IX.5 Life Cycle Analysis of Emerging Hydrogen Production Technologies

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Project Start Date: October 1, 2015
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Quantify environmental impacts associated with emerging hydrogen production pathways.
- Identify greenhouse gas (GHG) reduction potential of various hydrogen production technologies and pathways compared to natural gas steam methane reforming (SMR).
- Support existing DOE-sponsored tools for hydrogen production.

Fiscal Year (FY) 2016 Objectives

- Conduct life cycle analysis of emerging hydrogen production pathways, including dark fermentation of lignocellulosic biomass, high temperature electrolysis (HTE) with a solid oxide electrolysis cell (SOEC), and reforming of biomass-derived liquids (BDL).
- Quantify GHG emissions along the supply chains of investigated hydrogen production pathways.
- Identify sensitivity of life cycle GHG emissions to system performance parameters and GHG reduction potentials.

Technical Barriers

This project addresses the following technical barriers from the System Analysis section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan.

(B) Stove-piped/Siloed Analytical Capability

(C) Inconsistent Data, Assumptions and Guidelines

(D) Insufficient Suite of Models and Tools

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestones from the System Analysis section of the FCTO Multi-Year Research, Development, and Demonstration Plan.

- Milestone 1.13: Complete environmental analysis of the technology environmental impacts for hydrogen and fuel cell scenarios and technology readiness. (4Q, 2015)
- Milestone 1.15: Complete analysis of program milestones and technology readiness goals – including risk analysis, independent reviews, financial evaluations, and environmental analysis – to identify technology and risk mitigation strategies. (4Q, 2015)
- Milestone 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)
- Milestone 3.1: Annual update of Analysis Portfolio. (4Q, 2011 through 4Q, 2020)

FY 2016 Accomplishments

- Completed life cycle analysis of hydrogen production from dark fermentation of corn stover, HTE with SOEC, and steam reforming of BDL.
- Produced estimates of the GHG emissions and GHG reduction potentials of alternative hydrogen production pathways, and compared them to conventional hydrogen production technologies, such as SMR and electrolysis.
- Demonstrated that, compared with hydrogen from SMR, hydrogen from dark fermentation, HTE and BDL can reduce well-to-wheels (WTW) GHG by 26%, 82%, and 43%, respectively, when used in a fuel cell electric vehicle (FCEV). The corresponding GHG reductions are 58%, 90%, and 68% when compared to a gasoline internal combustion engine vehicle (ICEV) on a per mile driven basis.
- Expanded the Greenhouse gases, Emissions, and Energy use in Transportation (GREET®) model's capabilities to evaluate the environmental impacts of new and emerging hydrogen production pathways.

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INTRODUCTION

Argonne National Laboratory's GREET model has been used by DOE to evaluate environmental footprints of fuel production, vehicle production and vehicle operation [1]. In this study, three emerging hydrogen production technologies of interest to FCTO, including dark fermentation of lignocellulosic biomass, HTE with SOEC, and reforming of BDL, have been incorporated into the GREET model. Life cycle GHG emissions from the three hydrogen production pathways are evaluated, with major GHG emission sources identified. Together with existing techno-economic analysis of emerging hydrogen production pathways, this study enables FCTO to conduct a comprehensive evaluation of risks and benefits of different hydrogen production technologies, and to guide FCTO research, development, and demonstration planning.

APPROACH

Material and energy flows pertaining to the three hydrogen production pathways have been compiled based on engineering modeling and experimental measurements by partner labs, and incorporated in the GREET model. With GREET, GHG emissions along the supply chain of each hydrogen production pathway are calculated and compared with those of conventional hydrogen production technologies (SMR and water electrolysis). Since system performance dictates material and energy flows of the system, sensitivity analyses of WTW GHG to different assumptions of major system performance metrics have also been conducted. To fully illustrate the environmental benefits of the emerging hydrogen production technologies, the WTW per mile GHG emissions for a FCEV fueled by hydrogen produced from aforementioned technologies have been compared with that for an ICEV fueled by gasoline.

