portion of summer produced algae for winter processing; dryers idle rest of year	Investigate poly cultures, mixed feeds
Co-location	HTL conversion & bio-crude oil upgrading not at optimum scales	Model distributed small scale HTL conversion at farm with centralized upgrading

Work ongoing with researchers to **quantify** these **effects**

Technical Accomplishments: Experimental Support - Water Treatment

- **Objective:** Cost effective **HTL aqueous** phase **treatment**
  - **Low cost**
  - **Recyclable water**
  - **Nutrient recovery**
- CHG experimental flow reactor:
  - ~23 ml reactor
  - ~0.08 ml/min

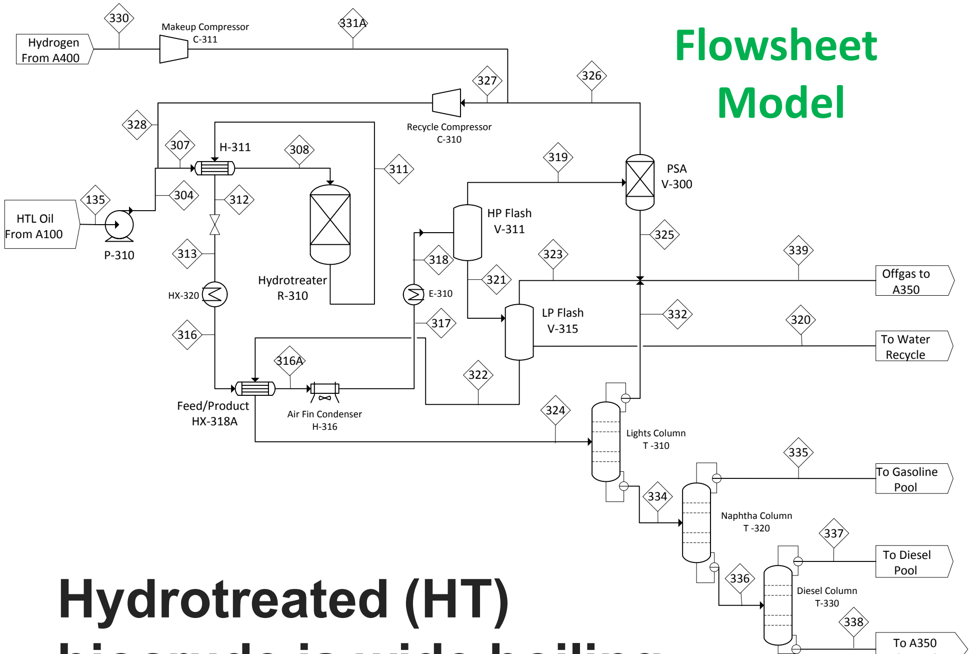


Experimental Focus

- **CHG catalyst maintenance**: calcium addition to **remove sulfates** (prior to HTL and prior to CHG); also investigating **ion exchange**
- **CHG Capital Cost**: investigate **higher space velocities** to reduce capex
- Subcontract in place with Washington State University (WSU) to investigate **anaerobic digestion**

