2016 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Life Cycle Analysis of Emerging Hydrogen Production Technologies

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SA057

Overview

Timeline

- Start: October 2015
- End: Determined by DOE
- % complete (FY16): 70%

Barriers to Address

- Indicators and methodology for evaluating environmental sustainability
- Inconsistent data, assumptions and guidelines
- Insufficient suite of models and tools

Budget

- Funding for FY15: N/A (new project)
- Funding for FY16: $100K

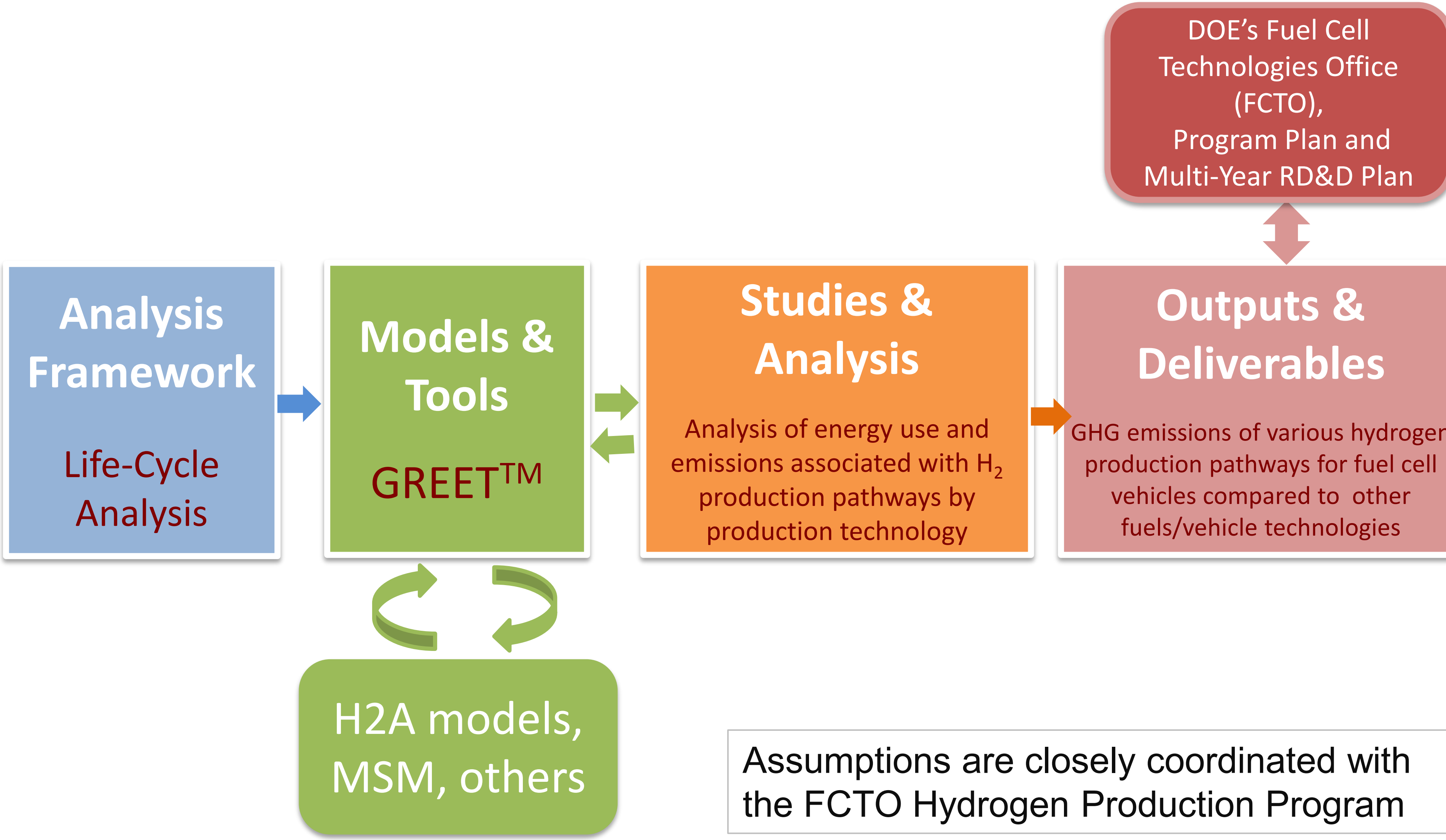
Partners/Collaborators

- Strategic Analysis Inc.
- NREL
- PNNL

Relevance/Impact

- Life-cycle analysis (LCA) estimates energy use and GHG emissions along supply chain of fuel production pathways
  - Provides a consistent platform for comparing environmental impacts of alternative hydrogen production technologies and pathways
  - Addresses the need for low-carbon hydrogen in various regions (e.g., California)
- Assist FCT Office with planning
  - Inform FCTO about environmental impacts and potential GHG reduction of the different hydrogen production technologies and pathway options
  - Facilitate understanding of the tradeoff between cost and GHG emissions of various hydrogen production pathways
- Support existing DOE-sponsored tools (e.g., H2A models, MSM)
  - Collaborate with other model developers and lab partners
  - Support other DOE sponsored activities (e.g., Program Records, C2G analysis)

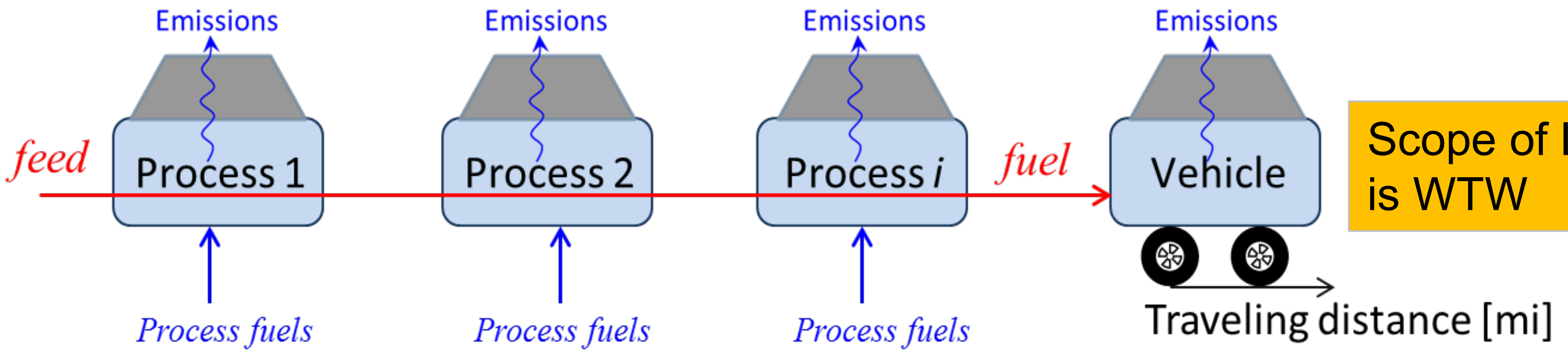
LCA GHG emissions of emerging hydrogen production pathways – Relevance



