Fuel-Cycle Analysis of Hydrogen-Powered Fuel-Cell Systems with the GREET Model

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Project ID # AN2

Overview

Timeline

- Project start date: Oct. 2002
- Project end date: Continuous
- Percent complete: N/A

Budget

- Total project funding from DOE: $2.04 million through FY08
- Funding received in FY07: $450k
- Funding for FY08: $840k

Barriers to Address

- Inconsistent data, assumptions, and guidelines
- Suite of models and tools
- Unplanned studies and analyses

Partners

- H2A team
- PSAT team
- NREL
- Industry stakeholders

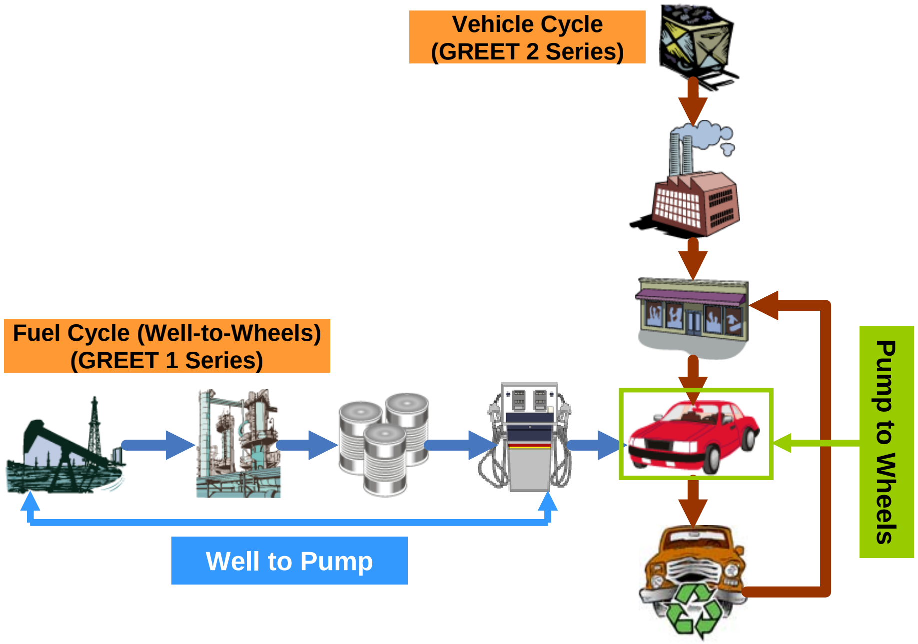
Objectives

- Expand and update the GREET model for hydrogen production pathways and for applications of FCVs and other FC systems
- Conduct well-to-wheels (WTW) analysis of hydrogen FCVs with various hydrogen production pathways
- Conduct life-cycle analysis of H2-powered FC systems
- Provide WTW results for OFCHIT efforts on the Hydrogen Posture Plan and the MYPP
- Engage in discussions and dissemination of energy and environmental benefits of hydrogen FCVs and other FC systems

Approach

- **Obtain data for hydrogen production pathways**
  - **Open literature**
  - **H2A simulation results**
  - **Process engineering simulations with models such as ASPEN**
  - **Interact with hydrogen producers**
- **Obtain data for hydrogen FCVs and other FC Systems**
  - **Open literature**
  - **PSAT simulations**
  - **Data of available FCV models**
  - **Data from industry sources**
- **Expand and update the GREET model**
- **Conduct WTW or fuel-cycle simulations with GREET**
- **Analyze and present WTW results**

Argonne Has Been Developing The GREET Model Since 1995



- **Emissions of greenhouse gases**
  - ➢ CO_2, CH_4, and N_2O
- **Emissions of six criteria pollutants**
  - ➢ Total and urban separately
  - ➢ VOC, CO, NO_x, SO_x, PM_{10} and $PM_{2.5}$
- **Energy use**
  - ➢ All energy sources
  - ➢ Fossil fuels (petroleum, NG and coal)
  - ➢ Petroleum
  - ➢ Coal
  - ➢ NG

- **GREET and its documents are available at http://www.transportation.anl.gov/software/GREET/index.html**
- **At present, there are over 7,500 registered GREET users from**
  - ➢ Auto industry, energy industry, governments, universities, etc.
  - ➢ North America, Europe, and Asia
- **The most recent GREET1.8 version was released in March 2008**

What's New In GREET1.8?

