# DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

# Integration of Sustainability Metrics into Design Cases and State of Technology Assessments

2.1.0.100/2.1.0.302 NREL
2.1.0.301 PNNL

March 24, 2015
Analysis and Sustainability

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# Goal Statement

- **Support the development of sustainable, economic biomass-derived liquid fuels**
  - Integration of TEA and LCA to identify **cost reduction opportunities** and **sustainability trade-offs** for BETO, researchers and key stakeholders
- **Directly supports BETO goal:**
  - "Identify conditions under which a hydrocarbon pathway, validated at a mature modeled price of $3/gge reduces GHG emissions by 50% or more and meets targets for water consumption, wastewater and air emissions" **(November 2014 MYPP)**

# Quad Chart Overview

## Timeline and Budget

- This presentation merges cross-cutting work from several projects supporting the Analysis & Sustainability and Conversion platforms, the budget and timelines for which are covered in other presentations.

## Barriers

- Barriers addressed
  - **At-A** Comparable, transparent and reproducible analysis
  - **St-C** Sustainability data across the supply chain
  - **St-D** Indicators and methodology
  - **Bt-J, Tt-R** Process Integration

## Partners

- Partners:
  - ANL, INL, NREL, PNNL

# Project Overview

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## HISTORY

- TEA is a long established tool used to assess technical progress. **Sustainability** has always been an **underlying theme.**
- Sustainability moves to the forefront with respect to TEA, and efforts were made to integrate the two to support more optimized designs:
  - 2011: sustainability discussed in detail in the MYPP
  - 2012: began to identify appropriate indicators and metrics
  - 2013: all new design cases and SOT reports include section on sustainability, including metrics and sensitivity analysis

## CONTEXT

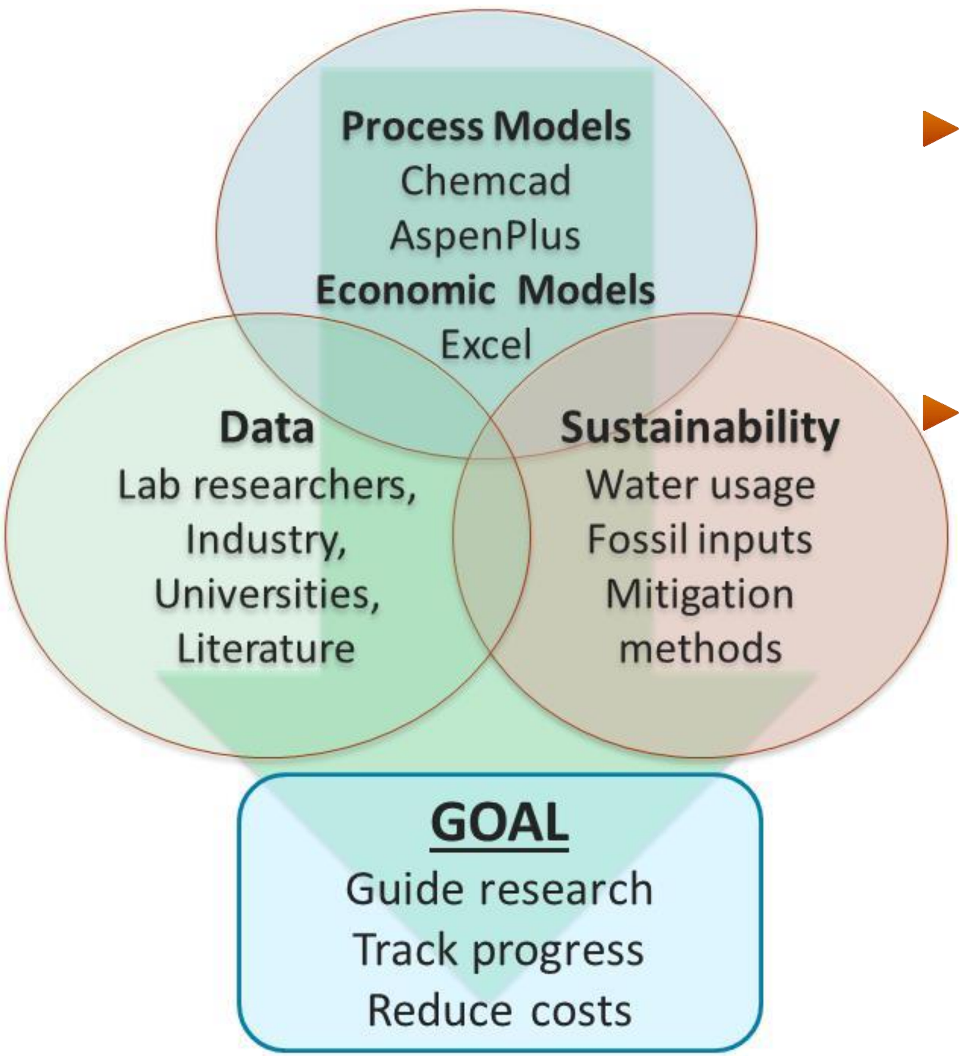
- **Sustainable** and **economic** deployment of biofuel

## OBJECTIVE

- **Combined TEA and environmental sustainability analysis** of emerging pathways helps to facilitate biorefinery designs that are economically feasible and minimally impactful to the environment.

# Approach (Technical)

## Overall Approach Structure




- **Approach** **Consistent** use of **BETO** technical, financial **assumptions;** set of defined sustainability **metrics**
- **Critical Success Factors**
  - Identify **cost reduction** strategies
  - Help **set research goals**
  - Quantify **sustainability impacts**
- **Potential Challenges – risk and uncertainty:**
  - **Sensitivity** studies to **identify** high **cost** and **sustainability impact** areas
  - Conclusion uncertainties **risk management**:
    - External peer review
    - Interaction with industry
    - Multi-lab collaborations
    - Make assumptions transparent

