DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

SPERLU Selective Process for Efficient Removal of Lignin and Upgrading

March 10, 2021

Biochemical Conversion and Lignin Utilization

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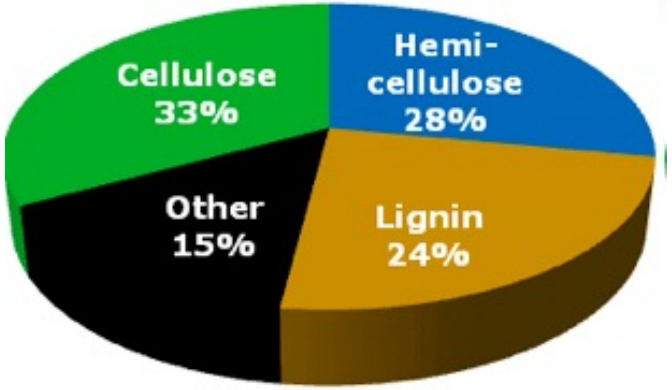
Spero Renewables

Mission & Value proposition

To provide renewable and cost-effective substitutes to petrochemicals – enhancing the quality of life and the environment

Moving towards a barrel of biomass will require making chemicals from lignin



$0.04 per kg

SPERLU™

"Selective Process for Efficient Removal of Lignin and Upgrading"

- Feedstock agnostic: wood, non-food, agricultural residues

- Replacement for Bisphenol A (BPA) in production of thermoset plastics

- Bio-based chemicals for consumer products

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Project Overview

Project Goals:

- Convert 50% of lignin carbon into bio-phenols.
- Make polymers from lignin bio-phenols.
- Bioprocess lignin bio-phenols into chemicals.
- Establish technoeconomic analysis (TEA) and life cycle analysis (LCA) for SPERLU™.

Advancing BETO Goals

- Deconstructing >50% lignin to < 10 monomers
- Upgrading lignin monomers to chemicals
  - Focus: high volume & value products from lignin
- Carbohydrates accessible after lignin removal
  - Modeling conversion to sugars & fuel
    - Verified experimentally (outside current scope)
- Spero enables biofuel cost reduction of $1-2 GGE (gallons gasoline equivalent)

Management - Objectives

Task 1: Scale SPERLU^{TM} to produce ≥ 200 g of bio-phenols per day

Task 2: Biotransformation optimization

Task 3: Bio-polymer synthesis and determine physical properties

Task 4: TEA of SPERLU^{TM}

Task 5: LCA of SPERLU^{TM}

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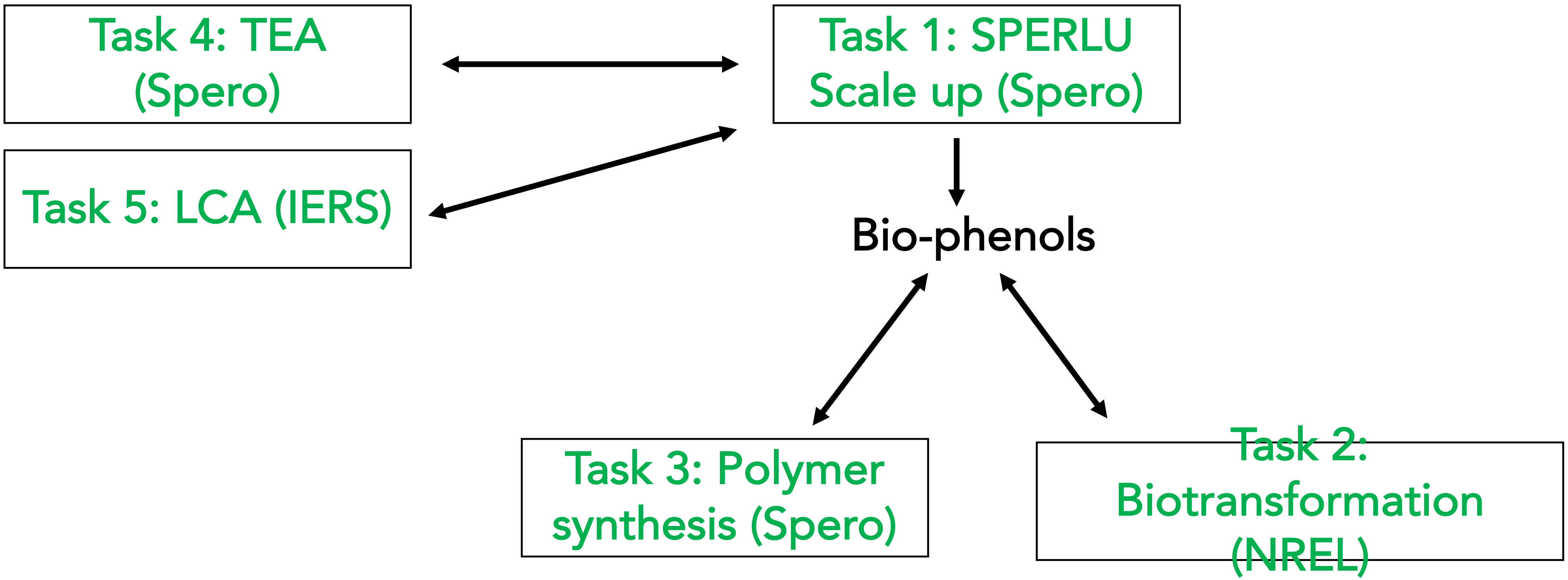
Management - Structure