Technical Accomplishments: Experimental Support – Bio-crude Hydrotreating

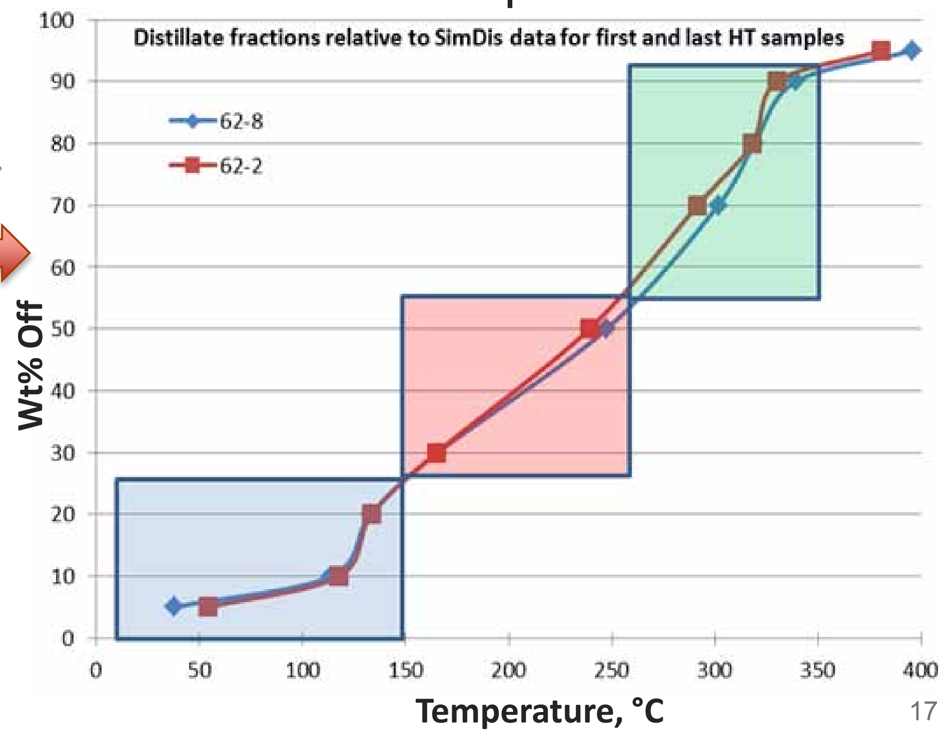
Flowsheet Model



- **Objective: Economically** make good **quality fuel**
- Experimental flow reactor:
  - 20 cm^3 catalyst bed
  - 0.1 ml/min nominal flowrate
- **100 hour test** completed & longer duration life test planned

Hydrotreated (HT) biocrude is wide boiling

(SimDis curve at right)



- HT oil **distilled** into **naphtha, jet** & **diesel** cuts
- Quality of fuel cuts **characterized**
- **Collaboration:** data package delivered to NREL for their Refinery Blend modeling project

Technical Accomplishments: External Collaborations

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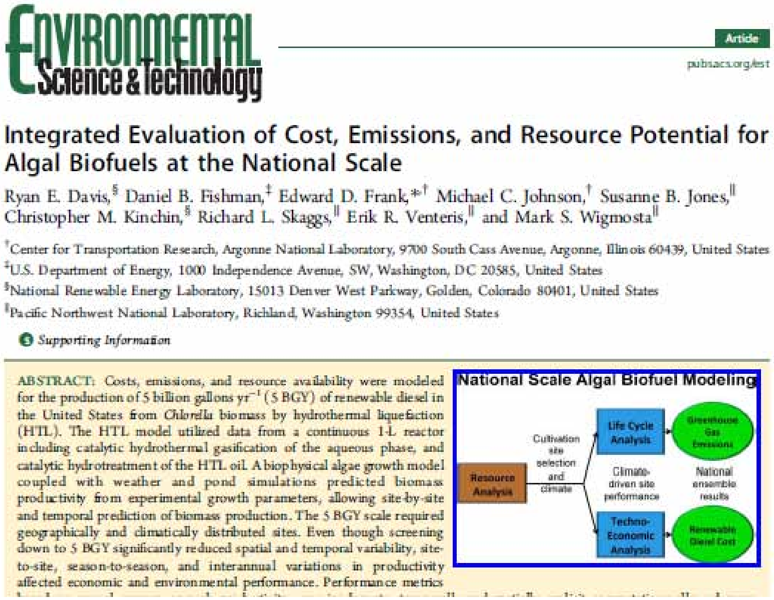
- **Harmonization** (2013)
  - **Multi-lab** effort: ANL, NREL, PNNL
  - Spatio-temporal resource assessment using **BAT** (PNNL)
  - **TEA** with consideration of seasonal variations (NREL & PNNL)
  - **Life cycle analysis** (ANL)



Environmental Science & Technology

Article

pubs.acs.org/est

Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale

Ryan E. Davis,[§] Daniel B. Fishman,[‡] Edward D. Frank,*[†] Michael C. Johnson,[†] Susanne B. Jones,[∥] Christopher M. Kinchin,[§] Richard L. Skaggs,[∥] Erik R. Venteris,[∥] and Mark S. Wigmosta[∥]

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Supporting Information

ABSTRACT: Costs, emissions, and resource availability were modeled for the production of 5 billion gallons yr^{-1} (5 BGY) of renewable diesel in the United States from *Chlorella* biomass by hydrothermal liquefaction (HTL). The HTL model utilized data from a continuous 1-L reactor including catalytic hydrothermal gasification of the aqueous phase, and catalytic hydrotreatment of the HTL oil. A biophysical algae growth model coupled with weather and pond simulations predicted biomass productivity from experimental growth parameters, allowing site-by-site and temporal prediction of biomass production. The 5 BGY scale required geographically and climatically distributed sites. Even though screening down to 5 BGY significantly reduced spatial and temporal variability, site-to-site, season-to-season, and interannual variations in productivity affected economic and environmental performance. Performance metrics

- **Biomass Assessment Tool (BAT)**
  - Prioritize site selection to achieve production targets via HTL
    - Open pond cultivation
    - Spatiotemporal biomass productivity from local climate
    - Water demand and availability
    - Site specific restrictions: land use, land cover, and slope
    - Access to downstream processing facilities
  - The TEA model can be used as a black box in the BAT