# Approach (Technical)

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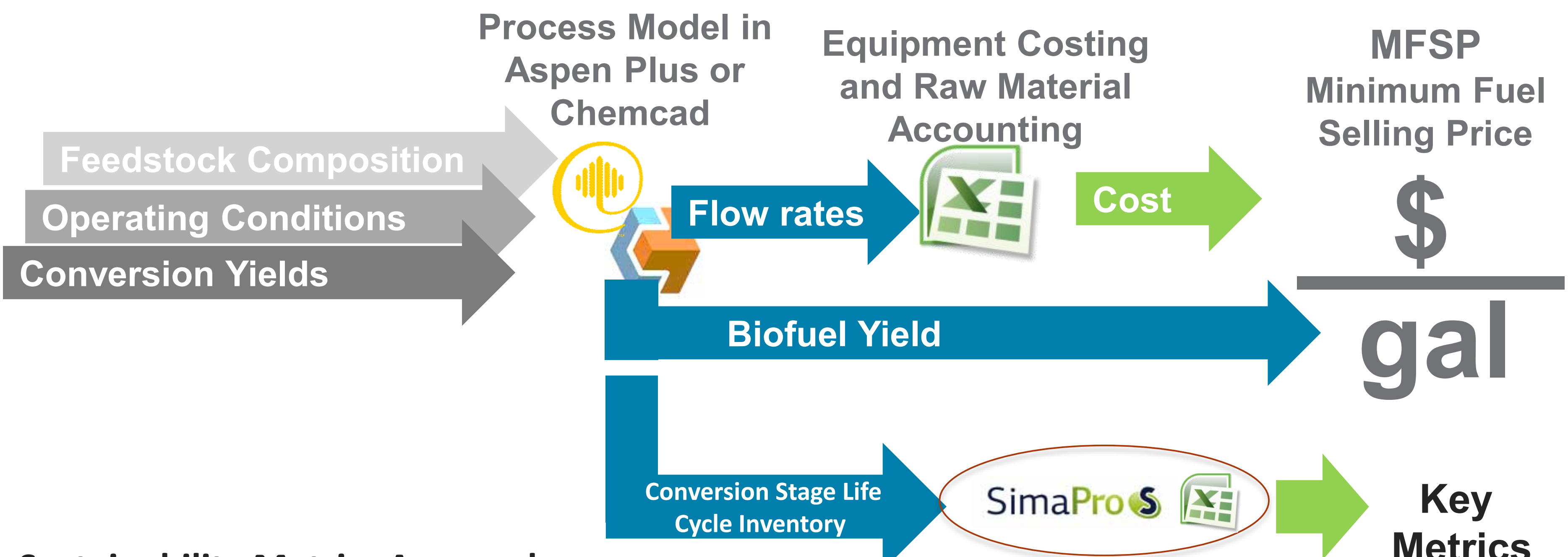
- **Consistent TEA and sustainability methodology used across all labs**




**Sustainability Metrics Approach:**

a) Partial LCA -- the boundary for the metrics is the biorefinery. The rationale for performing a partial LCA is that the overall focus of this study is the conversion stage. Therefore, to isolate this stage, all others are excluded for quantification of metrics.

b) Systematically quantify and assess key sustainability metrics which allow for conversion pathway evaluation and comparison.

c) For certain pathways, full LCA is performed for sensitivity cases to understand effects on feedstock stages and limitations around RFS thresholds.

- **Fossil GHGs**
- **Fossil Energy Use**
- **Fuel Yield**
- **Carbon-to-Fuel Efficiency**
- **Water Consumption**
- **Wastewater Generation**

# Approach (Management)

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- **Approach structure**
  - **Project Management Plan** (PMPs) indicating scope, budget, schedule
  - **Annual Operating Plans** (AOPs) prepared prior to each fiscal year
    - Details quarterly **milestones** and **deliverables** including sustainability
  - **Quarterly reporting** to BETO (written and regularly scheduled calls)
- **Potential Challenges and Risk Mitigation**
  - **Data availability**: experimental data for evaluation of alternative process configurations (e.g., renewable hydrogen from biomass)
  - **Data basis**: ensure underlying data quality and assumptions are consistent through harmonization efforts
- **Critical success factors**
  - Make **results public (MYPP and published reports)**
  - Deliver quality work **on-time**, **on-budget**

# Technical Progress

# Design Reports and MYPP

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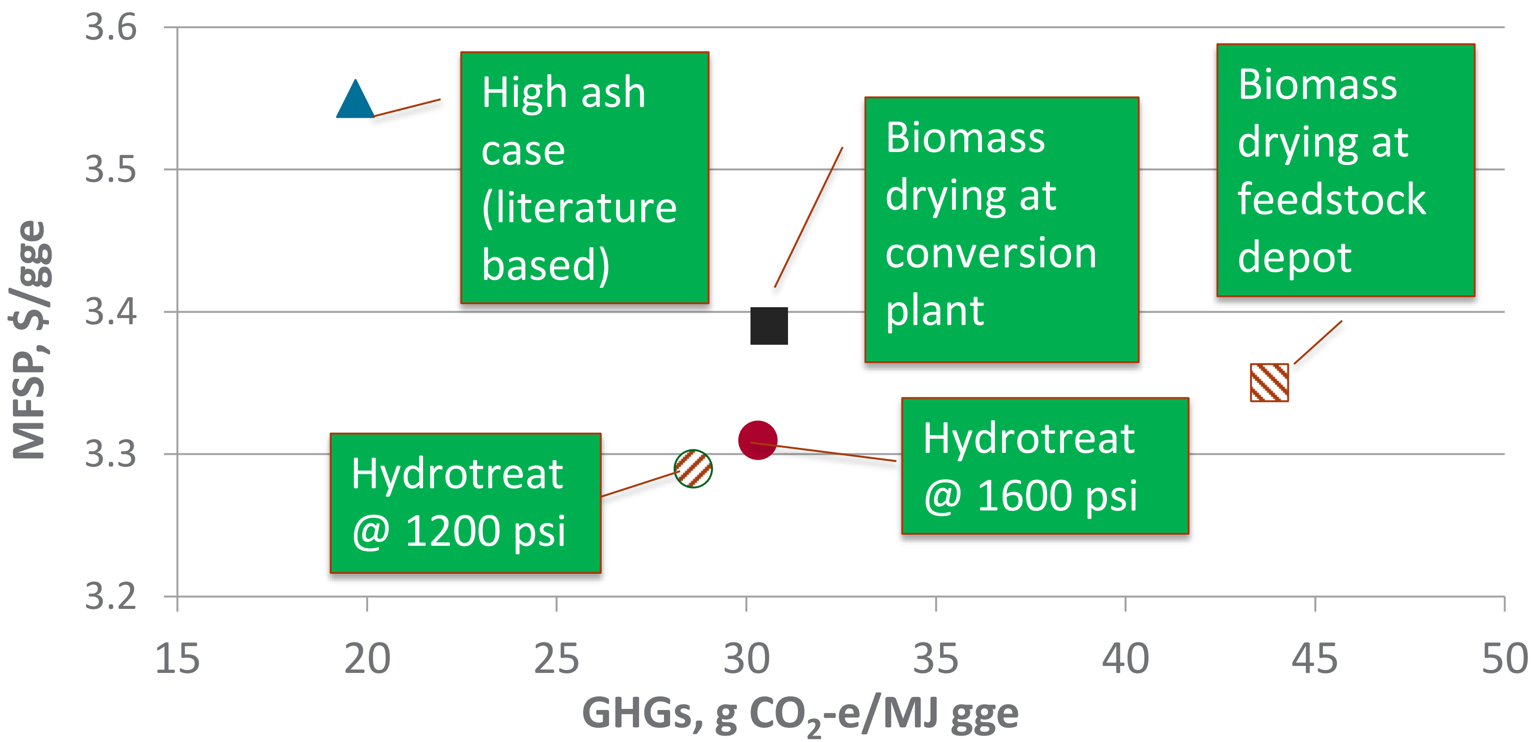
- **Incorporate Sustainability Metrics**:
  - Design reports for projected 2017/2022 targets including sustainability sensitivities
  - State of technology reports and MYPP include sustainability metrics