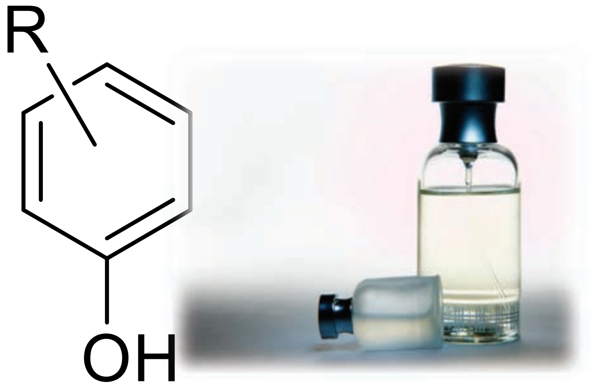
Spero Management team

- 20+ year of R&D management experience
- Technology translation & major JDA with multi-nationals
- Forbes 30 under 30
- Board/advisors include co-founder of a major oil exploration company, a former CTO of a major chemical company, and a world expert in polymers.

Technical Approach Task 1: Scale SPERLU™

Methodology

Extraction Kinetics → Catalysis Kinetics → Catalyst Regen. → Design & Construction → Produce 200 g bio-phenols (G/NG) → Purify bio-phenols



Bio-phenols

Technical Approach Task 2: Biotransformation Optimization

Team Members: Gregg Beckham, Christopher Johnson, Ilona Ruhl (NREL)

Strategy: Engineered *P. putida* for conversion of bio-phenols to chemicals

Methodology

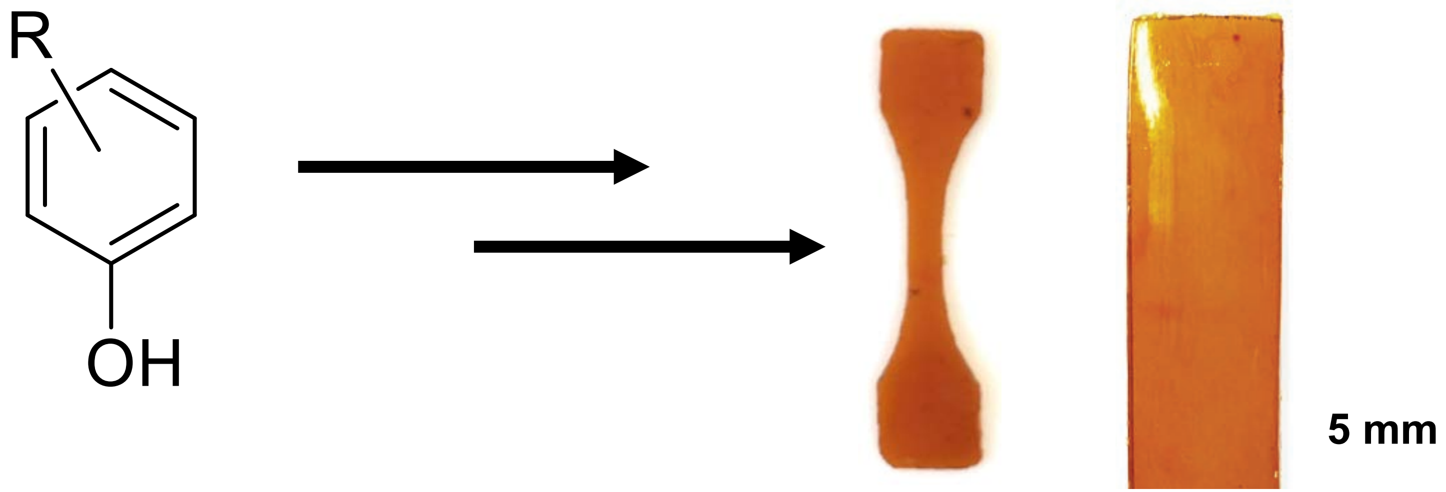
≥ 90% conversion yield → ≥ 90% conversion yield, titer ≥ 5 g/L →