Assumptions are closely coordinated with the FCTO Hydrogen Production Program

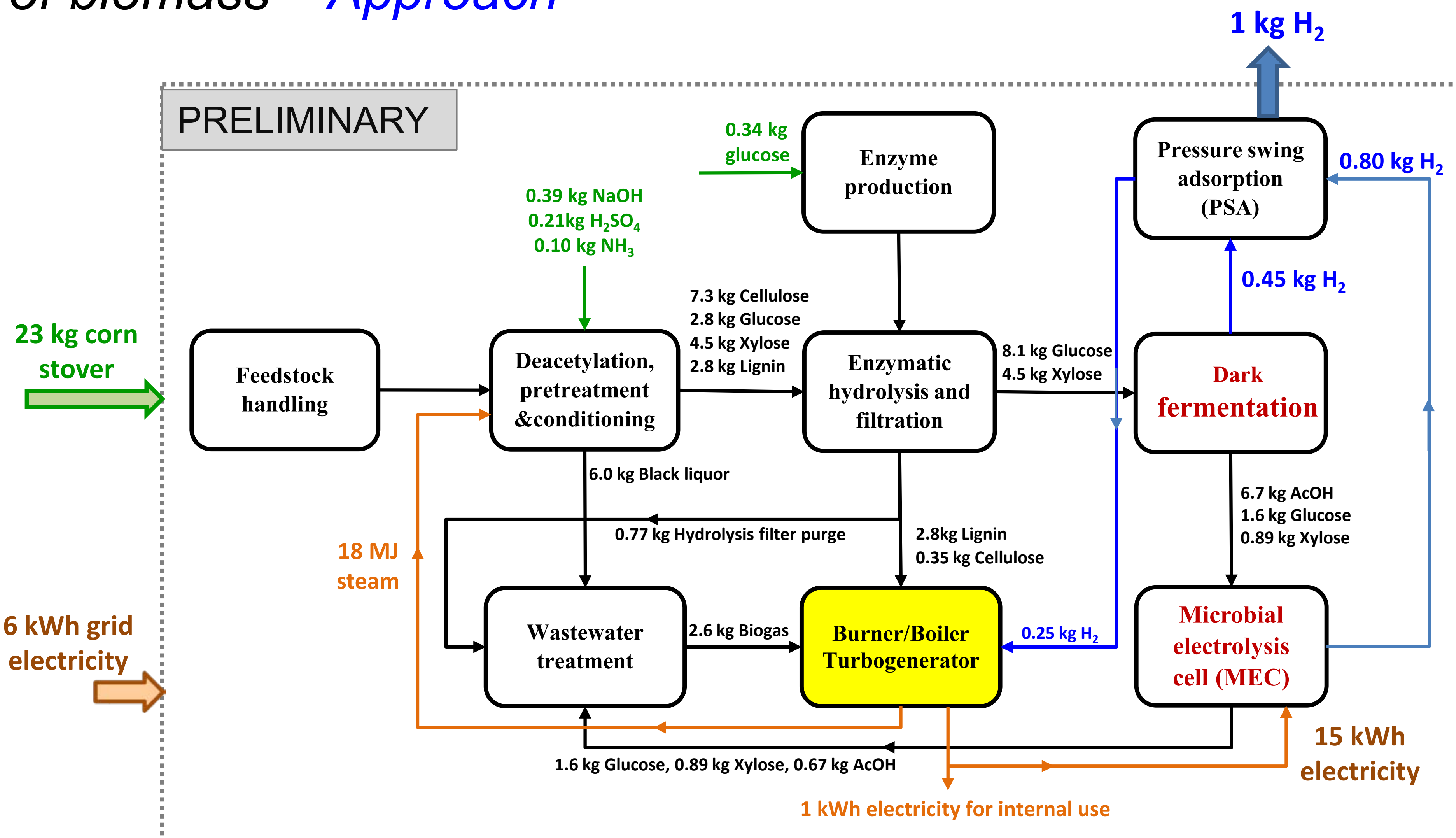
Expanded GREET™ model to include LCA of emerging hydrogen production pathways – Approach

- Acquire material and energy balance information for emerging hydrogen production technologies from modeling efforts developed by partner labs
  - ✓ Dark fermentation (DF) of cellulosic biomass: central production
  - ✓ High-temperature solid oxide electrolysis cell (SOEC): central production
  - ✓ Reforming of biomass-derived liquid hydrocarbon (BDL): distributed production
- Conduct Well-To-Wheels (WTW) of new pathways using GREET™
- Compare WTW GHG emissions of new hydrogen production pathways with baseline pathways
  - ✓ Steam methane reforming (SMR) and electrolysis for hydrogen production
  - ✓ Petroleum gasoline



Scope of LCA is WTW

Acquire data for H_2 production from Dark Fermentation (DF) of biomass – *Approach*



Green arrows represent feedstock and auxiliary materials flows; Blue arrows represent H_2 flows; Black arrows represent key intermediate materials flows; Peach arrows represent energy flows.

H_2 production via DF of biomass: Model Summary

– Approach

- Estimate greenhouse gas (GHG) emissions from material and energy flows associated with integrated DF and MEC system