# Sustainability Metrics
## Example: fast pyrolysis & upgrading

| Sustainability Metric for Conversion Process | 2009 SOT | 2012 SOT | 2013 SOT | 2014 SOT | 2017 Projected |
|---|---|---|---|---|---|
| **Fossil GHGs** **(g $CO_2$-e/MJ fuel)** | **22.1** | **19.8** | **20.5** | **19.4** | 18.9 |
| **Fossil Energy Use** **(MJ fossil energy/MJ fuel)** | **0.33** | **0.29** | **0.32** | **0.31** | 0.30 |
| **Fuel Yield** **(gal/dry ton wood; GGE/dry ton wood)** | **74; 78** | **74; 78** | **84; 87** | **84; 87** | 84; 87 |
| **Carbon-to-Fuel Efficiency** **(%biomass C in fuel product)** | **38** | **38** | **47** | **47** | 47 |
| **Water Consumption** **($m^3$/day; gal/GGE)** | **998; 1.5** | **998; 1.5** | **1124; 1.5** | **1088; 1.5** | 1050; 1.4 |
| **Wastewater Generation** **($m^3$/day; gal/GGE)** | **917; 1.4** | **917; 1.4** | **948; 1.3** | **975; 1.3** | 932; 1.3 |

- **Sustainability metrics** are included in the **MYPP**
- Chosen as **representative** of key indicators (McBride *et al* 2011) – (see extra slides)
- Serve as **input to** full life cycle analysis (GREET, ANL water analysis)
- **Inform** modeled plant **choices** (e.g. air fins vs. water cooling)

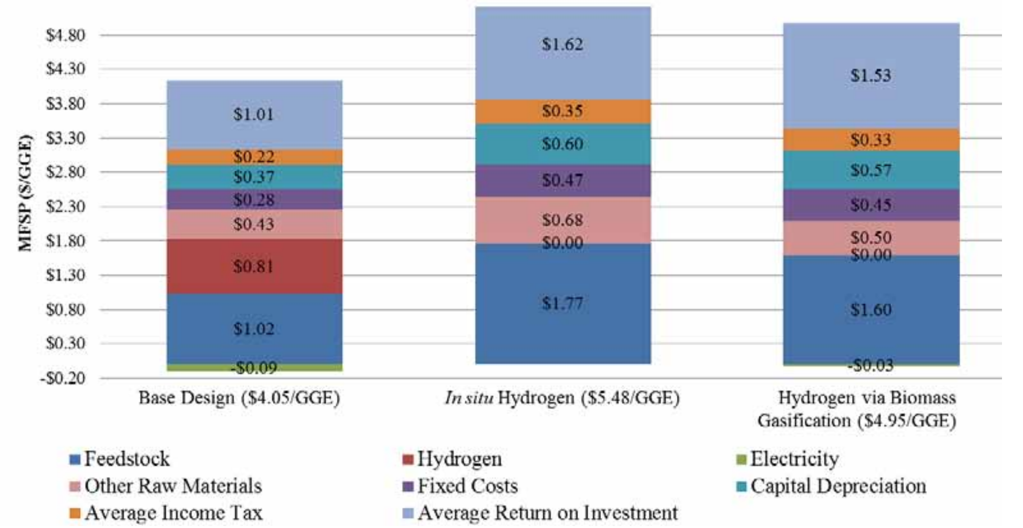
# GHG/Cost Trade-Offs & Synergies: Pyrolysis & Upgrading

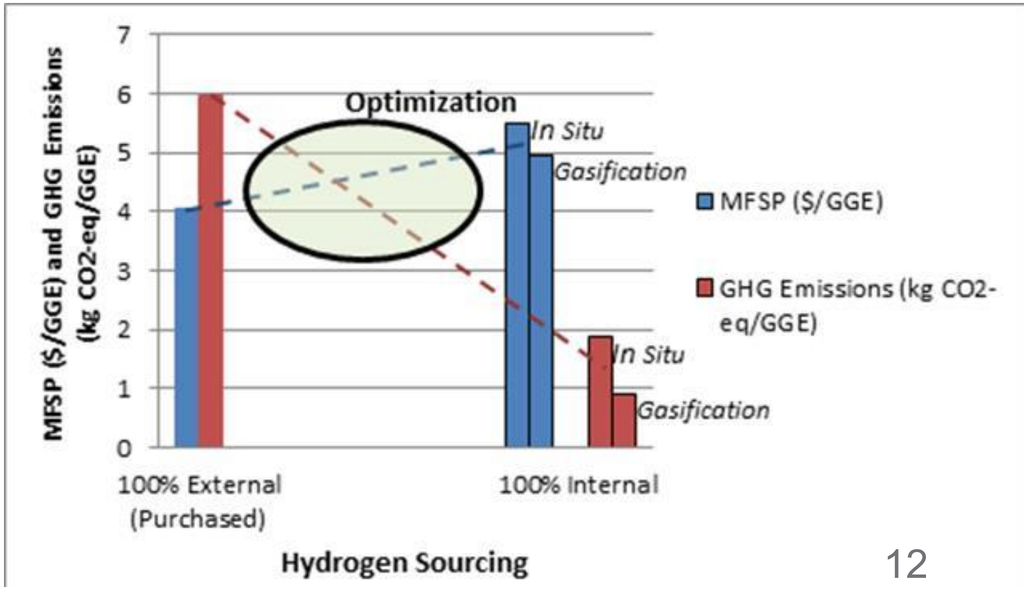



- Reducing hydrotreater pressure: reduced cost (↓ capital and electricity) & GHGs (↓ electricity)
- Higher feedstock ash content reduces GHGs (↓ NG ), increases MFSP (↓ yield)
- Moving the dryer offsite slightly reduces conversion cost, but increases GHGs (↑ NG)