- New fuel production pathways
  - Biomass to hydrogen with carbon capture and storage (CCS)
  - Brazilian sugarcane ethanol
  - Corn to butanol
  - Soybeans to renewable diesel via hydrogenation
  - Coal/biomass co-feeding for FT diesel production
  - Various corn ethanol plant types with different process fuels
- Hydrogen-powered FC systems (not available in public GREET1.8 yet)
  - FC forklifts vs. ICE and electric forklifts
  - FC distributed power generation vs. conventional distributed power generation
- Enhancements of existing pathways
  - Compression energy efficiencies for NG and H2 calculated with the first law of thermodynamics
  - Tube trailer delivery option for gaseous H2 to refueling stations
  - Inclusion of three methods in dealing with co-products for soybean-based biodiesel
  - Revision of petroleum refining energy efficiencies

Fuel-Cycle Analysis of FC Forklifts and FC Distributed Power Generation

- FC forklifts and distributed power generation are early markets to help development of hydrogen production and FC technologies
- Examine energy use for baseline and alternative technologies
- Track the energy use and emission occurrences throughout the upstream processes up to the primary source of energy for each technology
- The fuel cycle includes the following processes:
  - The recovery, processing, and transportation of the primary fuel (e.g., NG)
  - The conversion of the primary fuel (e.g., NG to H2 or electricity)
  - The conditioning of the fuels (e.g., compression of H2, AC-to-DC conversion, etc.)
  - The use of the conditioned fuels in forklifts or for distributed power generation
- Argonne's GREET model was expanded to estimate the fuel-cycle energy use and GHGs emissions for FC forklifts and distributed generation technologies

Key Assumptions for Fuel-Cycle Analysis of FC Forklifts and Distributed Power Generation

Forklifts

- Hydrogen consumption by FC forklifts based on data from early and current use; technological improvements and system optimization could reduce H_2 use
- Electricity consumption for electric forklifts from OEMs
- Equivalency ratio of energy use among different energy sources did not change with forklift class or size
  - The amount of hydrogen to substitute for 1 kWh of electricity was almost the same for all sizes and classes
  - 15 kWh electricity use at the wheels for electric forklifts is equivalent to 1 kg H2 use for FC forklifts, and 2.8 gal propane, 1.8 gal gasoline, or 1.6 gal diesel use for ICE forklifts
- Hydrogen is compressed from 300 psi to 3000 psi for storage onboard forklifts
- Battery efficiency for electric forklifts assumed to be 76%; charger 84%