RESULTS

Hydrogen from Dark Fermentation of Lignocellulosic Biomass

Process flow of the dark fermentation pathway is depicted in Figure 1. WTW GHG emissions is 9.8 kg CO_{2e}/kg of hydrogen produced via dark fermentation of corn stover, compared to 13 kg CO_{2e}/kg of hydrogen produced from SMR, and 29 kg CO_{2e}/kg hydrogen produced via electrolysis with electricity from U.S. average grid mix. Energy recovered through combustion of lignin, biogas from wastewater treatment, and purged hydrogen from the gas cleaning unit completely satisfies the steam requirement of the biomass pretreatment process, and partially offset the electricity requirement of the entire system. Without energy recovery (ER), the WTW GHG emissions associated with 1 kg

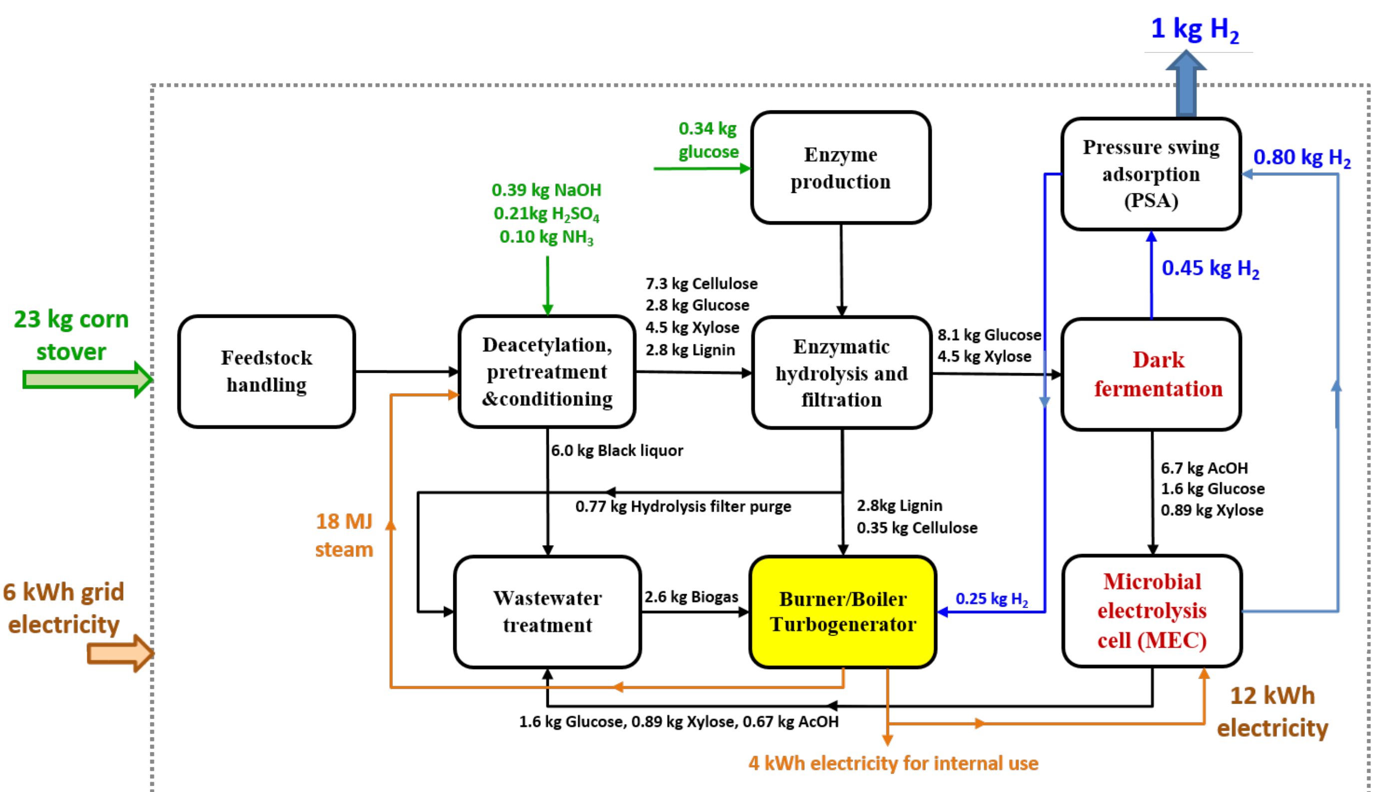


FIGURE 1. Hydrogen production process from dark fermentation of corn stover

hydrogen produced from the dark fermentation pathway increases to 19 kg CO_{2e}/kg. Therefore, ER offers the greatest potential of GHG reduction for hydrogen production from dark fermentation but likely at increased capital investment. In addition, electricity requirement by the production process is identified as a major contributor to the WTW GHG emissions of hydrogen produced from dark fermentation. Increasing hydrogen yield of the fermenter and the microbial electrolysis cell, and improving system energy efficiency are also viable means to achieve further GHG emissions reduction.

Hydrogen from HTE with SOEC

Process flow of the HTE pathway is depicted in Figure 2. Electricity consumed by the SOEC and heat required to produce the high temperature steam (at 900°C) are the major energy inputs for this process. When integrated with a high temperature gas-cooled nuclear reactor (HTGR) such that both heat and electricity are derived from non-fossil nuclear source (U_{235}), the system produces hydrogen with a WTW GHG emissions of 2.5 kg CO_{2e}/kg, which is 78% lower compared to hydrogen produced from SMR. In