# GHG/Cost Trade-Offs & Synergies : Catalytic Conversion of Sugars *Hydrogen Source*

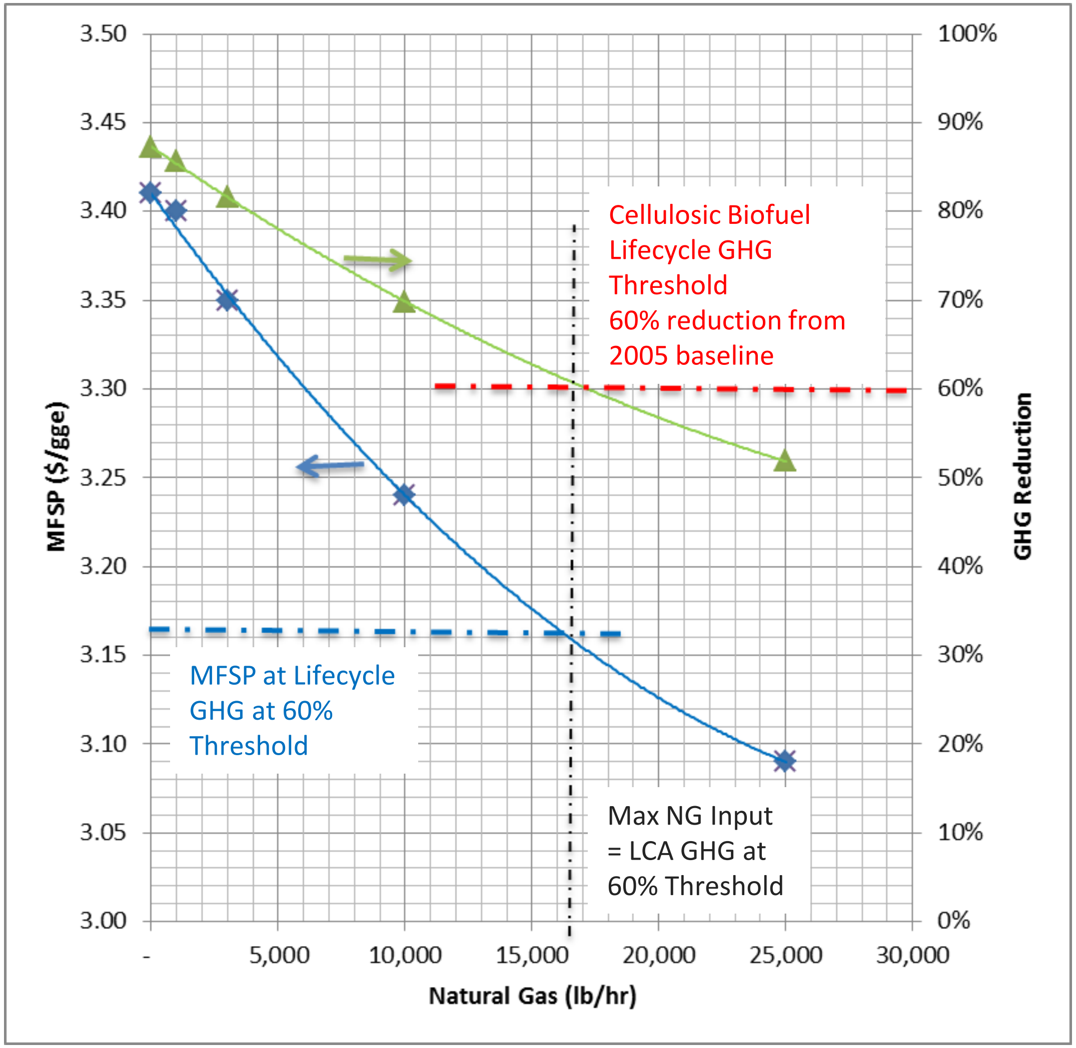
- Base case assumes large hydrogen import purchased from off-site natural gas SMR production (ex situ)
- Alternative case investigates producing hydrogen internally (in situ) via reforming reactions from a fraction of hydrolysate, or by diverting a fraction of feedstock biomass to gasification train
  - Increases cost to \$5.48/GGE (in situ), \$4.95/GGE (gasification)
  - Requires large fractional diversion of hydrolysate (41%, in situ) or biomass (36%, gasification) to generate required $H_2$ = reduced fuel yield
  - Although lower yield/higher cost, also tradeoffs in sustainability



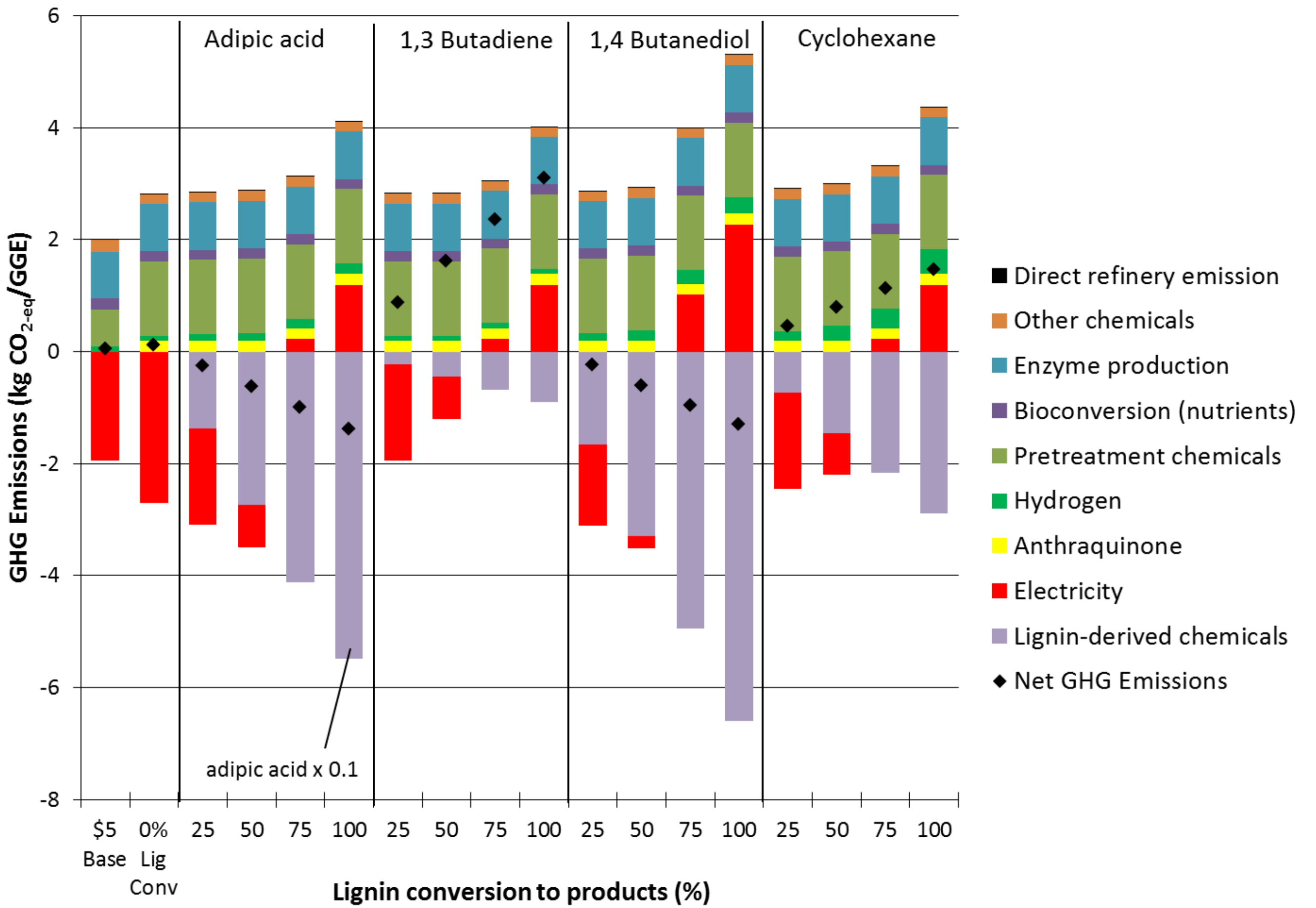
# GHG/Cost Trade-Offs & Synergies: Gasification
## *Co-conversion with natural gas*