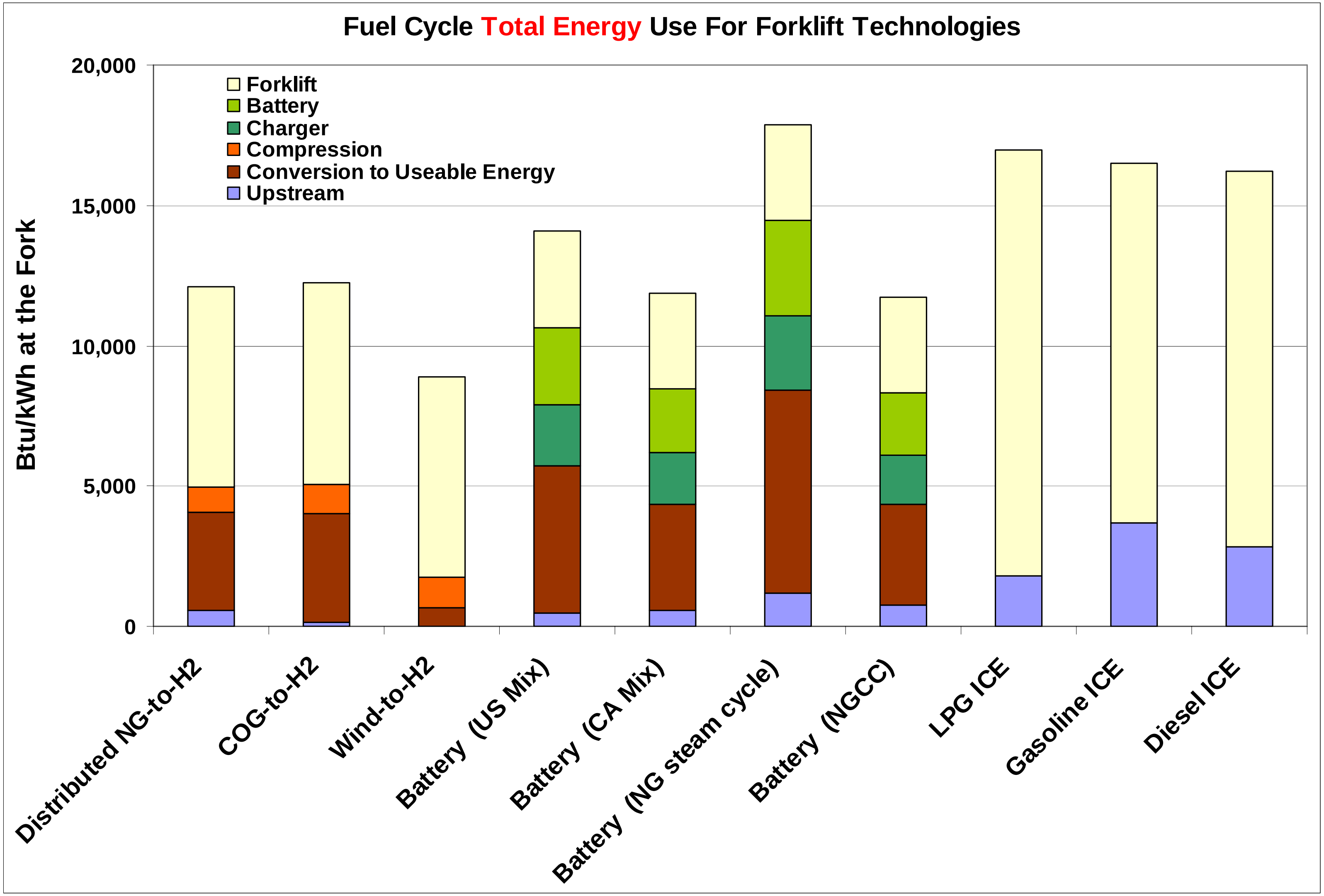
Distributed Power Generation

- Wide variation in generation capacity of 1-250 kW
- Efficiency of power generation is a strong function of the generator's capacity (higher efficiencies for larger capacities)
- Two general capacity ranges for fuel-cycle analysis:
  - Smaller capacity of power generation units (<10 kW)
  - Larger capacity of power generation units (>>10 kW)

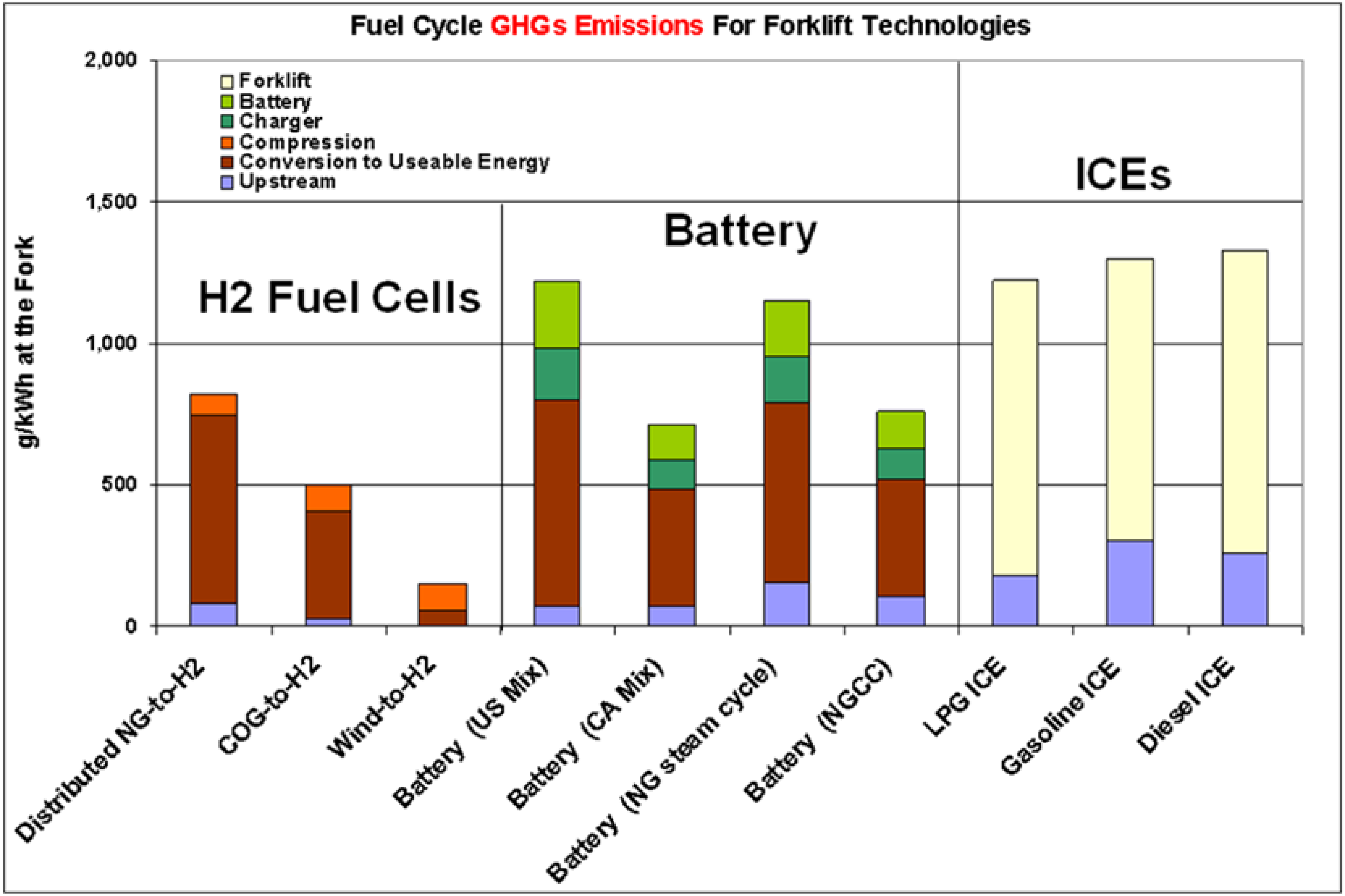
Results of Distributed Power Generation Are Based on the Following Key Assumptions

