2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review

Life-Cycle Analysis of Water Consumption for Hydrogen Production Pathways

Amgad Elgowainy, May Wu, David Lampert, Hao Cai, Jeongwoo Han and Michael Wang

Argonne National Laboratory

Argonne NATIONAL LABORATORY

AN039

June 17, 2014

Overview

Timeline

- Start: April 2013
- End: Determined by DOE
- % complete: 70%

Barriers to Address

- Indicators and methodology for evaluating sustainability
- Overcome inconsistent data, assumptions, and guidelines
- Develop models and tools
- Conduct unplanned studies and analyses

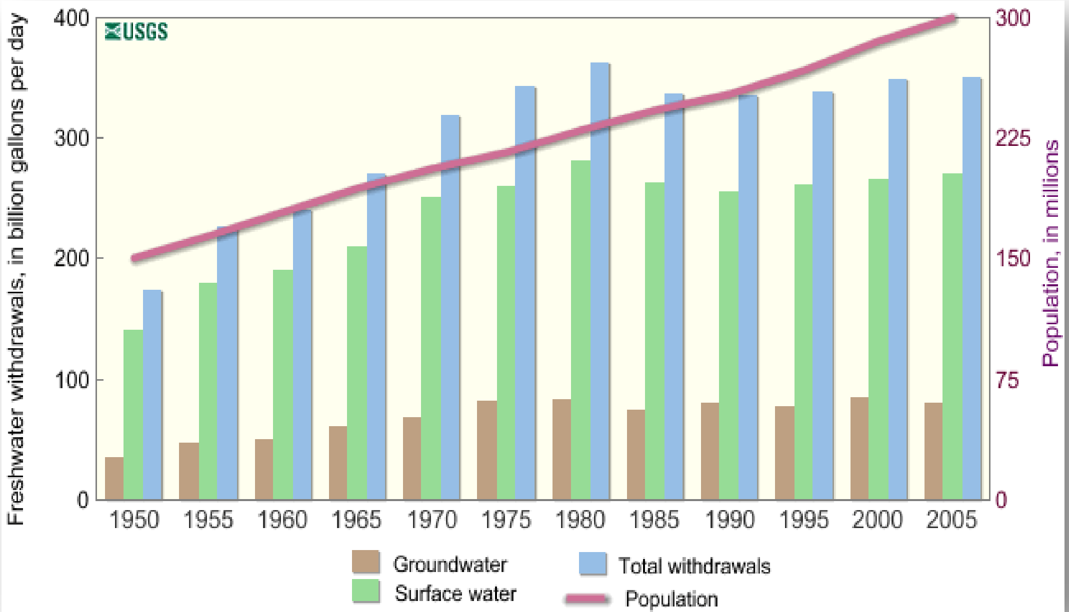
Budget

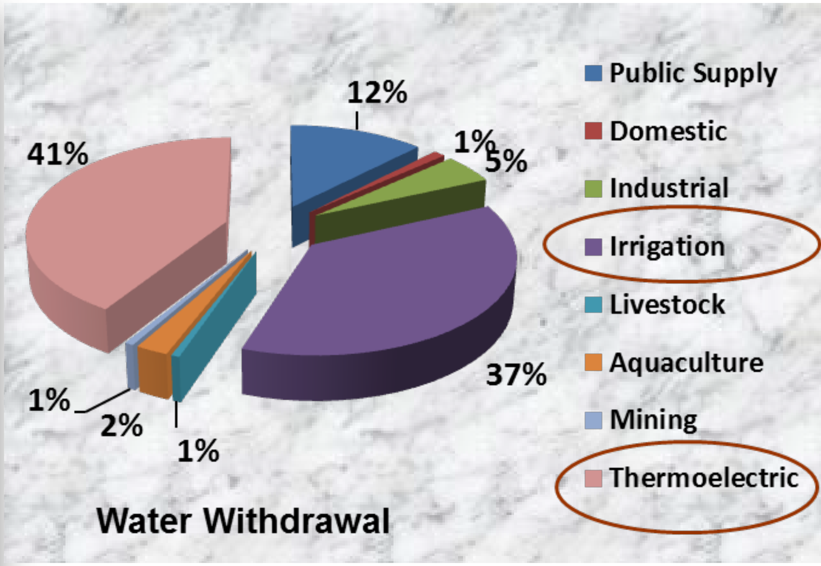
- Funding received in FY13: $100K
- Funding for FY14: $175K
- Total Project Funding: $275K