- Thermochemical pathway to high-octane gasoline blendstock through methanol/DME intermediates
  - Co-conversion of biomass with natural gas can simultaneously increase fuel yields and reduce fuel production costs provided that the life-cycle GHG thresholds specified in EISA is not violated.
  - Co-processing natural gas at the life-cycle GHG threshold limit (i.e., 60% GHG emissions reduction relative to the petroleum baseline) decreases the MFSP by 7%, from \$3.41/GGE to \$3.17/GGE.



# GHG/Cost Trade-Offs & Synergies: Biological Conversion of Sugars
## *Lignin to chemicals*

- High-level analysis shows that lignin conversion to oxygenated products can improve the process minimum fuel selling price and GHGs
  - Adipic acid and 1,4 butanediol provide increased GHG offset credit vs lignin combustion to power coproduct




- Conventional adipic acid production is very carbon-intensive
- Minimization and eventual loss of power coproduct, replaced by increasing offsets from chemical coproduct as more lignin diverted away from the boiler

# Supply Chain Sustainability Analysis

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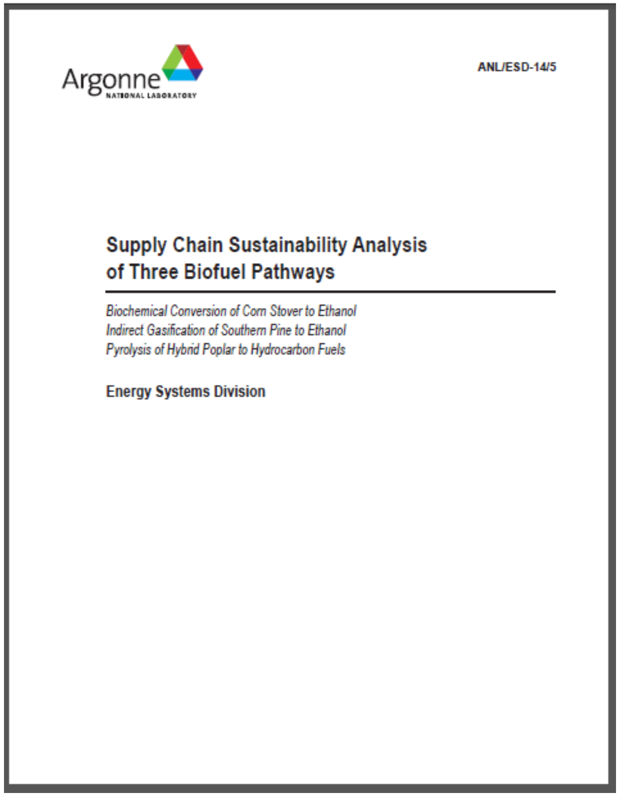
- Results from this work feed into ANL's GREET model and Supply Chain Sustainability Analyses (SCSA)
  - Emissions and energy analysis for entire supply chain from feedstock to end use
  - Incorporates new conversion data into the GREET model for SCSA – consistent basis of assumptions and data
  - SCSA's provide documentation for metrics included in the MYPP pathway technical tables
  - More details in the following GREET presentation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ANL/ESD-14/5

**Supply Chain Sustainability Analysis of Three Biofuel Pathways**

*Biochemical Conversion of Corn Stover to Ethanol*
*Indirect Gasification of Southern Pine to Ethanol*
*Pyrolysis of Hybrid Poplar to Hydrocarbon Fuels*

**Energy Systems Division**

# Project Relevance

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- **Address identified barriers (11/2014 MYPP)**
  - **At-A** Comparable, transparent and reproducible analysis
    - Collaborative effort amongst labs to ensure **consistent and transparent approach** to analysis
  - **St-C** Sustainability data across the supply chain
    - Provide **key data** needed for the conversion process to ANL for full supply chain analysis
  - **St-D** Indicators and methodology
    - Develop and document approach and indicators
    - Implementing methodology for **assessment and comparison** of conversion pathways
  - **Bt-J, Tt-R:** Process Integration
    - Integrated sensitivity analysis helps predict effects of feed and process variations on biorefinery economics and sustainability

# Project Relevance

- **Target Audience: BETO, researchers, and industrial stakeholders**
  - Provide **feedback** to BETO-supported R&D efforts **to improve process sustainability**
  - Utilize results in BETO analysis projects (e.g., water usage)
  - Support development of full **supply chain sustainability analysis** and expansion of GREET pathways
  - Identify **data gaps** needed for further consideration to BETO conversion platform
  - Design reports are externally **peer reviewed**

# Project Relevance

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- **Positive impact on commercial biofuel viability:**
  - Determine bio-fuel production **cost reduction opportunities**
  - Investigate **synergies/tradeoffs** between economics/sustainability
  - Consider alternative scenarios to reflect **potential design modifications** (e.g., use of alternate hydrogen sources)
  - Report all results in **publically available studies** including design reports and state of technology reports
  - Support the publication of results in the DOE BETO MYPP