contrast, if both electricity and heat are generated using natural gas, hydrogen produced from HTE pathway produces WTW GHG emissions of 20 kg CO_{2e}/kg. Utilizing a non-fossil energy source is therefore key to GHG emissions reduction for hydrogen produced from HTE. Electrolysis with high temperature steam produces oxygen in addition to hydrogen. If the co-produced oxygen is collected and sold as a commodity, heat and electricity input to the production process can be allocated based on the economic values of produced hydrogen and oxygen. After economic allocation, the WTW GHG emissions are estimated at 2.4 kg CO_{2e}/kg hydrogen produced from the HTGR-integrated system, and 16 kg CO_{2e}/kg hydrogen produced from the natural gas-fueled system.

Hydrogen from Steam Reforming of BDL

Process flow of the BDL pathway is depicted in Figure 3. WTW GHG emissions are estimated at 7.5 kg CO_{2e}/kg hydrogen produced via reforming of BDL, which is 43% lower compared to hydrogen production from SMR. Pyrolysis oil, which is the feedstock for this production process, and electricity input are the major GHG emissions contributors, accounting for 44% and 29% of the WTW GHG emissions, respectively. Recycling unreacted pyrolysis oil can increase the pyrolysis oil-to-hydrogen conversion rate from 64% to 80%, with the potential to further reduce the WTW GHG emissions to 6.8 kg CO_{2e}/kg hydrogen for the BDL pathway.

WTW GHG Emissions Comparison

WTW GHG emissions comparison of hydrogen from various hydrogen production pathways compared to gasoline ICEV are summarized in Figure 4. To account for the higher fuel economy of FCEVs relative to gasoline ICEVs (ratio of 2.1), a per-mile gallon of gasoline equivalent (GGE) is used as a functional unit to compare WTW GHG emissions of various vehicle–fuel pathways on a consistent basis. Compared with hydrogen from SMR, hydrogen from dark fermentation, HTE and BDL can reduce WTW GHG emissions by 26%, 82%, and 43% respectively. On a per