Partners/Collaborators

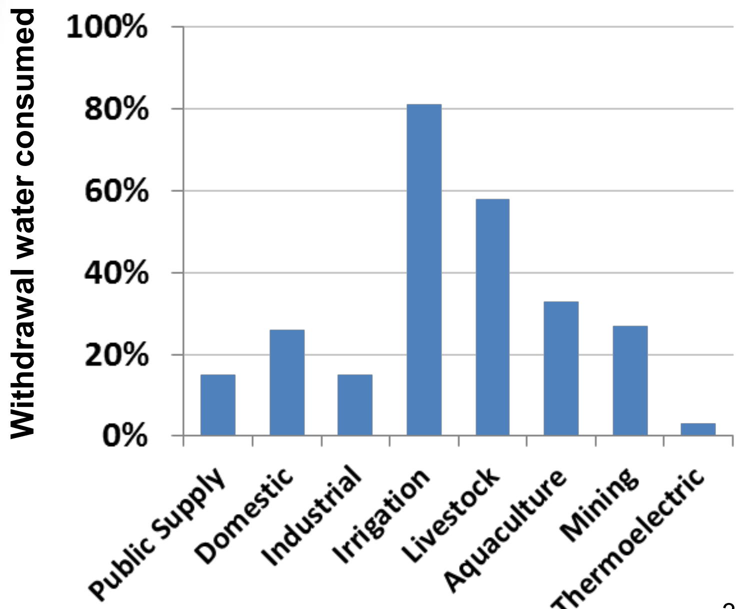
- Industry stakeholders

Relevance/Impact





- Water consumption equals water withdrawal minus water returned to the same withdrawal source
- Water consumption is an important metric for evaluating the sustainability of energy systems
  - ✓ Especially in regions with water resources constraints