– Key *assumptions*

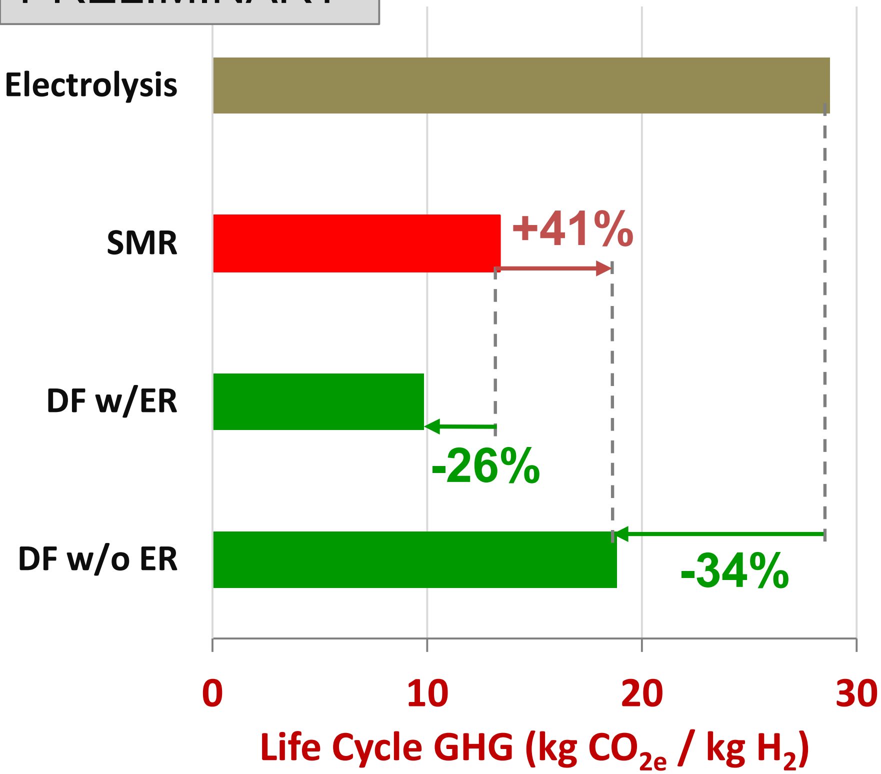
- 80 wt% of the glucose and xylose input to the fermenter goes through conversion to produce H_2 (NREL)
- 90 wt% of AcOH input to the MEC goes through conversion to produce H_2 (PSU)
- MEC electricity requirement: 15 kWh/kg H_2 (PSU)
- 80 wt% H_2 recovery for PSA (NREL)
- 300 mi H_2 transportation and distribution (T&D) distance

– Major variations

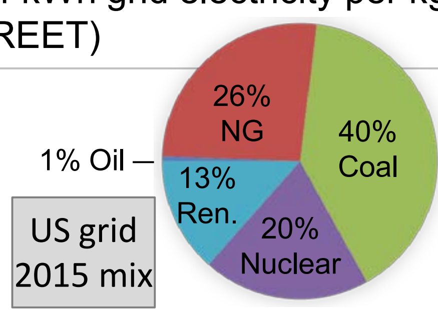
- Energy recovery (ER) from the combustion of lignin, biogas and purged H_2 may not be generally practiced
- Fermentation products (mixture of AcOH, EtOH and lactic acid) may vary
- The electricity consumption of the MEC depends on the applied voltage and can range from 6-22 kWh/kg H_2 (applied voltage impacts productivity)

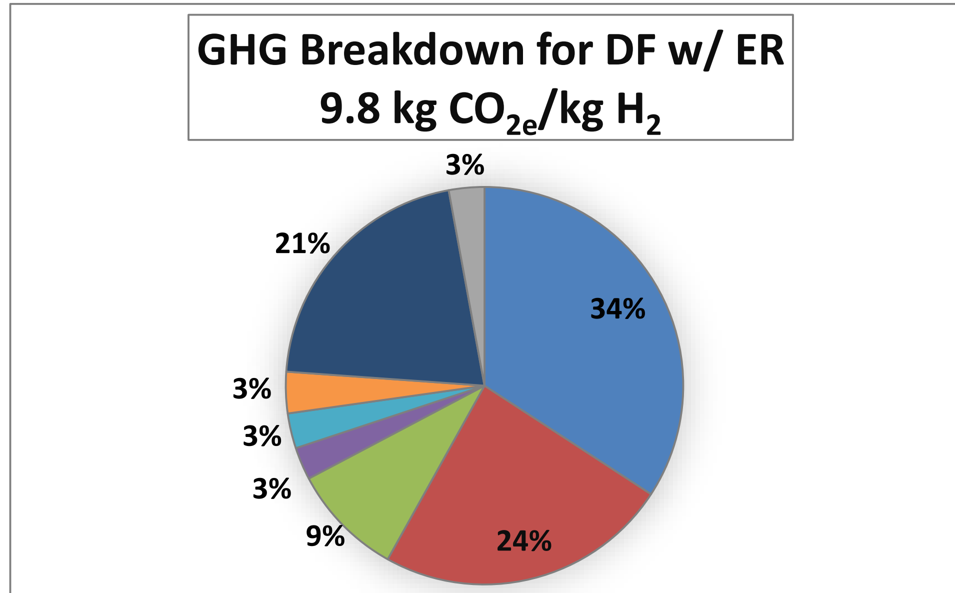
H_2 production via DF: LCA GHG results – Accomplishment

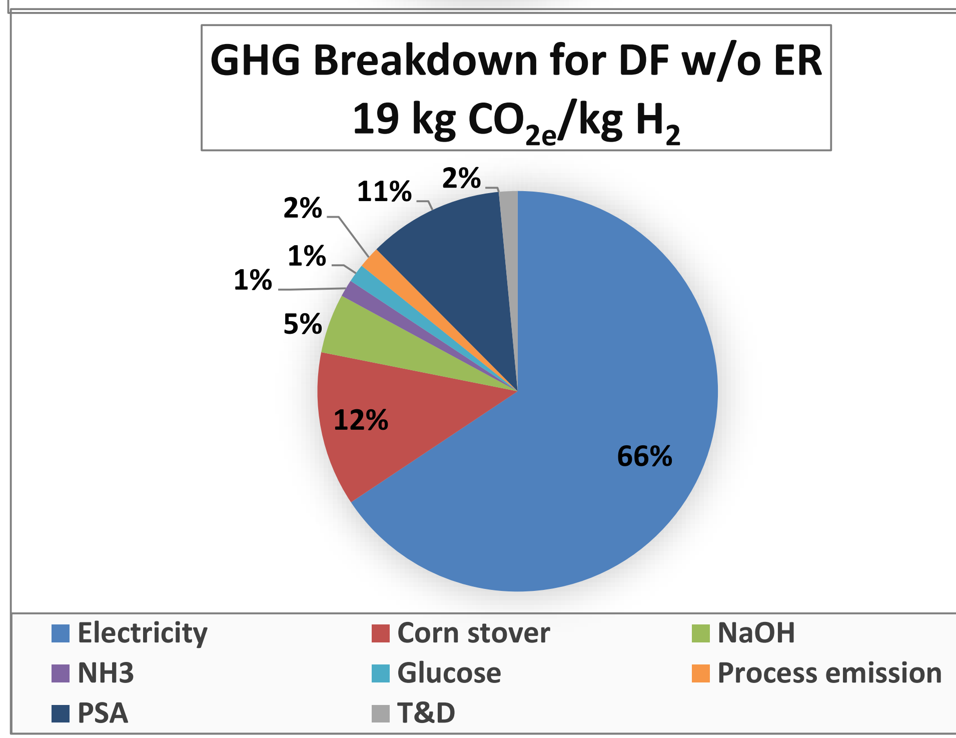
PRELIMINARY



- **Electrolysis**: 46 kWh grid electricity per kg of H_2 (DOE 2015 target)
- **Compression**: 3.4 kWh grid electricity per kg of H_2 (HDSAM, GREET)