≥ 90% conversion yield, titer ≥ 10 g/L, productivity ≥ 0.2 g/L/h

Technical Approach Task 3: Polymer Synthesis from Bio-phenols

Methodology

Polymers from mixed bio-phenols → Polymers from purified bio-phenols → Thermal and mechanical properties



Technical Approach Task 4: TEA of SPERLU™

Goal: develop a cost model for plant design guided by kinetic data

Methodology

Kinetics → Equipment Sizing → CAPEX/OPEX → Cash Flow → NPV

Reactor Design
Aspen Simulation

Cost correlations
Comparables

Product pricing
Project financing

Product pricing
Project financing

Technical Approach Task 5: LCA of SPERLU^{TM}

Team members: IERS, LLC

M5.1: Complete market research on the product systems affected by the SPERLU process

M5.2: Complete biophysical and market-mediated substitution models (poplar and miscanthus)

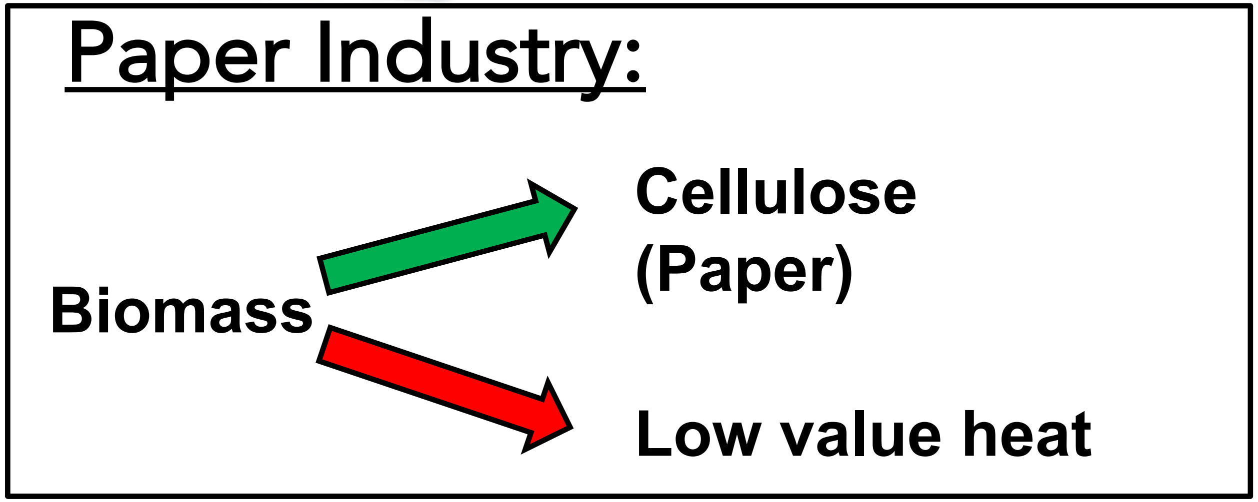
M5.3: Operational SPERLU-LCA model

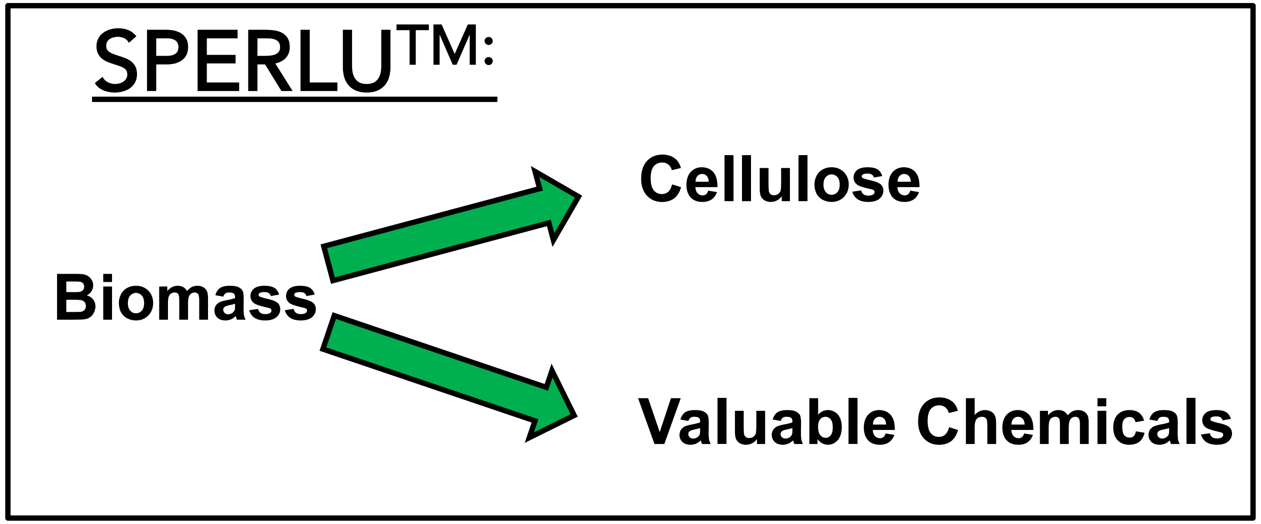
M5.4: Report SPERLU life-cycle GHG emissions and energy balance

M5.5: Deliver sensitivity and key issue (hotspot) identification results

M5.6: Recommendation for improving the LCA and the SPERLU process

Impact: SPERLU™ Optimizes Lignin Value





- Valuable feedstock from lignin
  - Materials (thermoset)
  - Specialty chemicals
- Integrated biorefinery
  - Up to 200% revenue increase for cellulosic ethanol production

Impact: Success through Industry Engagement

Spero collaborations

- Catalyst suppliers
- Separations companies
- Engineering firms (Reactor design)
- Contract manufacturers (scaling)
- Biomass producers & processors
- Cellulosic ethanol developers

Next: Pilot & commercialize through JDA

Progress and Outcomes
Task 1: Scaling SPERLU to 200 g bio-phenols

- M1.1 Lignin extraction kinetics ✓ (09/2019)
- M1.2 Catalyst selection ✓ (12/2019)
- M1.3 Reactor construction ✓ (02/2021)
  (200 g bio-phenols / day)
- M1.4 Catalyst kinetics ✓ (06/2020)
- M1.5 Catalyst regeneration methodology ✓ (06/2020)
- **M1.6/ GNG 2:** 200 g bio-phenols at 40% yield
- **M1.7** Bio-phenol separations at 200 g scale (BP3)