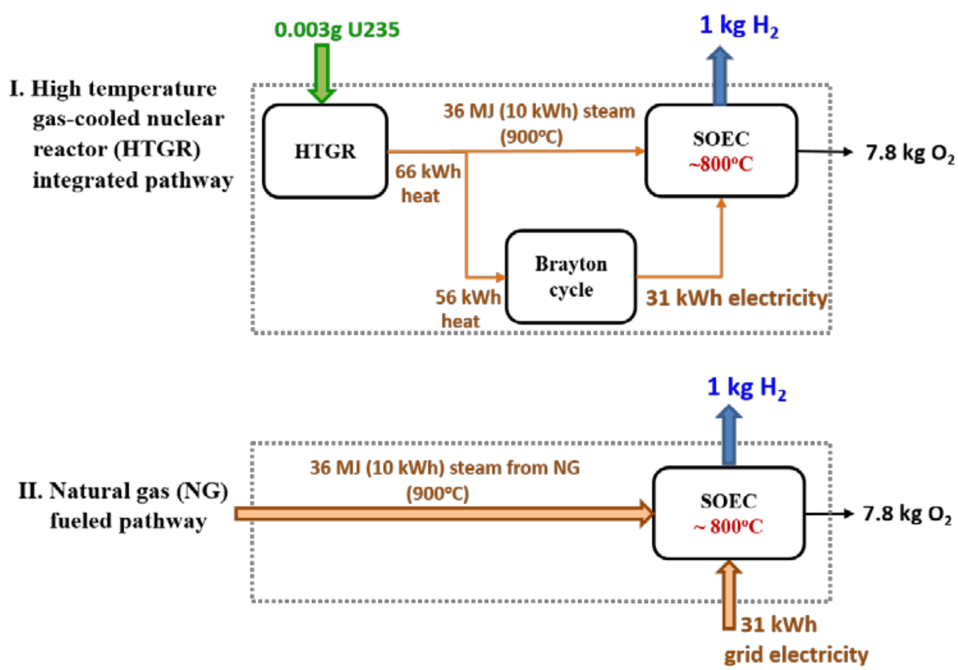
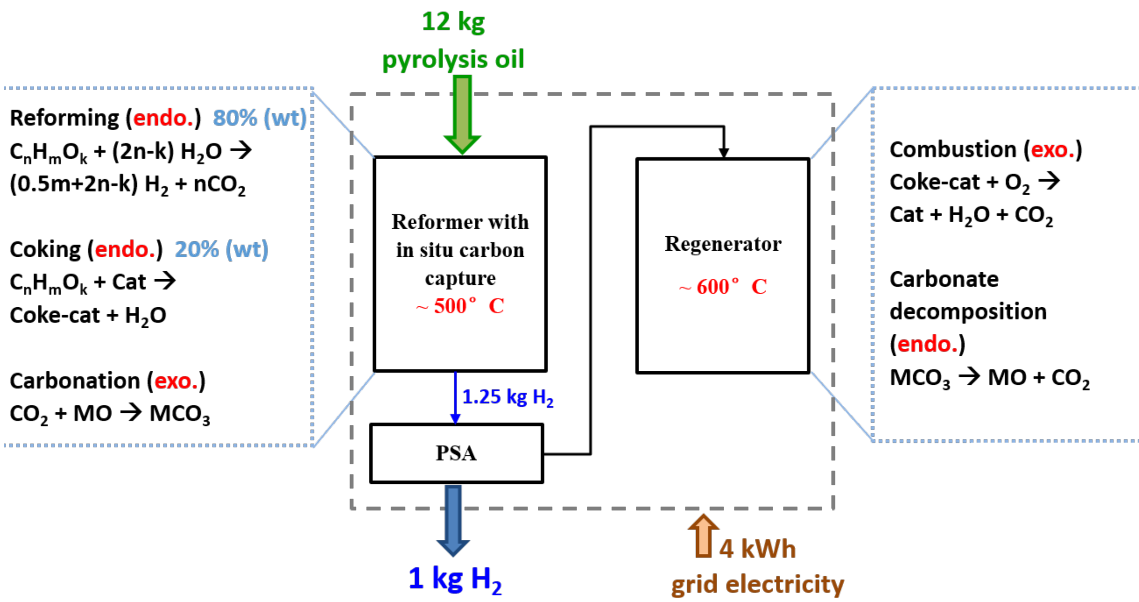
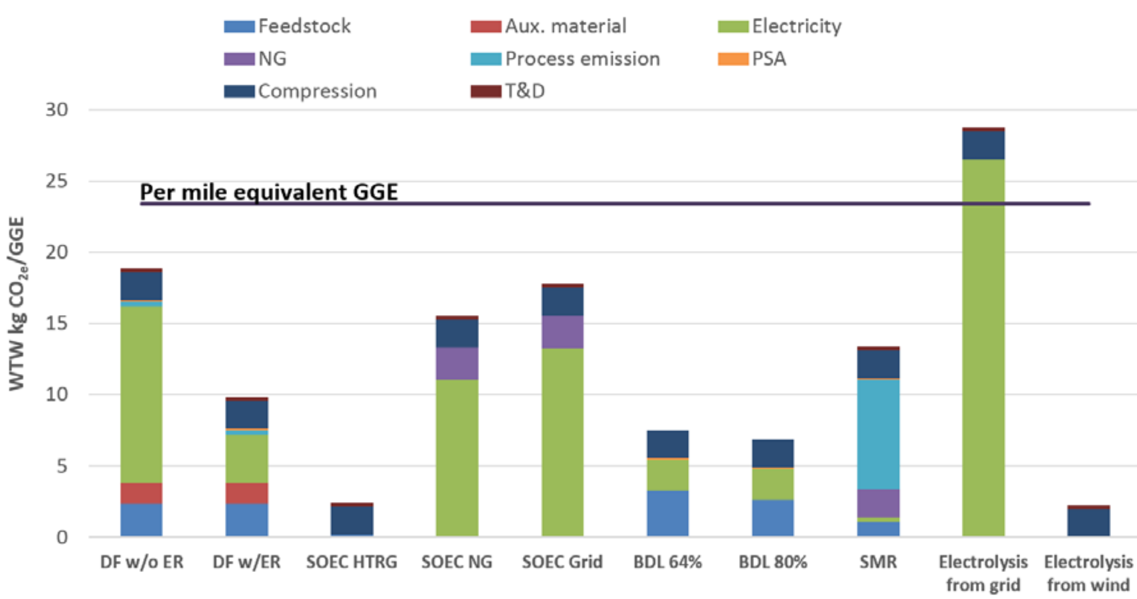