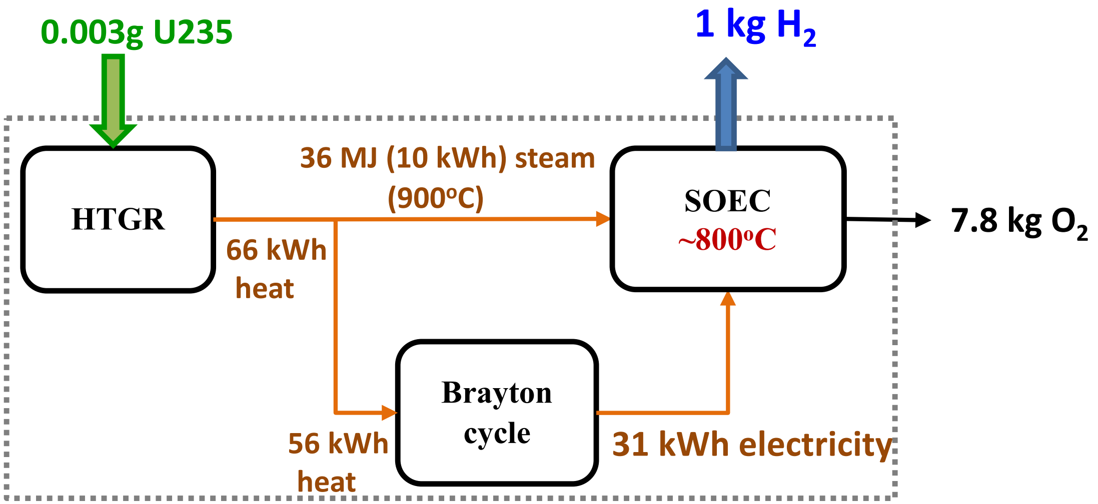




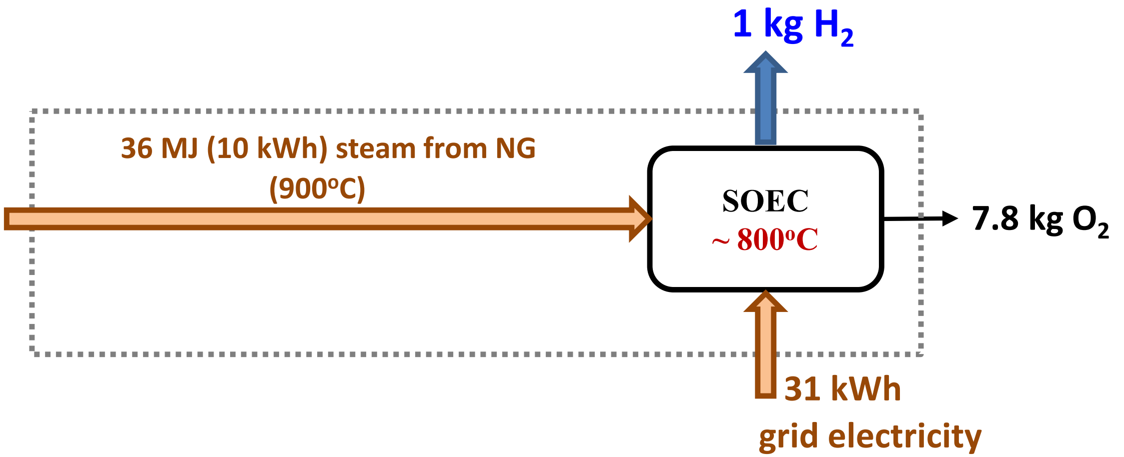
Acquire data for H_2 production via Solid Oxide Electrolysis Cell (SOEC) – Approach

PRELIMINARY

I. High temperature gas-cooled nuclear reactor (HTGR) integrated pathway



II. Natural gas (NG) fueled pathway



Green arrows represent feedstock and auxiliary materials flows; Blue arrows represent H_2 flows; Black arrows represent key intermediate materials flows; Peach arrows represent energy flows.

H_2 production via SOEC: Model Summary

– Approach

- Estimate GHG emissions from H_2 production via high temperature electrolysis (HTE) in a SOEC fueled by HTGR and compare to natural gas for source of heat

– Key *assumptions*

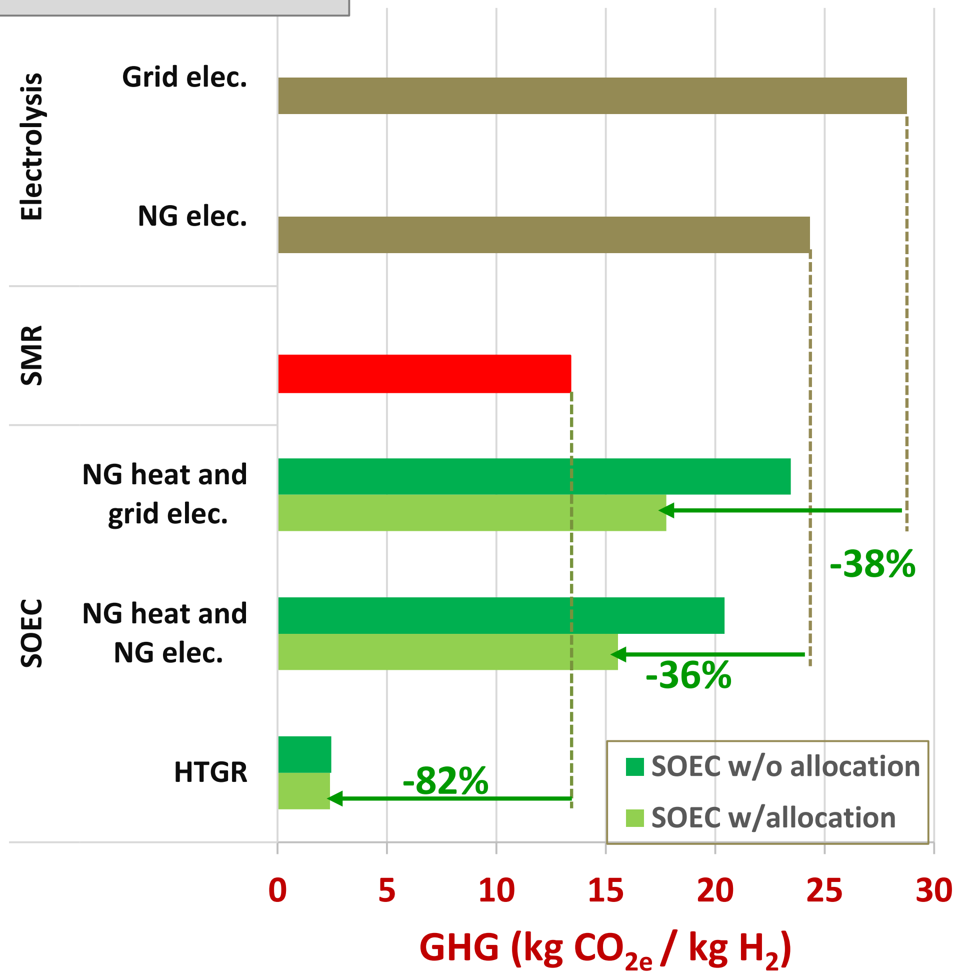
- 50% thermal-to-H_2 conversion efficiency for the HTGR-integrated pathway (INL)
- 80% natural gas boiler efficiency (LHV based) for the NG-fueled pathway (GREET)
- 300 mi H2 transportation and distribution (T&D) distance
- Economic value allocation between main product H_2 and coproduct O_2
  - ✓ H_2 market price: \$4.20/kg H_2 (GREET)
  - ✓ O_2 market price: \$0.20/kg O_2 (Chemicool)