Generation Technology	**Energy Conversion Efficiency (from primary fuel to consumed electricity)**	
	Capacity < 10 kW	Capacity >> 10 kW
Microturbine		25%
Natural Gas ICE	23%	35%
Diesel ICE		44%
NG PEMFC	24%	36%
NG PEMFC (DOE target)	40%	40%
NG SOFC	30%	48%
LPG SOFC		47%
Diesel SOFC		46%
NG PAFC		40%
NG MCFC		49%
US average mix (baseline)	38%	38%
CA average mix (baseline)	45%	45%

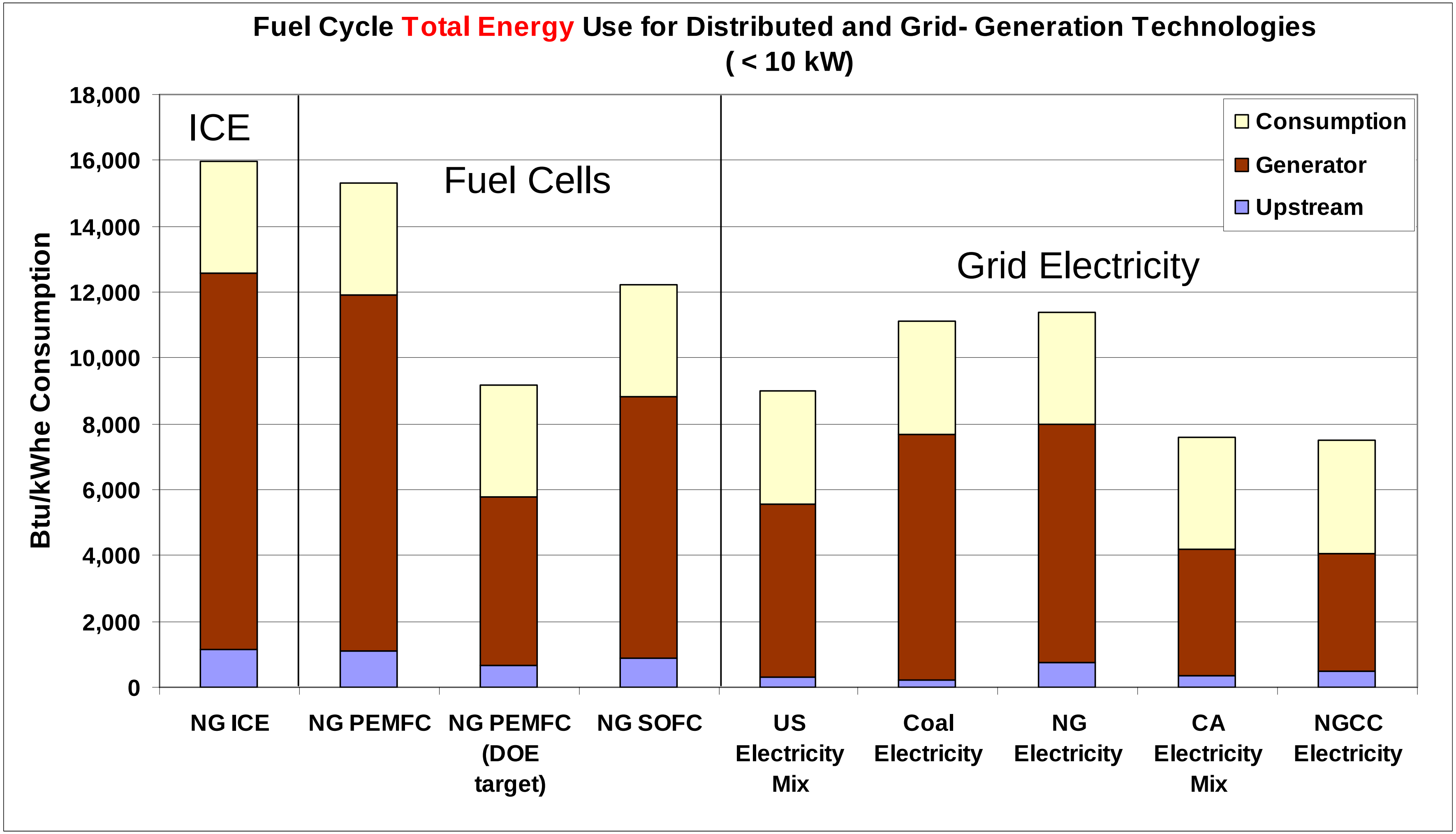
Fuel Cycle Results of Forklifts: Total Energy Use