FIGURE 2. Hydrogen production process via high-temperature electrolysis using SOEC



PSA – Pressure swing absorption

FIGURE 3. Hydrogen production process via reforming of pyrolysis oil



GGE – Gallon of gasoline equivalent; NG – natural gas; T&D – Transportation and distribution; DF – Dark fermentation

FIGURE 4. WTW GHG emissions comparison of hydrogen from the various hydrogen production pathways compared to gasoline ICEV

mile basis, FCEVs using hydrogen produced from dark fermentation, nuclear HTE and BDL provide WTW GHG emissions reductions of 58%, 90%, and 68% compared to gasoline ICEV.

CONCLUSIONS AND FUTURE DIRECTIONS

- In general, hydrogen produced from non-fossil energy sources outperforms hydrogen produced from fossil sources (e.g., SMR and grid electrolysis) in terms of life cycle GHG emissions.
- Increasing hydrogen yield and improving process efficiency of the investigated pathways offer GHG emissions reduction opportunities for all hydrogen production pathways.
- Energy recovery from lignin, biogas, and purged hydrogen is critical to materialize large reduction in GHG emissions for the dark fermentation pathway,

whereas the recycling of unreacted pyrolysis oil is important for GHG emissions reduction for the BDL pathway.

In the future, we will continue the development and implementation of other emerging hydrogen production technologies in GREET. In addition to GHG emissions, other environmental impact metrics, such as water consumption and criteria air pollutants emissions will be evaluated. To facilitate better understanding of the uncertainty of system performance parameters and their impact on life cycle GHG emissions, we will also develop probability distribution functions for key system parameters and conduct stochastic analyses on the various production pathways.

REFERENCES

1. "Argonne GREET Model," Argonne National Laboratory, accessed July 20, 2016, https://greet.es.anl.gov/