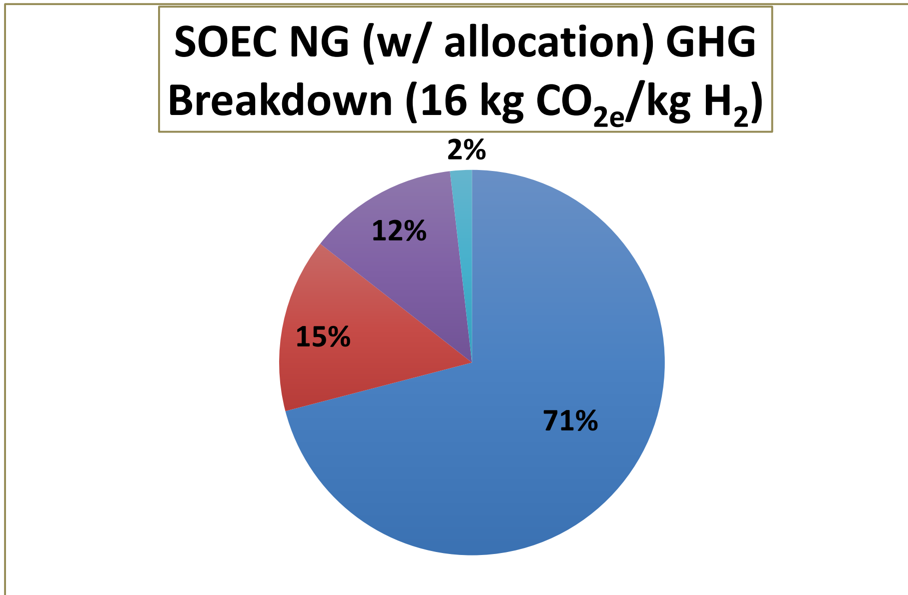
– Major variations

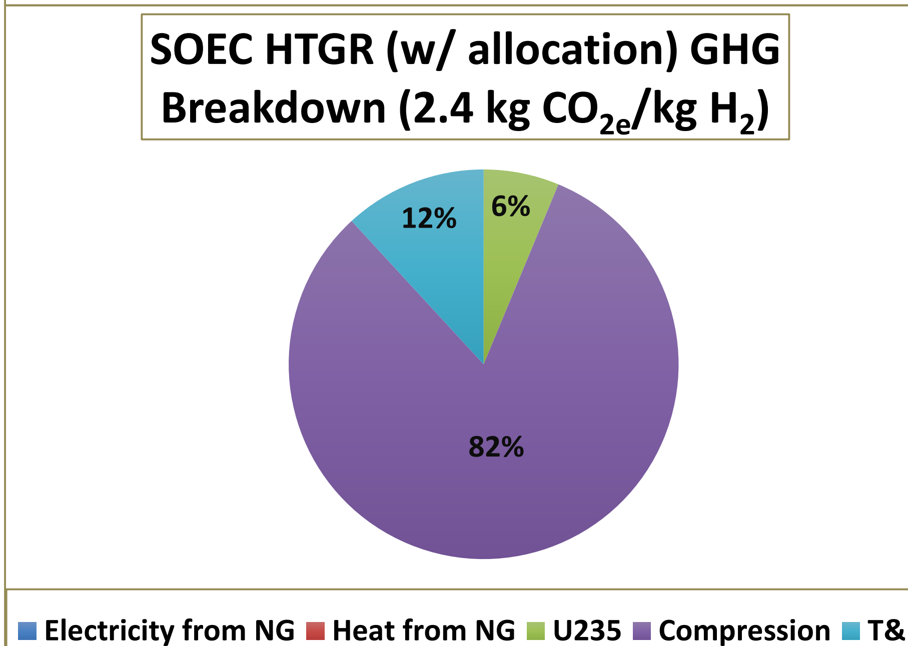
- Coproduced O_2 may not be collected and sold as a commodity
- The market prices of H_2 and O_2 are subject to variation over time