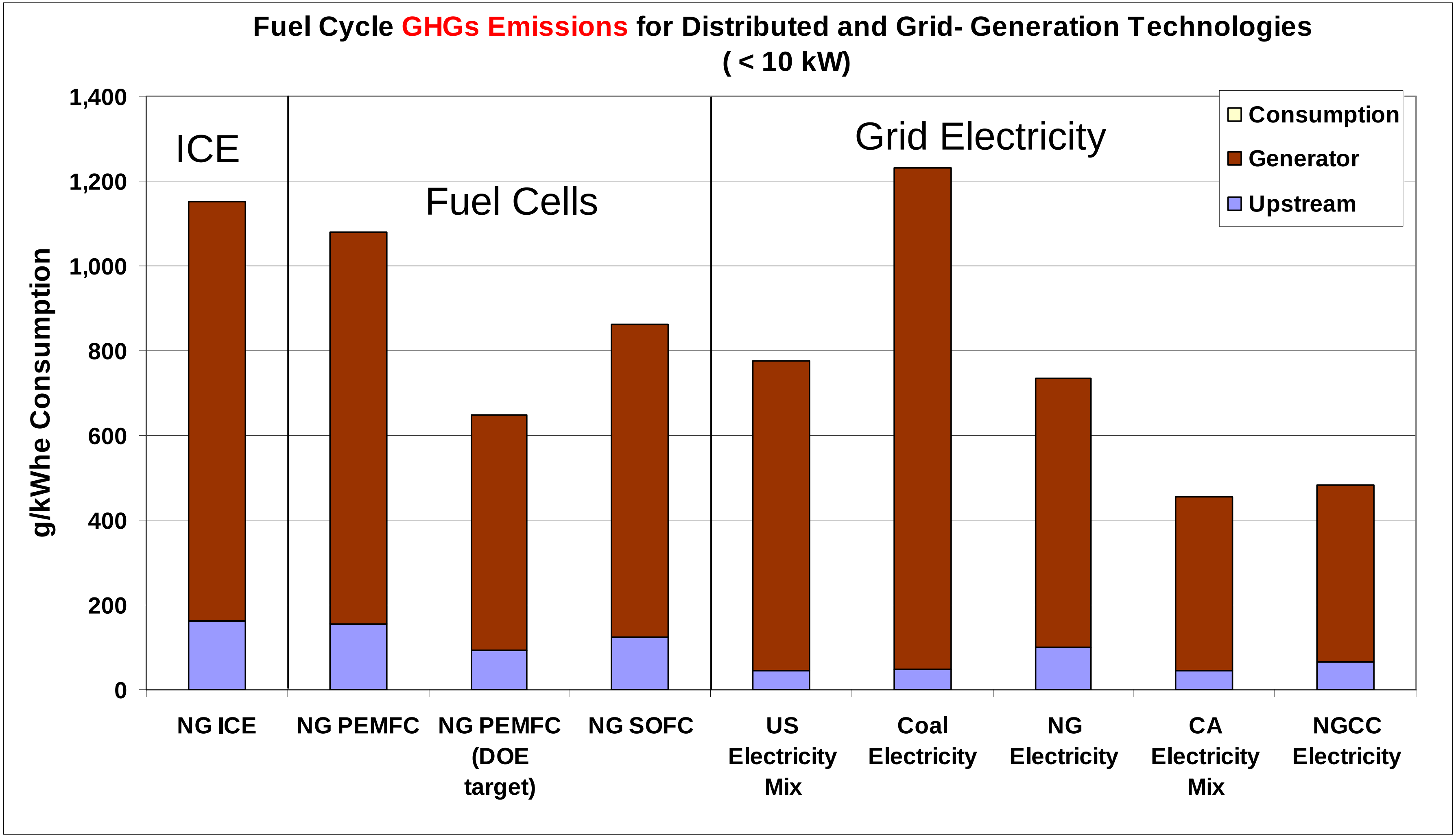
Fuel-Cycle Results of Forklifts: GHG Emissions