# Future Work

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- **FY15:**
  - **All Five Hydrocarbon Pathways**
    - Complete annual SOT modeled costs and sustainability metrics
    - Continue to explore sustainability tradeoffs (e.g. hydrogen from natural gas vs. renewable hydrogen)
    - Continue TEA/sustainability analysis for feedstock interface work
    - Continue to work with ANL on updates to GREET and SCSA
  - **Pyrolysis and Upgrading**
    - Complete draft manuscript of sustainability and economic effects related to processing different types of pure and blended feedstocks (experimental data from the INL, NREL PNNL Feedstock Interface Project)
    - Complete draft manuscript of bio-oil upgrading catalyst GHG analysis
    - Work with NREL on transferring relevant data for criteria emissions modeling
  - **Biological Upgrading of Sugars**
    - Consider cost implications for tradeoffs between full on-site, partial on-site, or full off-site treatment of biorefinery model wastewater
    - Quantify criteria air pollutant emissions and consider technology options for ways to mitigate them; estimate cost tradeoffs and implications on MFSP for adoption of these options

# Future Work

- **FY16:**
  - **All Pathways**
    - Complete 2015 SOT modeled costs, sustainability metrics, and waterfall for MYPP
    - Continue to explore sustainability tradeoffs (e.g. hydrogen from natural gas vs. renewable hydrogen)
    - Continue TEA/sustainability analysis for feedstock interface work
    - Continue to work with ANL on updates to GREET and SCSA
  - **Biological Upgrading of Sugars:**
    - Complete draft manuscript documenting outcomes of criteria air pollutant emissions work from FY15

# Summary

- **Overview**: Integrated TEA/sustainability analysis of emerging conversion technologies helps develop sustainable, economic biofuels.
- **Approach:** Iteration of TEA, sustainability analysis and researcher input to identify high impact areas and synergies/tradeoffs between cost/metrics
- **Technical Accomplishments/Progress/Results**
  - **FY14**: Included sustainability metrics in all design cases and MYPP; cost/sustainability sensitivity analyses for four pathways
  - **FY15**: Continued sensitivity analyses for additional technology optimizations; feed data to criteria air emissions analyses; journal drafts
- **Relevance:** this project aligns with BETO's mission by identifying opportunities for improved cost and sustainability performance of developing conversion routes.
- **Future work:** Continued multi-lab collaborations for integrated TEA/sustainability analysis for entire pathway supply chain; SOT and journal publications.
- **Status since 2013 Review**: Added sustainability metrics framework and analysis to all design cases and SOTs.

# Acknowledgements

- **Bioenergy Technologies Office**
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  - Kevin Craig, Bryna Guriel, Jay Fitzgerald, Nichole Fitzgerald, Prasad Gupte, Liz Moore (Conversion)
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- **INL:** Jack Jacobsen, Kara Cafferty

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# Additional Slides

Response to reviewers comments

Publications and presentations

Abbreviations and acronyms

# Responses to Previous Reviewers' Comments

- **2013 Peer Review**
  - "The portfolio has made great strides in taking a proactive approach to sustainability, moving beyond traditional net energy balances and greenhouse gas accounting"
  - "The research portfolio's robustness could be further improved through the creation of guidelines regarding the approaches to sensitivity, metric definition, model verification and validation of results"
  - "The first major element that could better support BETO's overall goals is improved integration of TEA and LCA"
- **Response:**
  - The NREL/PNNL team will continue to interface with the ORNL team to ensure consistency with their metrics framework, the PNNL/NREL team on development and understanding of metrics for biomass conversion technologies, and the ANL team on integration of conversion stage inventory data into the GREET model. While GREET documents full fuel cycle emissions for BETO technology pathways, it is critical to perform sensitivity analysis at the process development and modeling level to fully understand and facilitate improvement of the cost and environmental implications of key variables in the design, as well as to elucidate any impact of conversion design changes on upstream stages.

# Publications and Presentations

NREL NATIONAL RENEWABLE ENERGY LABORATORY

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- **Publications**
  
  - Jones SB, PA Meyer, LJ Snowden-Swan, AB Padmaperuma, E Tan, A Dutta, J Jacobson, and K Cafferty. 2013. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway . PNNL-23053; NREL/TP-5100-61178, Pacific Northwest National Laboratory, Richland, WA.
  - Dunn, J., M. Johnson, Z. Wang, M. Wang, K. Cafferty, J. Jacobson, E Searcy, M Biddy, A Dutta, D Inman, E Tan, L Tao, S Jones, and L Snowden-Swan. Nov. 2013. Supply Chain Sustainability Analysis of Three Biofuel Pathways: Biochemical Conversion of Corn Stover to Ethanol, Indirect Gasification of Southern Pine to Ethanol, Pyrolysis of Hybrid Poplar to Hydrocarbon Fuels. ANL/ESD-14/5.
  - Jones SB, LJ Snowden-Swan, PA Meyer, AH Zacher, MV Olarte, and C Drennan. 2014. Fast Pyrolysis and Hydrotreating 2013 State of Technology R&D and Projections to 2017 . PNNL-23294, Pacific Northwest National Laboratory, Richland, WA.
  - Dutta, A.; Sahir, A.; Tan, E.; Humbird, D.; Snowden-Swan, L.; Meyer, P.; Ross, J.; Sexton, D.; Yap, R.; Lukas, J. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Thermochemical Research Pathways With In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors. NREL/TP-5100-62455, PNNL-23823, 2015.
  - Tan, E.; Talmadge, M.; Dutta, A.; Hensley, J.; Schaidle, J.; Biddy, M.; Humbird, D.; Snowden-Swan, L.; Ross, J.; Sexton, D.; Lukas, J. Process Design for the Conversion of Lignocellulosic Biomass to High Octane Gasoline - Thermochemical Research Pathway With Indirect Gasification and Methanol Intermediate. NREL/TP-5100-62402, PNNL-23822, 2015.
  - Davis, R.; Tao, L.; Tan, E. C. D.; Biddy, M. J.; Beckham, G. T.; Scarlata, C.; Jacobson, J.; Cafferty, K.; Ross, J.; Lukas, J.; Knorr, D.; Schoen, P. . (2013). Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons. 147 pp.; NREL Report No. TP-5100-60223.
  - Davis, R., et al. "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons" NREL/TP-5100-62498. Golden, CO: National Renewable Energy Laboratory, Manuscript in Preparation.
  