H_2 production via SOEC: LCA GHG Results –Accomplishment

PRELIMINARY



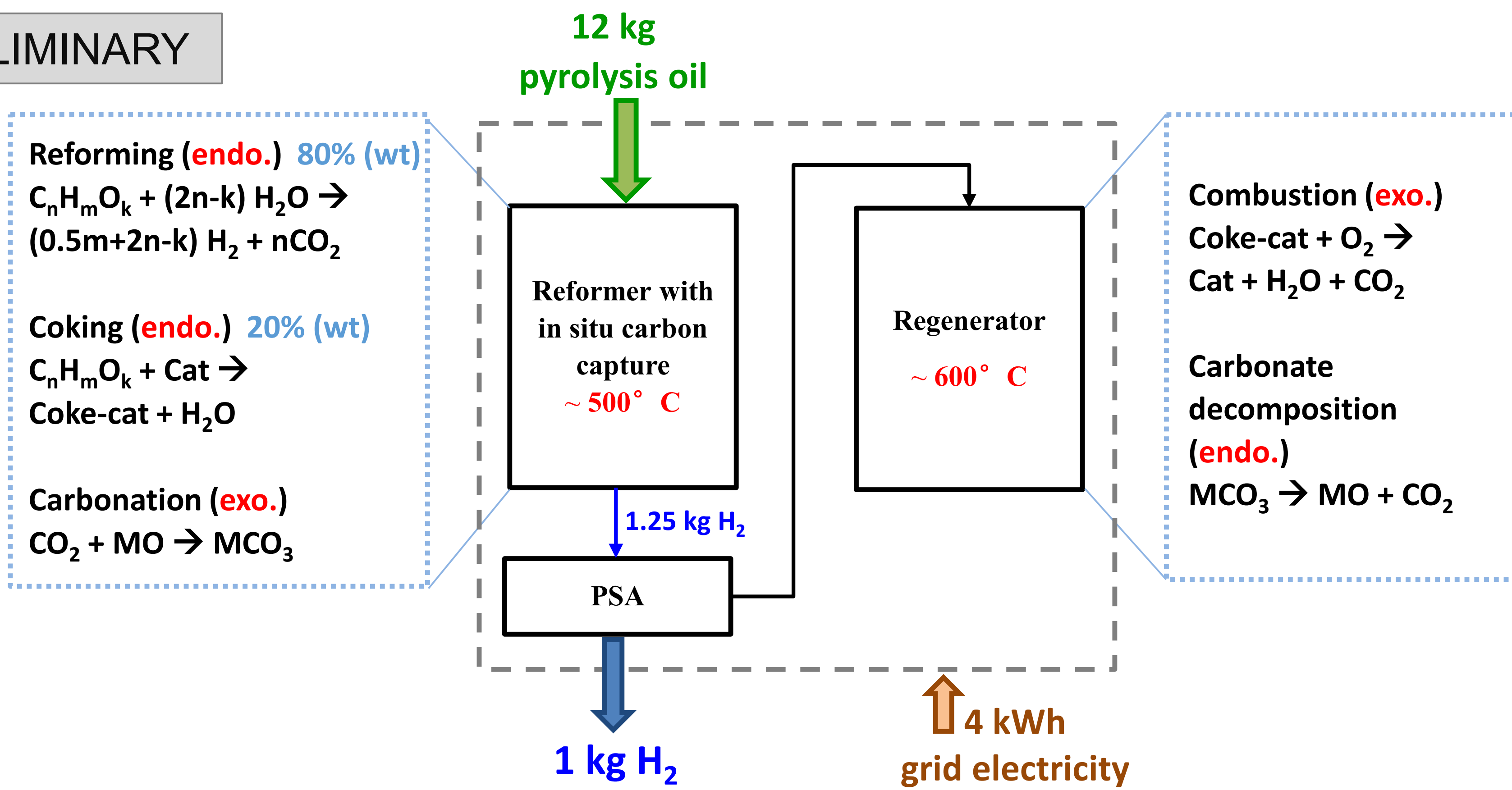


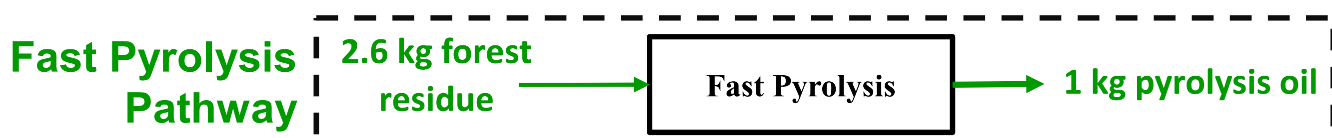


- **Compression: 3.4 kWh grid electricity per kg of H_2 (GREET)**

Acquire data for H_2 production via reforming of Biomass-Derived Liquid (BDL) – *Approach*

PRELIMINARY





Green arrows represent feedstock and auxiliary materials flows; Blue arrows represent H_2 flows; Black arrows represent key intermediate materials flows; Peach arrows represent energy flows.

H_2 production via reforming of BDL: Model Summary

– Approach

- Estimates GHG emissions from H_2 production via reforming of pyrolysis oil derived from forest residue

– Key *assumptions*

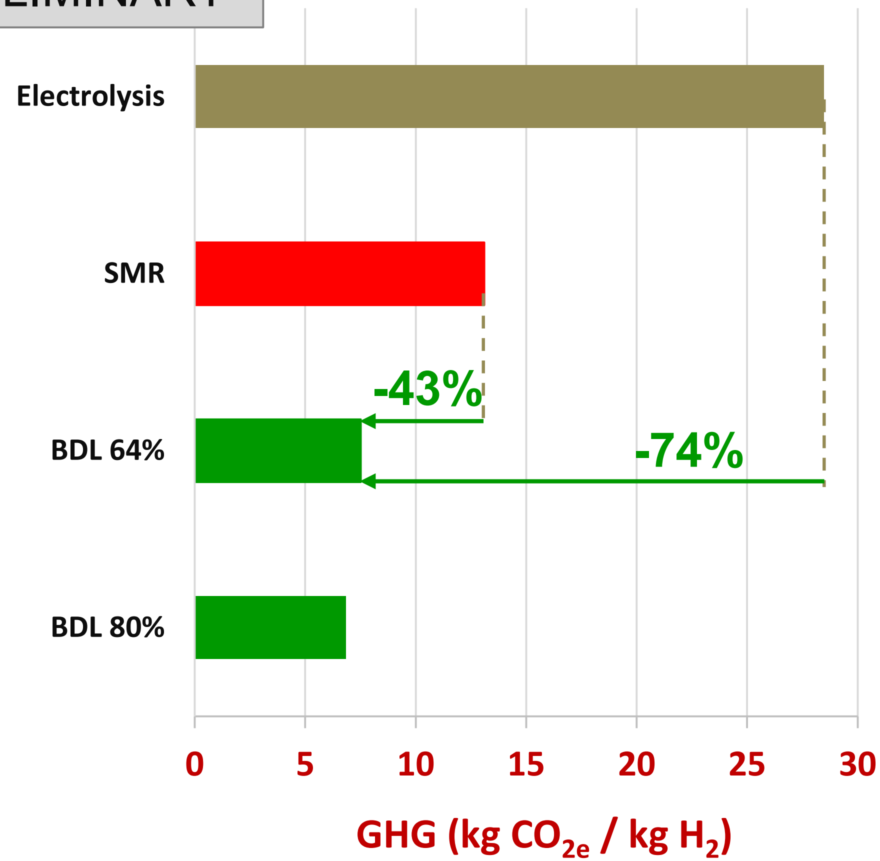
- Pyrolysis oil-to-H_2 (excluding aux. electricity from grid) energy conversion efficiency can be up to 80% (PNNL)
- Pyrolysis oil LHV: 17.4 MJ/kg (PNNL)
- Pyrolysis oil composition: 45% C, 48% O, and 7% H (mass basis, PNNL)
- 64% (wt%) of pyrolysis oil goes through conversion to produce H_2 (80% single pass conversion rate [i.e., 20% unreacted] x 80% conversion by reforming) (PNNL)
- 80% H_2 recovery for PSA (NREL). Conservative as part of CO_2 is captured in MO