Task 1: 50% Lignin conversion

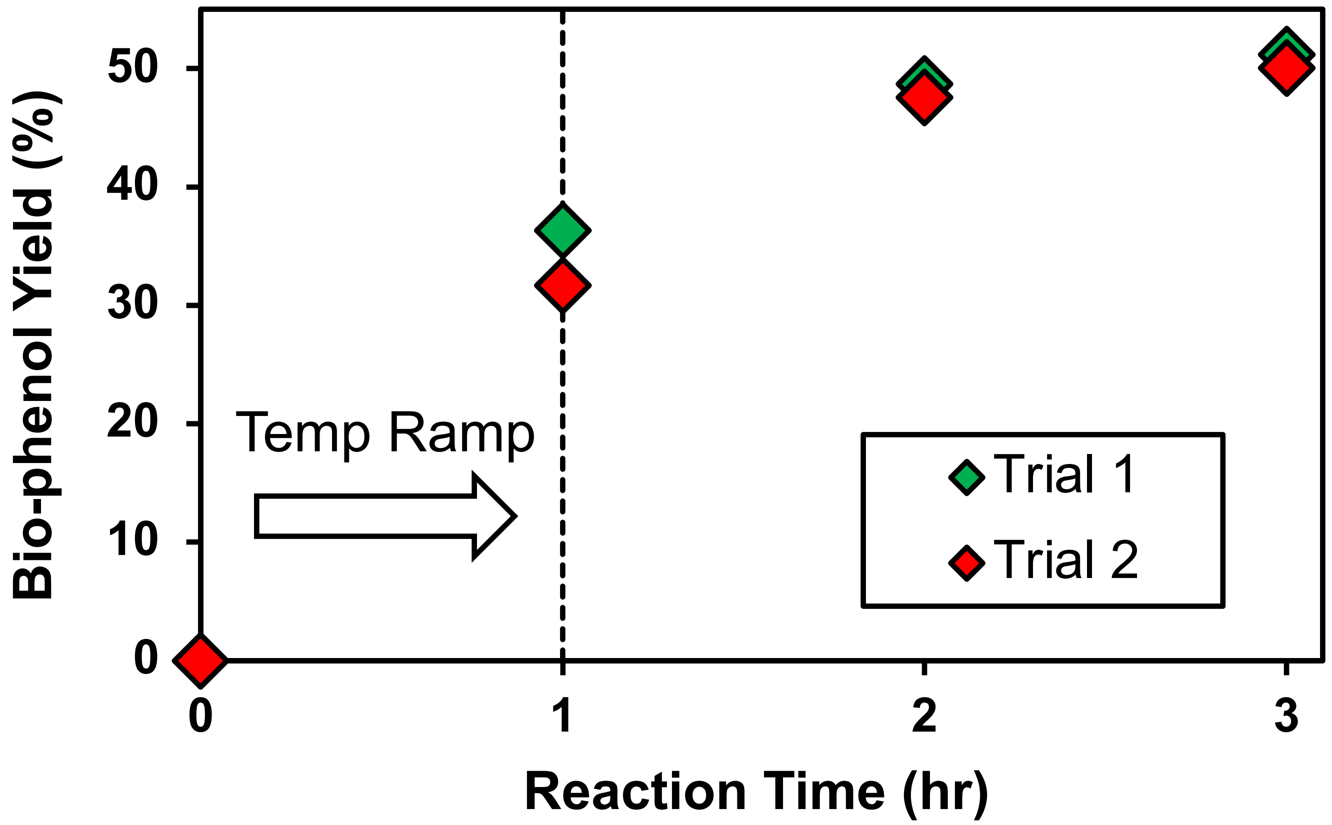
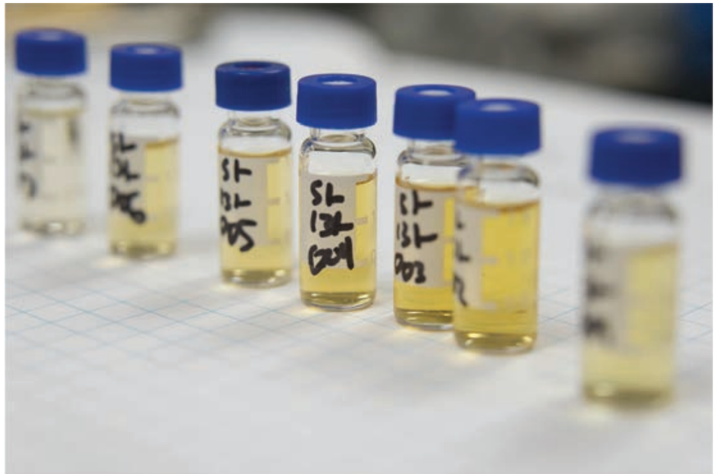


Figure 1: Bio-phenol yield vs time

- Biomass: poplar
- Yield = mass bi-phenols / mass lignin

Progress and Outcomes
Task 2: Biotransformation Optimization

- M3.1 Production of flavoring chemicals from bio-phenols at 90% molar yield ✓ (12/2020)
- M3.2 90% molar yield, titer 5 g/L (BP3)
- M3.3 90% molar yield, titer 10 g/L, productivity 0.2 g/L/h (BP3)