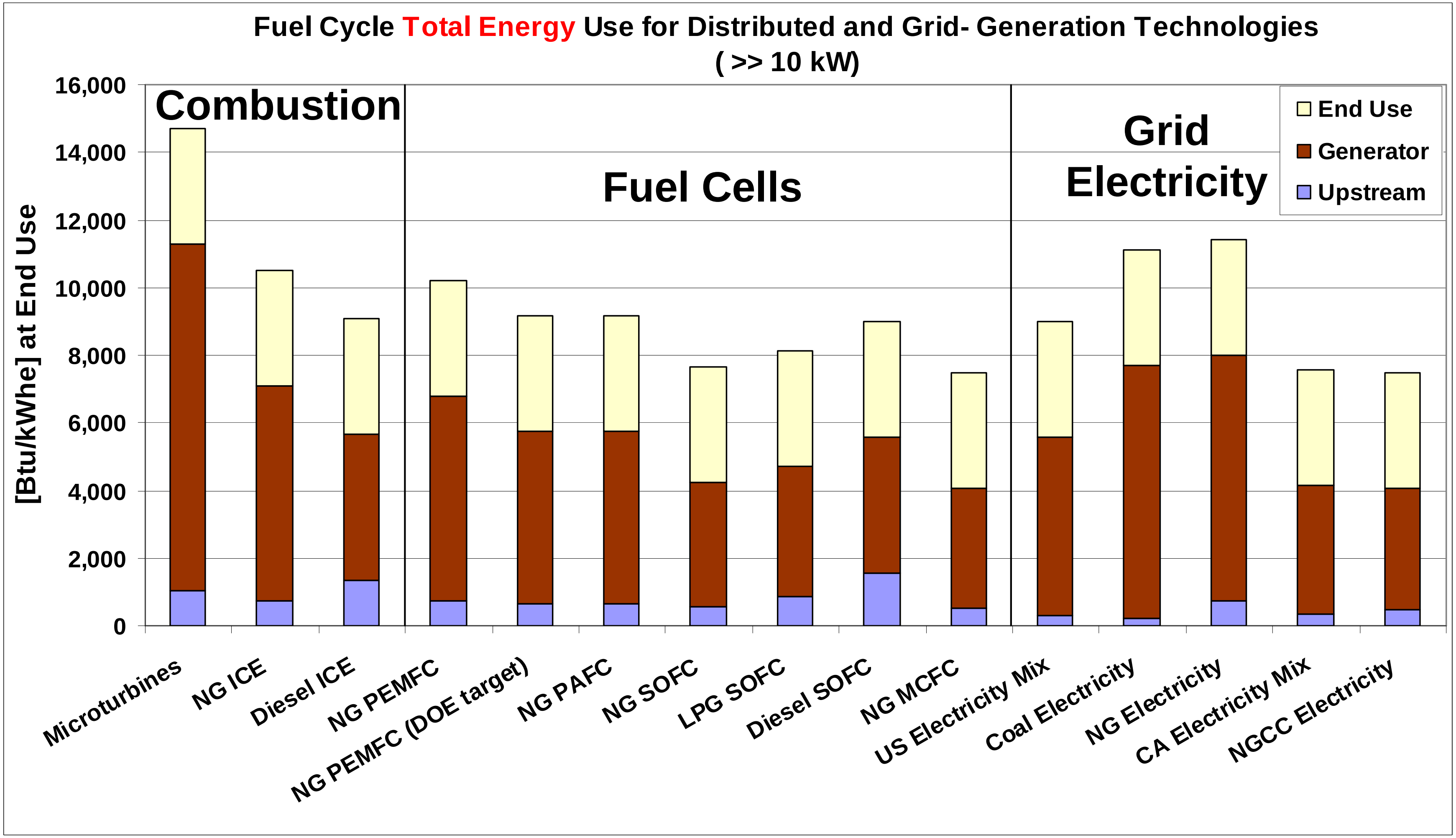
Fuel-Cycle Results of Distributed Power Generation: Total Energy Use (Capacity < 10 kW)