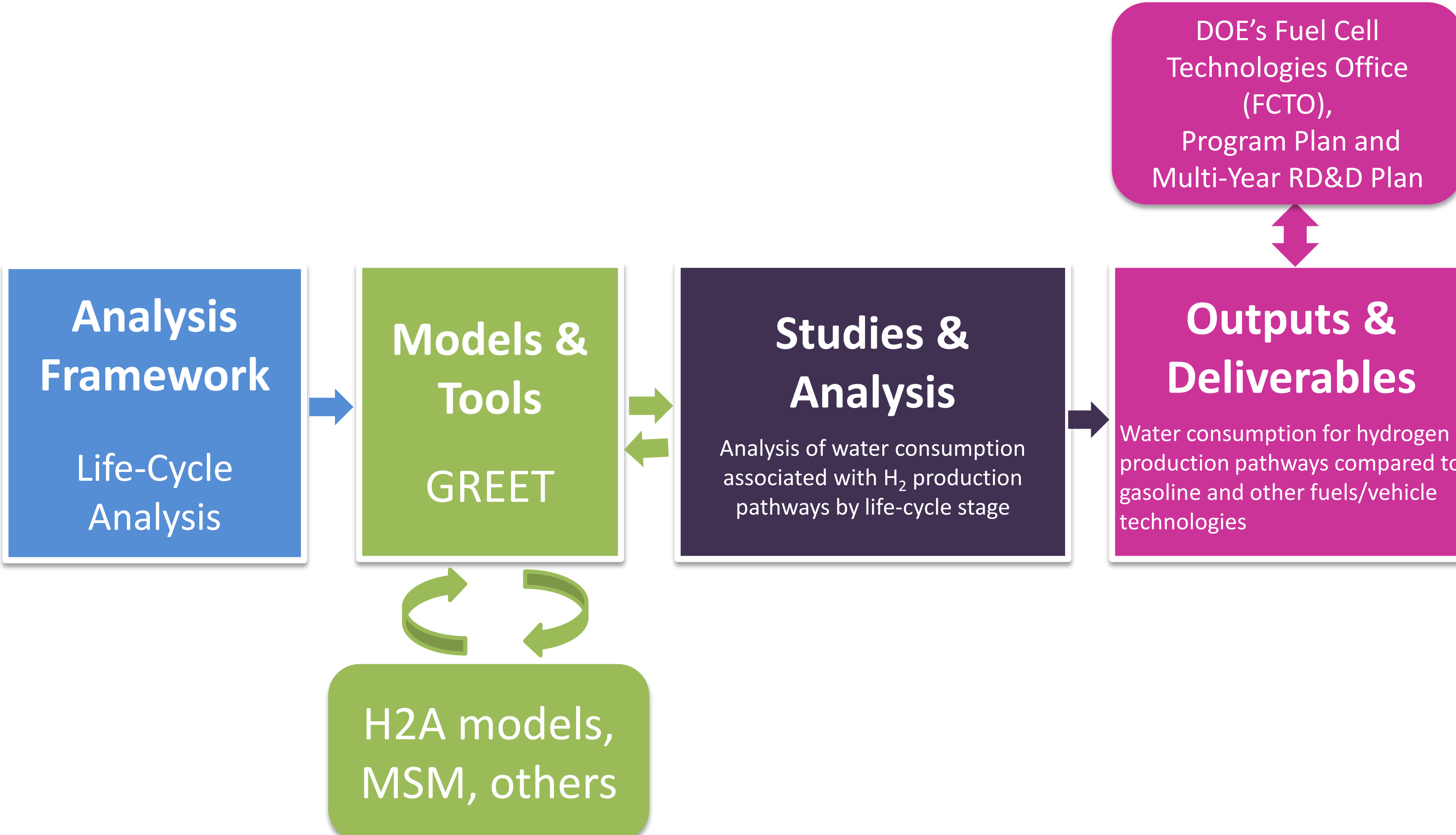


Source: USGS http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf

Relevance/Impact

- Water consumption is an important sustainability metric for evaluating the production of transportation fuels
- Life cycle analysis(LCA) is needed to estimate water consumption of different transportation fuels
  - Water consumption can happen at various stages of fuel cycles
  - LCA provides a consistent accounting of water consumption of transportation fuel pathways (including hydrogen)
- Hydrogen is a zero-carbon fuel with great potential to improve energy efficiency and reduce GHG and air emissions
  - Water consumption, together with energy and GHG impacts, needs to be evaluated for hydrogen pathways in relationship to other fuel pathways
- Hydrogen is also essential for processing, refining and upgrading of other fuels, e.g.,
  - Upgrading heavy crude (e.g., bitumen from oil sands)
  - Refining crude to produce petroleum products (e.g., gasoline and diesel)
  - Hydroprocessing of biofuels (e.g., plant oils, pyrolysis oil, waste oil)

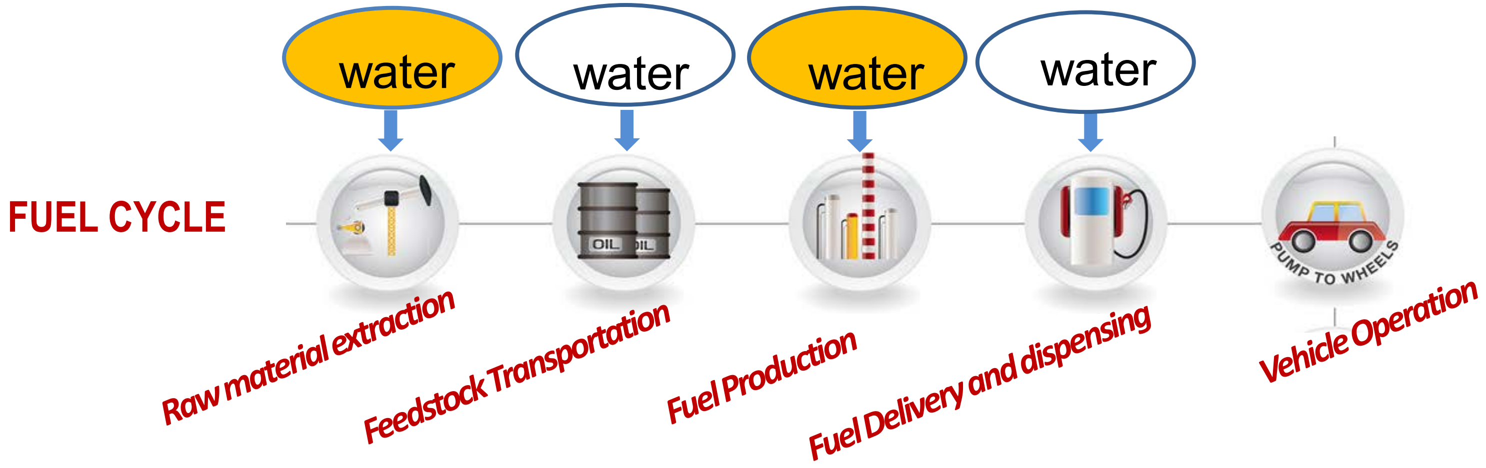
LCA of water consumption for hydrogen production pathways – Relevance



Expand GREET to include water consumption – Relevance/*Approach*

- Water LCA of a fuel: accounts for fresh water consumption along the pathway of producing the fuel from its feedstock