# Publications and Presentations

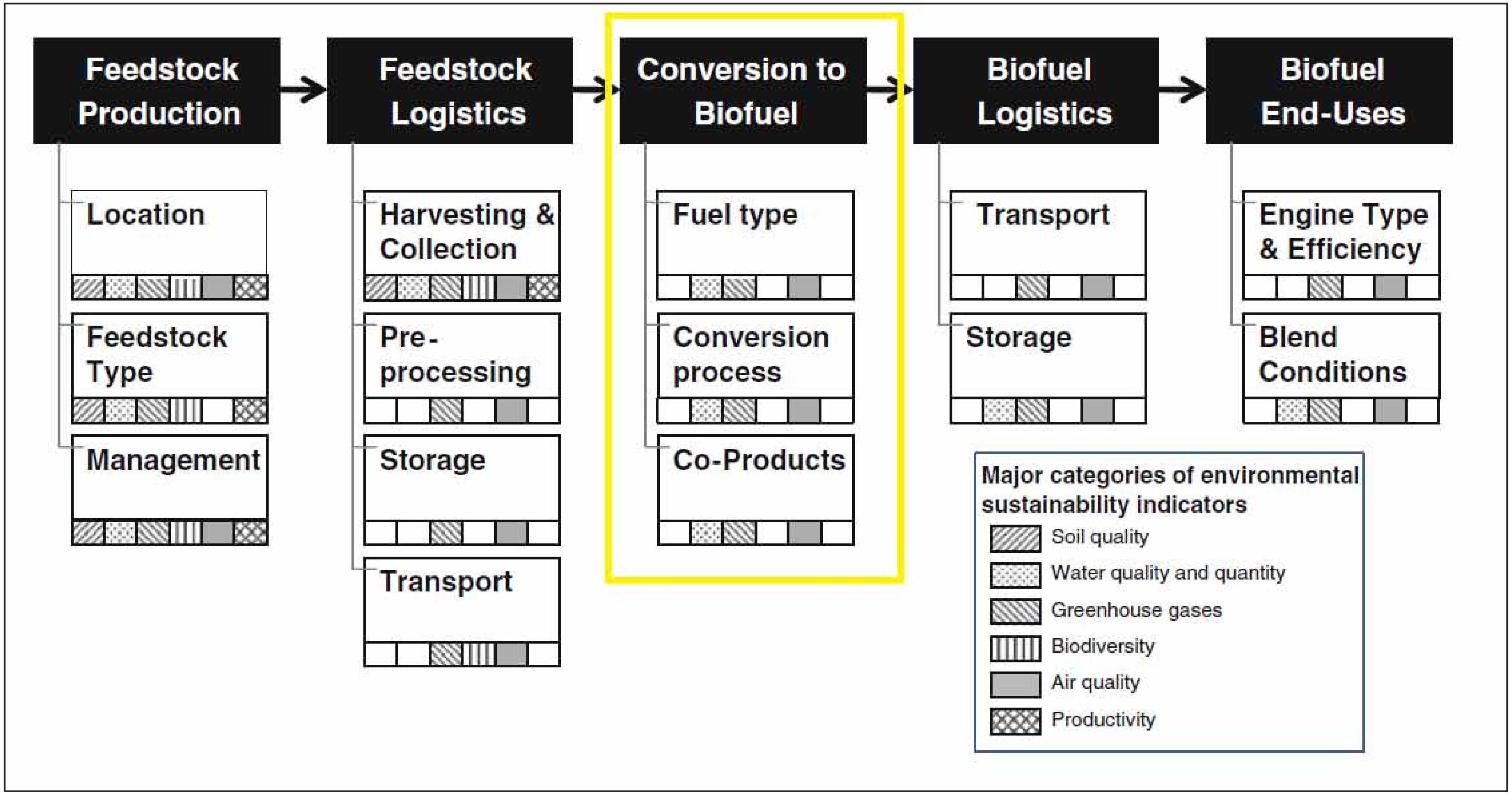
- **Presentations**
  - S Jones, L Snowden-Swan, P Meyer. "Bio-Oil Upgrading Economics and Sustainability", presented at the Thermochemical Workshop, University of Delaware, October 8, 2013
  - Olarte MV, AH Zacher, SB Jones, LJ Snowden-Swan, PA Meyer, AB Padmaperuma, LJ Rotness, Jr, GG Neuenschwander, DC Elliott, and C Drennan. 2014. "Current State of the Technology (SOT) of the Fast Pyrolysis-Hydrotreating Pathway." Presented by Mariefel V. Olarte at Biomass 2014, Washington DC, DC on July 29, 2014. PNNL-SA-104180
  - E Tan, J Jacobson, K Cafferty, D Inman, C Wright. "Techno-economic Analysis and Environmental Sustainability of Biochemical Biorefinery Sizing", 2013 AIChE Annual Meeting, San Francisco, CA, November 3-8, 2013.
  - E Tan, J Jacobson, K Cafferty, A Dutta, E Searcy. "Conventional Versus Advanced Depot Biomass Supply Systems for a Thermochemical Conversion Process and Biorefinery Sizing: Life-Cycle Assessment and Techno-Economic Analysis", 2014 AIChE Annual Meeting, Atlanta, GA, November 16-21, 2014.

# Abbreviations and Acronyms

- ANL: Argonne National Laboratory
- AOP: Annual operating plan
- BETO: Bioenergy Technologies Office
- GGE: Gasoline gallon equivalent
- INL: Idaho National Laboratory
- LCA: Life-cycle analysis
- MFSP: Minimum fuel selling price
- MYPP: Multi-year program plan
- NREL: National Renewable Energy Laboratory
- PMP: Project management plan
- PNNL: Pacific Northwest National Laboratory

# Sustainability Metrics Framework

- Conversion metrics were chosen in accordance with the framework documented by ORNL in McBride et al. (2011) and Efroymson et al. (2013)




From Efroymson et al., 2013. "Environmental Indicators of Biofuel Sustainability: What About Context?", *Environmental Management*, DOI 10.1007/s00267-012-9907-5.