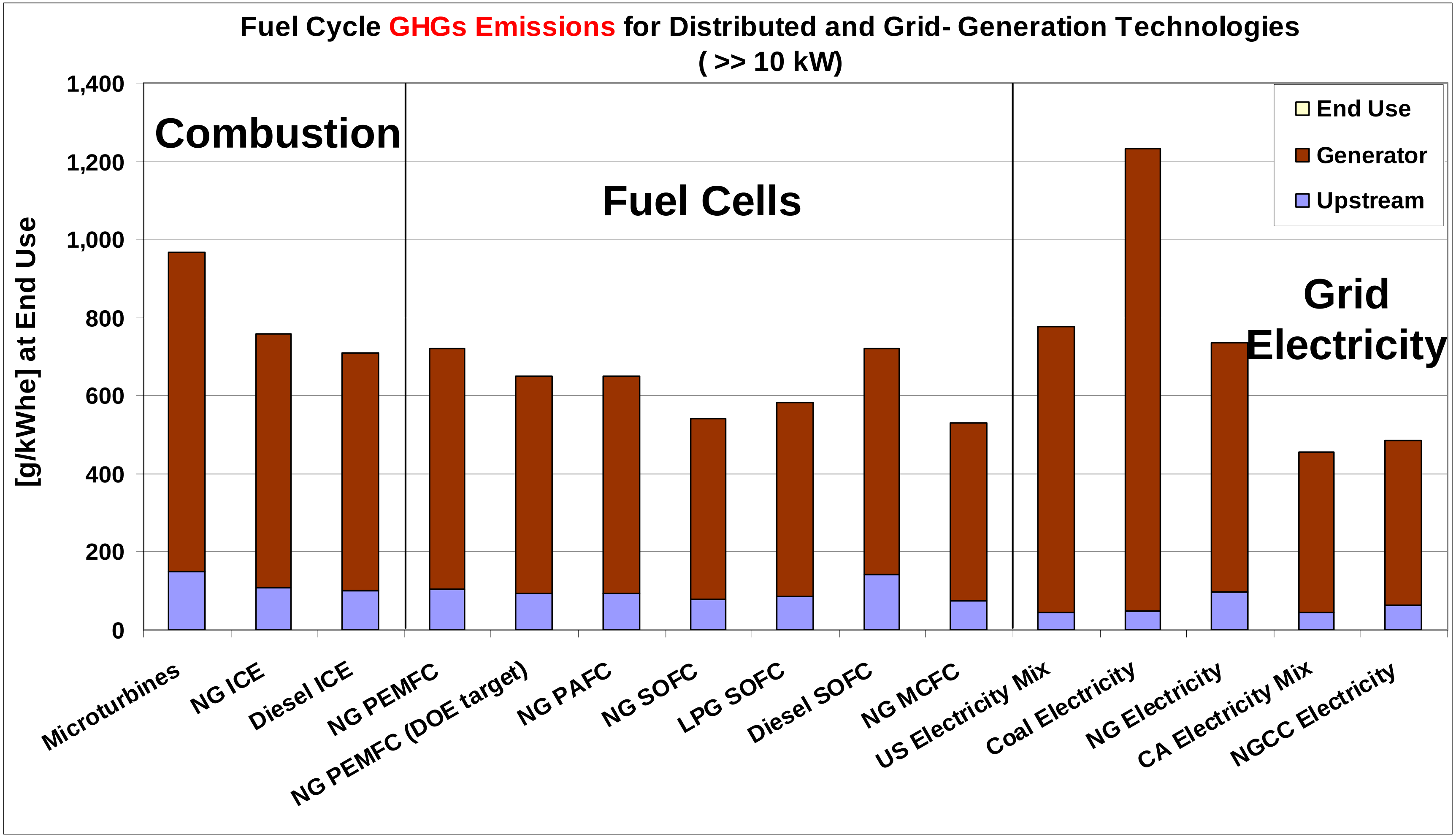
Fuel-Cycle Results of Distributed Power Generation: GHG Emissions (Capacity < 10 kW)