– Major variations

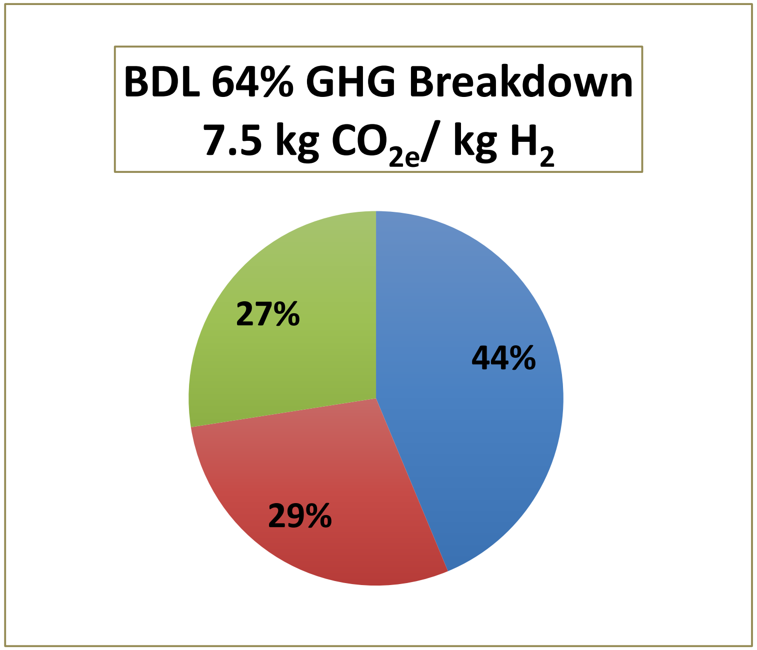
- Chemical compositions and LHVs of the pyrolysis oil vary depending on forest residue compositions and pyrolysis technologies
- Unreacted pyrolysis oil can be recycled and consequently drive up the pyrolysis oil-to-H_2 conversion rate to 80%

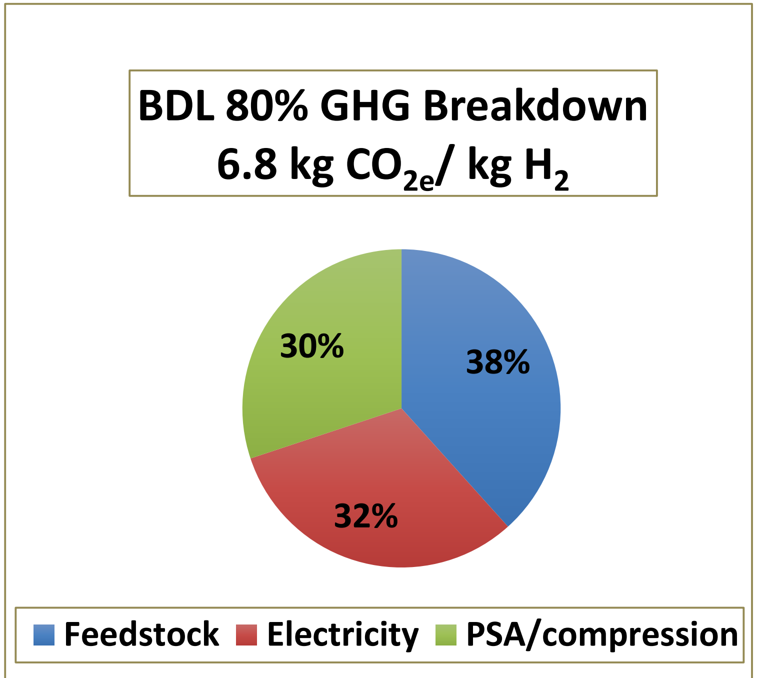
H_2 production via reforming of BDL: LCA GHG Results –Accomplishment

PRELIMINARY



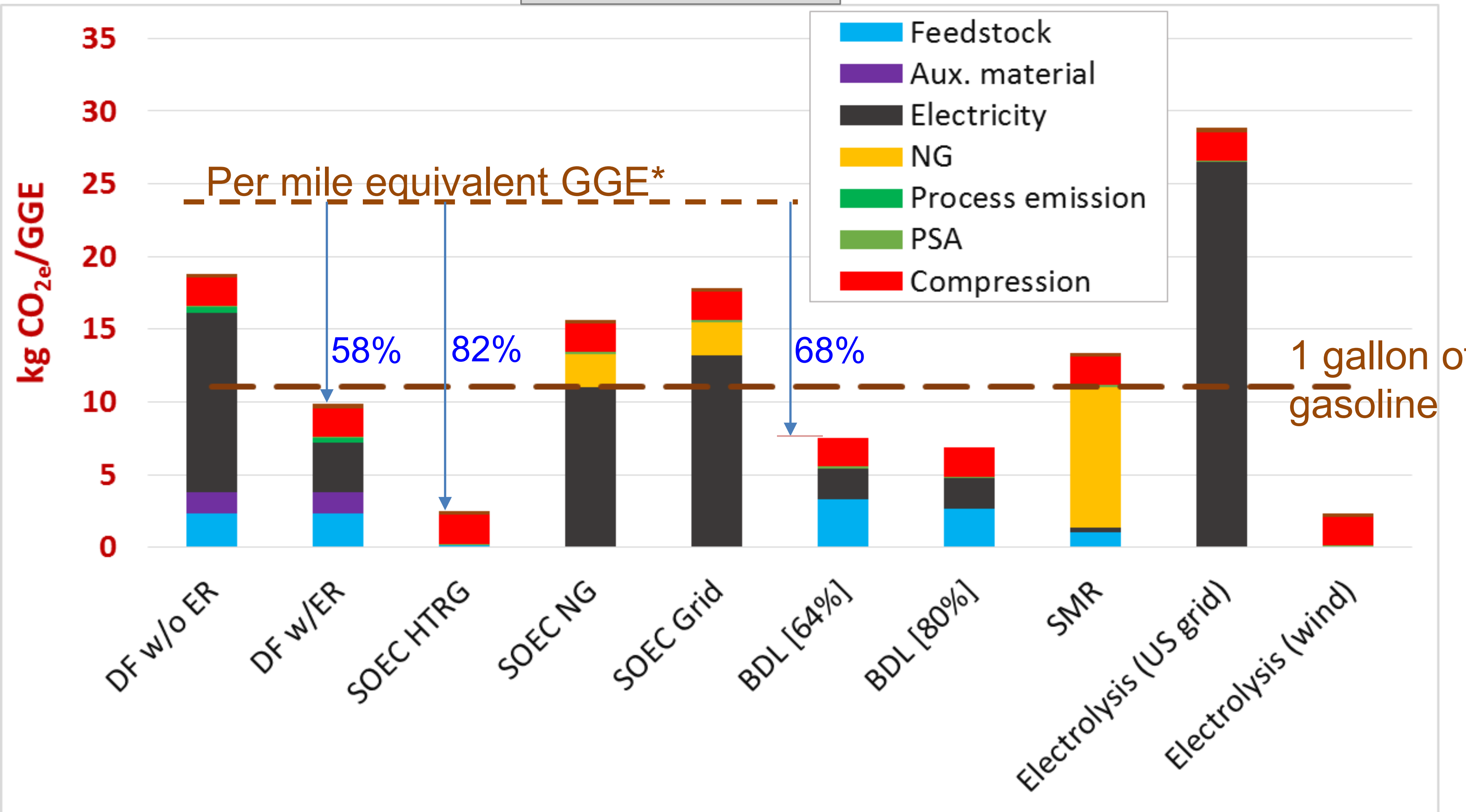
- Distributed production scale (1500 kg/day)
- Compression: 3.4 kWh grid electricity per kg of H_2 (GREET)