Progress and Outcomes
Task 3: Polymer synthesis

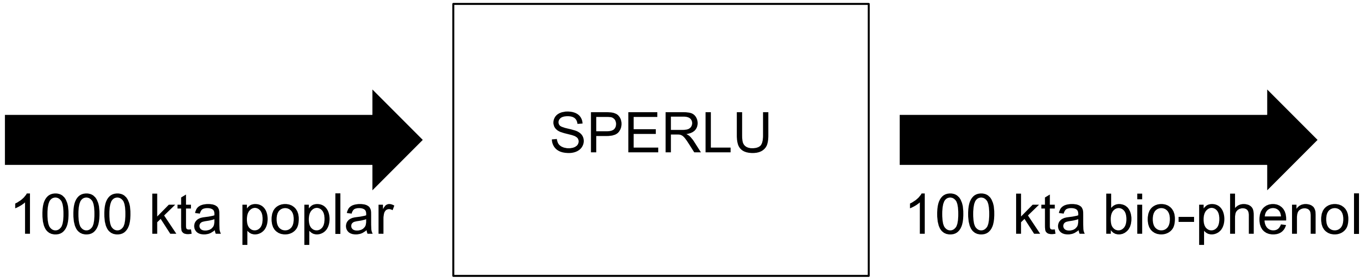
- M3.1 Thermoset polymers from monomer blends. (BP3)
- M3.2 Thermoset polymers from purified monomers. (BP3)
- M1.3 Optimize polymer synthesis. (BP3)
  - Properties matching BPA (petroleum based) thermosets

Product	Epoxy index [Eq/Kg]	T_g (DMA) [°C]	Storage modulus [Mpa @ r.t.]
SPERLU-517	3.8	85	3500

Progress and Outcomes
Task 4: TEA of SPERLU

- M4.1 TEA of SPERLU bio-phenols ✓ (09/2020)
  - ASPEN/HYSYS modeling

- M4.2 TEA polymer synthesis (BP3)