Technical Accomplishments: External Collaborations

- **Algal Biofuels Strategy – Spring 2014 Workshop**
  - Presented Whole Algae Hydrothermal Liquefaction & Upgrading
  - Co-facilitated Analysis and Sustainability breakout session
- **Fuel Quality Data** sent to **NREL** for refinery blending project
  - 4.1.3.30 Advanced Biofuels and Bioproducts Modeling
  - Potential **cost reductions** through **integration** into a **petroleum refinery** for fuel finishing versus producing a finished fuel at the algae farm
  - Upgraded (or partially upgraded) biocrude quality makes it a good first entry candidate
- Provided input and review to **ANL** for the Supply Chain Sustainability Analysis (**SCSA**) - full **LCA for GREET** model

Project Relevance

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- **Design case TEA projecting 2022 targets completed** with review from **industry, laboratory** and **university partners**
  - Whole algae conversion to fuels modeled progress and targets are published in the **MYPP** (Section 2.1.2.5 and Appendix B)
- **Directly supports BETO Algal conversion milestones:**
  - *"By 2016, **review** integrated R&D **approaches** for **high-yielding algal biofuel intermediates** to evaluate potential approaches **for achieving** the 2018 and **2022 milestones**."* (11/14 MYPP)
- **Directly supports BETO Algal conversion strategic goal:**
  - *"**develop algae** production and logistics **technologies** that, if scaled-up and deployed, could **support** the production of **5 billion gallons per year of** sustainable, reliable, and affordable algae-based **advanced biofuels** by 2030."* (11/14 MYPP)

> *"…whole **algae hydrothermal liquefaction and upgrading** is established as a **priority technology pathway**"* (November 2014 MYPP)

Project Relevance

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- Project provides an **effective** and **data driven approach** to formulate robust and detailed **techno-economics** and **sustainability metrics** for this pathway
  - Provides the associated **modeled production costs** indicating high impact research areas for conversion and feedstock types
  - Assist researchers in defining **technical targets** to be achieved experimentally
  - **Addresses MYPP Barriers** (November 2014 MYPP)
    - **At-A**: Comparable, transparent and reproducible **analysis**
    - **St-C**: **Sustainability** data across the supply chain
    - **Aft-I**: **Algal Feedstock Preprocessing**
      - *"Process options for commercial scale-up have been identified and are being researched (e.g., conversion of whole algal biomass via **thermal liquefaction**), but few data exist on the **cost**, **sustainability**, and **efficiency** of these processes."*
- Results **published** for use (whole or in part) by interested industrial & other entities

Future Work

Next 18 months: continue to support program needs

- **Algae HTL and upgrading model:**
  - Complete **2015 SOT** for input into the MYPP
  - Complete **out year** modeled **targets** for input into the MYPP
  - Assess **sustainability impacts**: Provide input as needed for NREL's farm model and ANL's LCA
- **HT Experimental:** assess degree of **bio-crude cleanup** needed
- **Water Treatment Experimental:** investigate sulfur removal options & work with WSU regarding alternative treatment
- **Continue to publish results:**
  - **Present results** to date at a public conference
  - Complete **journal draft** for high lipid/low lipid feedstock economics and experimental results

Continuous dialogue with experimentalists to capture key information and provide insights into areas of potential cost reduction

Future Work

- **Key milestones**
  - **May 2015**: **Go/No-Go** for water treatment
    - A determination will be made for the future direction of water treatment process development research for AHTL pathway.
  - **Sept 2015**: **analysis** and **experimental**
    - Complete hydrotreating and water treatment tests for each HTL run from the Interface Task
    - Complete **2015 SOT for MYPP**
    - Complete 2016 through 2021conversion targets for MYPP
  - **Sept 2016**: **analysis** and experimental
    - Complete hydrotreating and water treatment tests
    - Complete **2016 SOT** for **MYPP**

Summary

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Overview: TEA modeling coupled with **experimental research** to advance economic conversion of algae to liquid fuels

Approach: effective and **consistent approach** to formulate robust, and detailed techno-economic analysis for algae conversion to fuels

Technical Accomplishments/Progress/Results

- FY13: Completed Design Report
- FY14: Published Design Report and 2014 SOT baseline
- FY13&14: Completed experimental HT and CHG work for model input

Relevance: aligns with BETO's mission to reduce dependence on petroleum and achieve cost parity with conventional transportation fuels through **high fuel yield algal processing**

Future work: targeted research to optimize processing conditions and **modeling** of experimental results to develop meaningful technical targets leading to an **optimized economic process**

Status since 2013 Review: published design case and 2014 SOT and generated targeted experimental data