Well-to-Wheels GHG Comparison of 1 GGE (or 1 kg H_2) –Accomplishment

PRELIMINARY



***Assuming fuel economy of 26 MPG for gasoline ICEV and 55 MPGGE for FCEV (GREET)**

- H_2 produced from energy sources other than fossil fuels outperforms gasoline and SMR H_2 in terms of WTW GHG emissions

Summary – Accomplishment

- Dark fermentation of cellulosic biomass for hydrogen production
  - Can reduce life cycle GHG emissions by 26% compared to SMR-H_2, and by 58% when used in FCEV compared to gasoline ICEV
- High-temperature solid oxide electrolysis cell for hydrogen production
  - Can reduce life cycle GHG emissions by 82% compared to SMR-H_2 if produced from nuclear source
  - Results in much higher GHG emissions compared to SMR-H_2 if produced from fossil sources
- Reforming of biomass-derived liquid hydrocarbon for hydrogen production
  - Can reduce life cycle GHG emissions by 43% compared to SMR-H_2, and by 68% when used in FCEV compared to gasoline ICEV
- In general, H_2 produced from energy sources other than fossil fuels outperforms SMR-H_2 in terms of WTW GHG emissions

Collaborations and Acknowledgments

- NREL: **Pin-Ching Maness** provided energy and mass balance information on dark fermentation (**DF**) process
- Strategic Analysis Inc.: **Daniel Desantis** provided energy and mass balance information on Solid Oxide Electrolysis Cell (**SOEC**) process
- PNNL: **Kenneth Rappe** provided energy and mass balance information on Biomass-Derived Liquid (**BDL**) process

Future Work

- Continue development and implementation of pathways for emerging hydrogen production technologies in GREET
  - e.g., photobiogical, photoelectrochemical, solar thermochemical (STCH), etc
- Evaluate environmental metrics other than GHG such as water consumption and air pollutant emissions
- Develop probability distribution functions for key inputs of various processes and conduct stochastic analysis on variability/uncertainty of various parameters
- Update GREET model with new production pathways
- Document the data sources, LCA methodology, and results of emerging hydrogen production pathways in peer reviewed publications

Project Summary

- **Relevance:** Inform FCTO about environmental impacts and potential GHG reduction of the different hydrogen production technologies and pathway options. Facilitate understanding of the tradeoff between cost and GHG emissions of various hydrogen production pathways.
- **Approach:** Expanded GREETTM model to include LCA of emerging hydrogen production pathways.
- **Collaborations**: Acquire material and energy balance information for emerging hydrogen production technologies from modeling efforts developed by partner labs and organizations (NREL, PNNL, SA).
- **Technical accomplishments and progress:**
  - Expanded the GREET model and evaluated LCA GHG emissions of the following hydrogen production pathways:
    - Dark fermentation (DF) of cellulosic biomass: central production
    - High-temperature solid oxide electrolysis cell (SOEC): central production
    - Reforming of biomass-derived liquid hydrocarbon (BDL): distributed production
- **Future work**:
  - Continue development and implementation of pathways for emerging hydrogen production technologies in GREET, such as photobiogical, photoelectrochemical, and solar thermochemical
  - Evaluate environmental metrics other than GHG such as water consumption and air pollutant emissions
  - Update GREET model with new production pathways
  - Document the data sources, LCA methodology, and results of emerging hydrogen production pathways in peer reviewed publications

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Acronyms

- AcOH: Acetic acid
- ANL: Argonne National Laboratory
- BDL: Biomass-Derived Liquid
- CO_{2e}: CO_2 equivalent for combined GHG
- DF: Dark Fermentation
- DOE: Department of Energy
- ER: Energy Recovery
- EtOH: Ethanol
- FCTO: Fuel Cell Technologies Office
- FY: Fiscal Year
- GHG: Greenhouse Gases
- GGE: Gallon of gasoline equivalent
- GREET: Greenhouse gases, Emissions, and Energy use in Transportation
- H2A: Hydrogen Analysis
- HTE: High Temperature Electrolysis
- HTGR: High Temperature Gas-cooled Reactor
- ICEV: Internal Combustion Engine Vehicle
- INL: Idaho National Laboratory
- LCA: Life-Cycle Analysis
- LHV: Lower Heating Value
- MEC: Microbial Electrolysis Cell
- MO: Metal Oxide
- MPGGE: Miles Per Gallon of Gasoline Equivalent
- NG: Natural Gas
- NREL: National Renewable Energy Laboratory
- PNNL: Pacific Northwest National Laboratory
- PSA: Pressure Swing Adsorption
- PSU: Pennsylvania State University
- RD&D: Research, Development, and Demonstration
- SA: Strategic Analysis Inc.
- SMR: Steam Methane Reforming
- SOEC: Solid Oxide Electrolysis Cell
- T&D: Transportation and Distribution
- U235: Uranium 235
- US Mix: US electricity grid mix
- w/: With
- w/o: Without
- WTW: Well-To-Wheels

Backup Slides

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