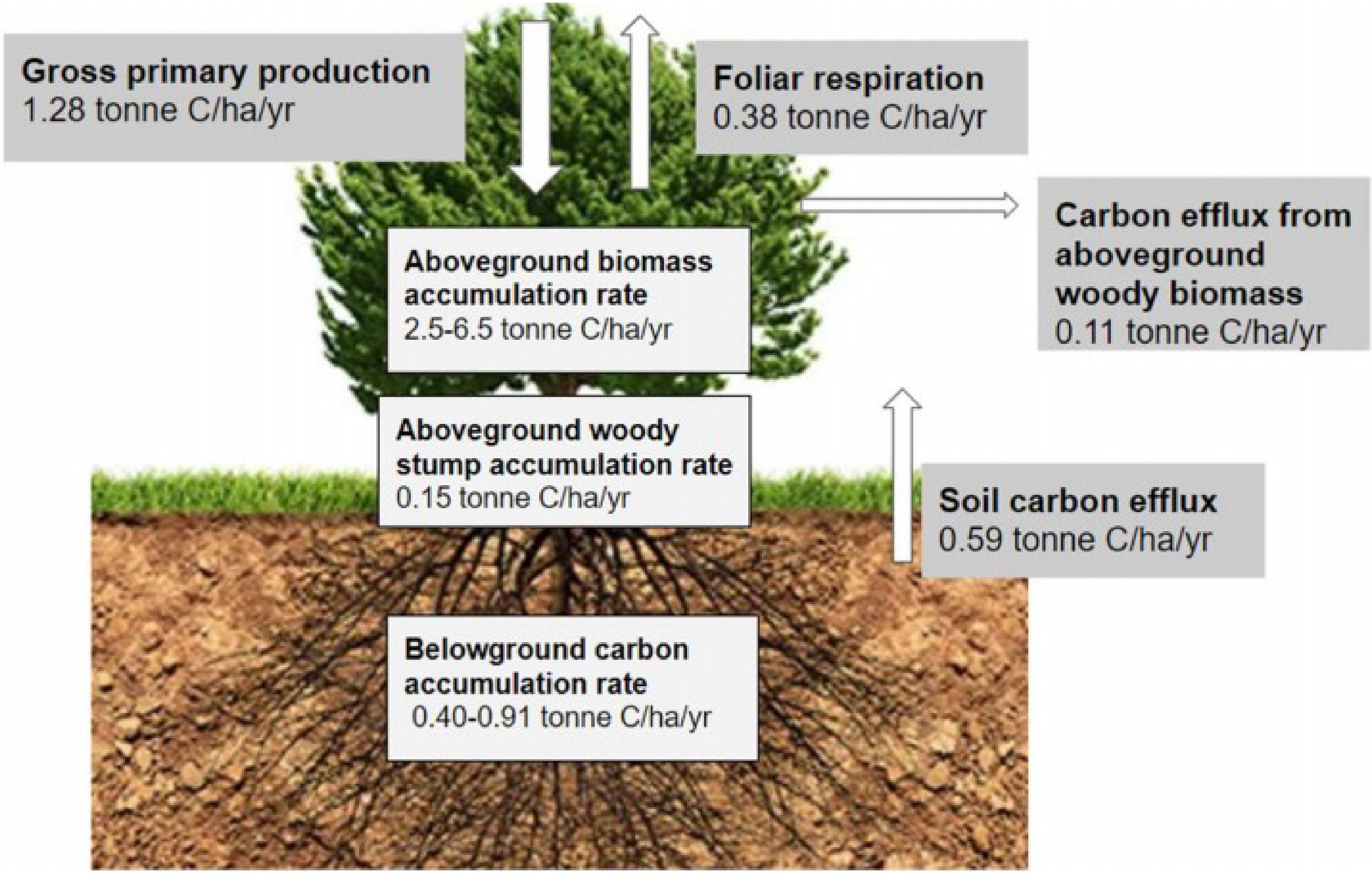
<u>SPERLU vs Current Tech</u>

- Favorable NPV
- Product value 2.5x larger
- Complete biomass utilization

Progress and Outcomes
Task 5: LCA of SPERLU

- M5.1 Report on product systems affected by SPERLU (poplar feedstock)✓ (06/2020)
- M5.2 Biophysical & market-mediated substitution models ✓ (06/2020)
- M5.3 Operational SPERLU-LCA model ✓ (12/2020)
- M5.4 Life-cycle GHG emissions & energy balance (BP3)
- M5.5 Report sensitivity & key issues (BP3)
- M5.6 Recommendations for improving LCA (BP3)

LCA Market Research



- Carbon can be sequestered if only above-ground poplar is harvested for SPERLU

Summary

- 50% yield bio-phenols from lignin achieved
- Scaled up reactor completed to process 200 g biomass per day
- Biotransformation achieving target of 90% conversion
- TEA & LCA models constructed and informing process
- Polymer synthesis & process optimizations in BP3

Acknowledgements

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NATIONAL RENEWABLE ENERGY LABORATORY

INDUSTRIAL ECOLOGY RESEARCH SERVICES

Sergei Hanukovich
John Stair
Mahdi Abu-Omar
Ian Klein
Eric McFarland

Ilona Ruhl
Christopher Johnson
Gregg Beckham

Ilayda Dinc
Yirui Zhang
Sangwon Suh

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

Quad Chart Overview

Timeline
- Project start 10/1/2018
- Project end 3/31/2022

	FY20 Costed	Total Award
DOE Funding	$505,665	*$1,613,457*
Project Cost Share	$166,804	$419,707

Project Partners*
- NREL (Dr. Gregg Beckham)
- IERS (Dr. Sangwon Suh)

Project Goal
Scale-up & validate SPERLU process, converting >50% lignin in non-food biomass to bio-phenols. Make polymers from lignin monomeric bio-phenols and bioprocess bio-phenols into chemicals.

End of Project Milestone
- Produce 1 kg bio-phenols
- ≥ 50% lignin conversion to bio-phenols
- Purify bio-phenols to ≥ 90% purity
- Synthesize bio-polymers matching properties of BPA thermosets
- Optimize biotransformation of select bio-phenols

Funding Mechanism
BEEPS DE-FOA-0001916
Lignin valorization
2018