# Conversion Stage Sustainability Metrics: Catalytic Sugar Conversion

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| Sustainability Metric [1] | 2014 SOT | 2015 Projection | 2016 Projection | 2017 Design Case | 2022 Projection [2] |
|---|---|---|---|---|---|
| GHGs (g $CO_2$-e/MJ fuel) (fossil emissions) | **39.8** | 42.7 | 45.8 | 49.2 | -69.4 |
| Fossil Energy Consumption (MJ fossil energy/MJ fuel) | **0.73** | 0.75 | 0.78 | 0.82 | 0.3 |
| Total Fuel Yield (GGE/dry ton) | **50** | 59 | 68 | 78 | 76 |
| Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass) | **29%** | 34% | 39% | 45% | 41% |
| Total Carbon-to-Fuel Efficiency (C in fuel/C in biomass + NG) | **25%** | 28% | 32% | 36% | 33% |
| Water Consumption ($m^3$/day; gal/GGE fuel) | **5,038 $m^3$/day (12.0 gal/GGE)** | 4,635 $m^3$/day (9.4 gal/GGE) | 4,269 $m^3$/day (7.6 gal/GGE) | 3,817 $m^3$/day (5.8 gal/GGE) | 3,496 $m^3$/day (5.3 gal/GGE) |
| Net Electricity Export (KWh/GGE) | **4.9** | 3.6 | 2.6 | 1.7 | 0.6 |

[1] *Note, all cases based on external SMR $H_2$ sourcing basis*

[2] *2022 projection represents one possible scenario based on converting a fraction of lignin to adipic acid co-product*

- Sustainability metrics above only consider conversion stage (not a full WTW LCA)
- Alternative $H_2$ scenarios in design report proved very useful in quantifying large differences between SMR $H_2$ sourcing and alternative scenarios via *in situ* reforming of sugars or biomass gasification
    - 3-6X lower GHG emissions from conversion stage for alternative (internal) $H_2$ scenarios vs SMR basis

# Conversion Stage Sustainability Metrics: Biological Sugar Conversion

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| Sustainability Metric [1] | 2014 SOT | 2015 Projection | 2016 Projection | 2017 Design Case | 2022 Projection [2] |
|---|---|---|---|---|---|
| GHGs (g $CO_2$-e/MJ fuel) (fossil emissions) | **-63.8** | -58.0 | -72.0 | -78.6 | -301 |
| Fossil Energy Consumption (MJ fossil energy/MJ fuel) | **-0.9** | -0.8 | -1.0 | -1.1 | -1.3 |
| Total Fuel Yield (GGE/dry ton) | **18** | 20 | 20 | 22 | 44 |
| Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass) | **10%** | 11% | 12% | 13% | 26% |
| Biomass Carbon-to-Coproduct Efficiency (C in succinic acid coproduct/C in biomass) | **9%** | 9% | 11% | 12% | NA [2] |
| Water Consumption ($m^3$/day; gal/GGE fuel) [1] | **6,294 $m^3$/day (42 gal/GGE)** | 6,146 $m^3$/day (48 gal/GGE) | 5,817 $m^3$/day (45 gal/GGE) | 5,773 $m^3$/day (42 gal/GGE) | 4,553 $m^3$/day (12 gal/GGE) |
| Net Electricity Import (KWh/GGE) | **19.9** | 19.8 | 21.1 | 24.0 | 0.3 |

[1] *Note, gal/GGE water metric is fully allocated to fuel product (not distributed to coproduct train), thus appears high in this format*

[2] *2022 projection represents one possible scenario based on converting a fraction of lignin to adipic acid co-product; pathway reverts back to whole-hydrolysate conversion to fuels, thus removes C5 sugars-to-succinic acid process train*

- Sustainability metrics above only consider conversion stage (not a full Well-to-Wheel LCA)
- Demonstrated improvements in GHG emissions alongside TEA costs when routing lignin to select coproduct options in support of 2022 targets for $3/GGE

# Conversion Stage Sustainability Metrics: Ex-Situ Pyrolysis

| Sustainability Metric Trends | 2014 SOT | 2015 Projection | 2016 Projection | 2017 Projection | 2022 Projection |
|---|---|---|---|---|---|
| Fossil GHG Emissions† (g CO2-e / MJ Fuel) | **-41.5** | -36.5 | -27.9 | -19.3 | -1.2 |
| Fossil Energy Consumption† (MJ FE / MJ Fuel) | **-0.47** | -0.41 | -0.31 | -0.22 | -0.01 |
| Total Fuel Yield (GGE / Ton) | **42** | 44 | 50 | 56 | 78 |
| Carbon Efficiency to Fuel Blendstock (%C in Feedstock) | **23.5** | 25.0 | 27.6 | 30.6 | 41.5 |
| Water Consumption (gal H2O / GGE Fuel Blend) | **1.4** | 1.3 | 1.2 | 1.1 | 0.7 |
| Electricity Production (kWh/GGE) | **21.0** | 19.2 | 16.0 | 13.1 | 6.2 |
| Electricity Consumption (for entire process, kWh/GGE) | **12.7** | 12.0 | 10.4 | 9.1 | 5.7 |

**† Includes electricity credit**

# Conversion Stage Sustainability Metrics: In-Situ Pyrolysis

| Sustainability Metric Trends | 2014 SOT | 2015 Projection | 2016 Projection | 2017 Projection | 2022 Projection |
|---|---|---|---|---|---|
| Fossil GHG Emissions† (g CO2-e / MJ Fuel) | **-32.8** | -28.6 | -23.8 | -16.1 | -2.6 |
| Fossil Energy Consumption† (MJ FE / MJ Fuel) | **-0.37** | -0.32 | -0.27 | -0.18 | -0.03 |
| Total Fuel Yield (GGE / Ton) | **46** | 49 | 52 | 59 | 75 |
| Carbon Efficiency to Fuel Blendstock (%C in Feedstock) | **25.8** | 27.3 | 29.2 | 32.6 | 40.4 |
| Water Consumption (gal H2O / GGE Fuel Blend) | **1.3** | 1.2 | 1.1 | 0.9 | 0.8 |
| Electricity Production (kWh/GGE) | **18.5** | 16.8 | 14.9 | 12.2 | 7.0 |
| Electricity Consumption (for entire process, kWh/GGE) | **11.7** | 10.9 | 10.0 | 8.7 | 6.3 |

**† Includes electricity credit**

# Conversion Stage Sustainability Metrics: Gasification

| Sustainability Metric Trends | 2014 SOT | 2015 Projection | 2016 Projection | 2017 Projection | 2022 Projection |
|---|---|---|---|---|---|
| Fossil GHG Emissions† (g CO2-e / MJ Fuel) | **1.64** | 1.42 | 1.19 | 0.96 | 0.60 |
| Fossil Energy Consumption† (MJ FE / MJ Fuel) | **0.023** | 0.019 | 0.011 | 0.013 | 0.006 |
| Total Fuel Yield (GGE / Ton) | **57** | 57 | 59 | 61 | 62 |
| Carbon Efficiency to Fuel Blendstock (%C in Feedstock) | **28.2** | 28.7 | 29.9 | 31.0 | 31.2 |
| Water Consumption (gal H2O / GGE Fuel Blend) | **12.4** | 9.3 | 5.8 | 5.2 | 1.7 |
| Electricity Production (kWh/GGE) | **11.5** | 11.8 | 7.1 | 6.7 | 6.5 |
| Electricity Consumption (for entire process, kWh/GGE) | **11.4** | 11.7 | 7.1 | 6.7 | 6.5 |

**† Includes electricity credit**