Acknowledgements

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- **Bioenergy Technologies Office**:
  - Algae: Neil Rossmeissl, Dan Fishman
  - Analysis & Sustainability: Zia Haq, Alicia Lindauer, Kristen Johnson
- **ANL**: Ed Frank, Jennifer Dunn, Ambica Koushik Pegallapati
- **NREL**: Ryan Davis, Chris Kinchin
- **PNNL:** Rick Skaggs, Mark Wigmosta
- **WSU**: Keith Thompson

Additional Slides

- Response to comments from 2013 Review
- Publications & Presentations
- List of abbreviations

Responses to Previous Reviewers' Comments

- **2013 Review Comment:** "This is a necessary project that would be best implemented in terms of developing cost points for each technology step and sensitivity of the entire pathway to changing algal or cultivation points"

  Response: the design case published in early 2014 details the costs associated with each processing section. Additionally, sensitivity analysis was (and is) conducted to identify significant opportunities for cost reduction. HTL data from a sister project provides model input for a wide variety of algal feedstock types.

- **2013 Review Comment:** "Having a good understanding of the feed composition and paying attention to proper materials of construction is vital to avoiding costly delays and shutdowns associated with equipment failure"

  Response: With regard to oil hydrotreating, pretreatment methods (such as desalting) for HTL oil are being investigated. With regard to water treatment, methods to prevent premature catalyst deactivation are being pursued, as are alternate processing methods. Note that research into the HTL conversion step itself is being pursued in a separate project.

Publications & Presentations

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Publications

- Zhu Y, KO Albrecht, DC Elliott, RT Hallen, and SB Jones. 2013. "Development of Hydrothermal Liquefaction and Upgrading Technologies for Lipid-Extracted Algae Conversion to Liquid Fuels." *Algal Research* 2(4):455-464. doi:10.1016/j.algal.2013.07.003 http://www.sciencedirect.com/science/article/pii/S2211926413000805
- Biddy MJ, R Davis, SB Jones, and Y Zhu. 2013. Whole Algae Hydrothermal Liquefaction Technology Pathway . PNNL-22314, Pacific Northwest National Laboratory, Richland, WA.
- Jones SB, Y Zhu, DM Anderson, R Hallen, DC Elliott, A Schmidt, K Albrecht, T Hart, M Butcher, C Drennan, LJ Snowden-Swan, R Davis, C Kinchin. 2014, "Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading." PNNL-23227 Pacific Northwest National Laboratory, Richland WA http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf
- Ryan E. Davis, Daniel B. Fishman, Edward D. Frank, Michael C. Johnson, Susanne B. Jones, Christopher M. Kinchin, Richard L. Skaggs, Erik R. Venteris, and Mark S. Wigmosta "Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale" Environmental Science & Technology, 2014, 48:6035-6042 http://pubs.acs.org/doi/abs/10.1021/es4055719
- Jones SB, Y Zhu, LJ Snowden-Swan, D Anderson, RT Hallen, AJ Schmidt, KO Albrecht, and DC Elliott. 2014. "Whole Algae Hydrothermal Liquefaction: 2014 State of Technology." PNNL-23867, Pacific Northwest National Laboratory, Richland, WA. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23867.pdf
- Elliott DC, P Biller, A Ross, AJ Schmidt, and SB Jones. 2015. "Hydrothermal liquefaction of biomass: Developments from batch to continuous process." Bioresource Technology 178:147-156.

Presentations

- "Algae Conversion to Liquid Transportation Fuels: Overview of Whole Algae Hydrothermal Liquefaction and Upgrading" Presented by S. Jones at the Algae Strategy Workshop, March 26, 2014, Charleston SC

Abbreviations and Acronyms

- ABY: Advancements in Algal Biofuel Yield
- AFDW: ash free dry weight
- ANL Argonne National Laboratory
- AOP: annual operating plan
- CHG: catalytic hydrothermal gasification
- CSU: Colorado State University
- BETO: Bioenergy Technologies Office
- GGE: gasoline gallon equivalent
- HT: hydrotreating
- HTL: hydrothermal liquefaction
- LCA: life-cycle analysis
- MFSP: minimum fuel selling price
- MT: material transfer
- MYPP: multi-year program plan
- NAABB: National Alliance for Advanced Biofuels and Bio-products
- NABC: National Advance Biofuel Consortium
- NPV: net present value
- PMP: project management plan
- PNNL: Pacific Northwest National Laboratory
- RAFT: Regional Algal Feedstock Test-bed
- SCSA: Supply Chain Sustainability Analysis
- SimDis: ASTM D2887 simulated distillation curve
- TEA: techno-economic analysis
- WFO: work for others
- WSU: Washington State University