Fuel-Cycle Results of Distributed Power Generation: Total Energy Use (Capacity >> 10 kW)



Fuel-Cycle Results of Distributed Power Generation: GHG Emissions (Capacity >> 10 kW)



Approach for FC PHEV WTW Analysis

- GREET is being expanded to include FC PHEV
- PSAT simulations are being conducted
  - Li-ion battery is assumed
  - FC PHEV with electric driving range of 10, 20, 30, and 40 miles
  - Size of FC stack and battery varies with different electric ranges
- VMT shares between FC operation and grid electricity operation will be estimated based on:
  - Daily VMT distribution
  - Electric driving range of FC PHEV
  - Charge depletion (CD) and charge sustaining operations are assumed to be sequential and separate
- Various hydrogen production options will be included
- Several electricity generation mixes will be included

Future Work

- New hydrogen production options
  - ➢ Biogas/landfill gas to hydrogen
  - ➢ Finalizing biomass to H2 with CCS
- Fuel-cycle analysis of FC forklifts and distributed power generation
  - ➢ Criteria pollutants emissions
  - ➢ Potential market size for FC forklifts and distributed power generation
  - ➢ Cost analysis of distributed power generation technologies by market size and location
  - ➢ Combined fuel cell/gas turbine or CHP applications for high-temperature fuel cells

➢ FC PHEV WTW analysis (see previous slide)

Summary

- WTW analysis is an integral part of examining energy and environmental effects of hydrogen FCVs and other FC systems
- The GREET model has been developed as standard tool to examine energy and emission benefits of hydrogen-powered FC technologies
- H2 FC forklifts and distributed power generation achieve energy and GHG reduction benefits
- H2 FC PHEVs may offer energy and GHG reduction benefits

Publications

- **Elgowainy, A. and M. Wang, 2008*, Fuel Cycle Comparison of Distributed Power Generation Technologies*, prepared for Office of Fuel Cell, Hydrogen, and Infrastructure Technologies, U.S. DOE, April.**
- **Gaines, L., A. Elgowainy, and M. Wang, 2008, *Full Fuel Cycle Comparison of Forklift Propulsion Systems*, prepared for Office of Fuel Cell, Hydrogen, and Infrastructure Technologies, U.S. DOE, April.**
- **Joseck, F., Wang, M., and Wu, Y., 2007. *Potential Energy and Greenhouse Gas Emissions Effects of Hydrogen Production from Coke Oven Gas in U.S. Steel Mills,* in proceedings of 2007 National Hydrogen Association Meeting, San Antonio, TX, March 18-22.**
- **Wang, M., Wu, Y., and Elgowainy, A., 2007. *Operation Manual: GREET Version 1.7*, Center for Transportation Research, Argonne National Laboratory, ANL/ESD/05-03, Argonne, IL, Feb.**
- **Wu, Y., Wang, M., Sharer, P., etc, 2006. *Well-to-Wheels Results of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions of Selected Vehicle/Fuel Systems*, SAE 2006 Transactions, Journal of Engines, SAE Paper 2006-01-0377.**
- **Wu, Y., Wang, M., Vyas, A., etc., 2006. *Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Hydrogen Produced with Nuclear Energy*, Nuclear Technology, 155: 192-207**
- **Wang, M., 2006. *Well-to-Wheels Analysis of Advanced Vehicle Systems with New Transportation Fuels*, Workshop on WTW Efficiency Analysis, Tokyo, Japan, March 7–8.**
- **Wang, M., 2006. *Life-Cycle Analysis of Advanced Vehicle Technologies and New Fuels*, Sustainable Systems Symposium, Ohio State University, Columbus, OH, March 2–3.**
- **Larsen, R., Wang, M., Wu, Y., etc., 2005. *Might Canadian Oil Sands Promote Hydrogen Production for Transportation? Greenhouse Gas Emission Implications of Oil Sands Recovery and Upgrading.* World Resource Review, 17(2): 220-242.**
- **Wang, M., 2005. *Well-to-Wheels Results of Advanced Vehicle Technologies Fueled with Different Transportation Fuels*, Advanced Transportation Workshop, Global Climate Change Project of Stanford University, Palo Alto, CA, October 10–11.**