> ✓ Water withdrawal: fresh water uptake from surface or groundwater
>
> ✓ Water consumption: net water consumed through the production process (evaporated, rejected or incorporated into the product)



- BETO, FCTO, and VTO supported incorporation of water consumption in GREET
- FCTO project is on life-cycle water consumption for hydrogen production pathways
- GREET is expanded to evaluate water consumed per MJ of fuel and per mile for various vehicle/fuel systems

Strategy for including water consumption in GREET – Approach

Phase I: Incorporate water consumption for key fuel production pathways in GREET

- ✓ Baseline gasoline and diesel fuels
- ✓ Gasoline is E10 → incorporate corn ethanol pathway
- ✓ Key primary energy feedstocks and process fuels for most pathways
  - ❖ Petroleum (diesel and residual oil)
  - ❖ Natural gas (will also serve CNGV and LNG pathways)
  - ❖ Electricity → requires coal, NG, nuclear, and biomass for upstream (will also serve PHEVs and BEVs)
  - ❖ Hydrogen from SMR and electrolysis (also serves FCEVs)

Strategy for including water consumption in GREET (continued) – Approach

Phase II: Incorporate water consumption for other fuel production pathways in GREET

- ✓ Other hydrogen pathways (e.g., biomass gasification, reforming of biogas and other hydrocarbon fuels)
- ✓ Renewable gasoline and diesel (e.g., pyrolysis and HEFA*)
- ✓ Alternative diesel fuels (e.g., FTD, DME, BD)
- ✓ Renewable natural gas (e.g., LFG, AW, MSW)
- ✓ Jet and marine fuels
- ✓ Cellulosic ethanol (e.g., from SWG, miscanthus, corn stover)
- ✓ Algae pathways

*HEFA = Hydrotreated esters and fatty acids

Life cycle stages and data sources for GREET Expansion – Approach

- Identify major contributors in upstream supply chain to water consumption
  - Feedstock production and fuel production
- Evaluate water consumption for fuel production stage
  - Water treatment options
  - Process water
  - Cooling water (wet vs. dry, once through vs. recycling)
  - Upstream and indirect water use
- Data Sources:
  - Industrial sources
  - National Agricultural Statistics Service (NASS), part of USDA and USGS
  - Open literature
  - Water footprint database and assessment tools developed at Argonne and other National laboratories

Key water consumption stages for hydrogen production include water treatment – Approach

Water Source

- Municipal
- Well
- Surface

Water Treatment

- Reverse Osmosis (RO)
- Deionization (DI) → zero discharge

Process

and/or

Cooling

- Dry (zero consumption)
- Cooling Tower

— Municipal
- Total dissolved solids (TDS) < 500 ppm
- Small scale consumption (e.g., forecourt production)

— Well (ground)
- TDS ~ 1000 ppm
- Small or large scale consumption

— Surface
- TDS ~ 500-3000 ppm
- Large scale (e.g., central production)

- Steam @ 600 : 750 psi, max TDS =1000 ppm (as P⬆→ max TDS ⬇)
- Increased TDS → higher blowdown rate in boilers and cooling towers

Water consumption by hydrogen production is dominated by water treatment and conversion process– Accomplishment

Process

$4\ gal_{water}$ / kg_{H2} SMR consumption)

$4\ gal_{water}$ / kg_{H2} electrolysis consumption

Stoichiometry: 1.2 gal_{water} per kg_{H2} for SMR and 2.4 gal_{water} per kg_{H2} for water electrolysis

Industry sources: 3.9-4.2 gal_{water} / kg_{H2} for SMR and 3.6-5.4 gal_{water} / kg_{H2} for electrolysis

Water Treatment

RO with 75% recovery (central production)

→ 1.3 gal_{water}/kg_{H2} consumption

RO with 50% recovery (forecourt production)

→ 4 gal_{water}/kg_{H2} consumption

Cooling

0.2 gal_{water}/kg_{H2} consumption

- ✓ 0.1 $gpm_{circulating\_water}$ per kg_{H2}/h of production (industry range 0.08-0.12)
- ✓ Cooling tower makeup water: 3% of circulating water

Water consumption varies by feedstock and fuel production technology – Accomplishment

Life-cycle water footprint of other fuels (in gal/gge)

	Estimate	Range	
Petroleum gasoline	5.4	1.3-9	Conventional and Canadian oil sand
Natural gas	0.7	0.3-1.2	Conventional and shale gas
Corn ethanol	55	2.2-300	Midwest regions

Sources: https://greet.es.anl.gov/publication-watertool
https://greet.es.anl.gov/publication-consumptive-water

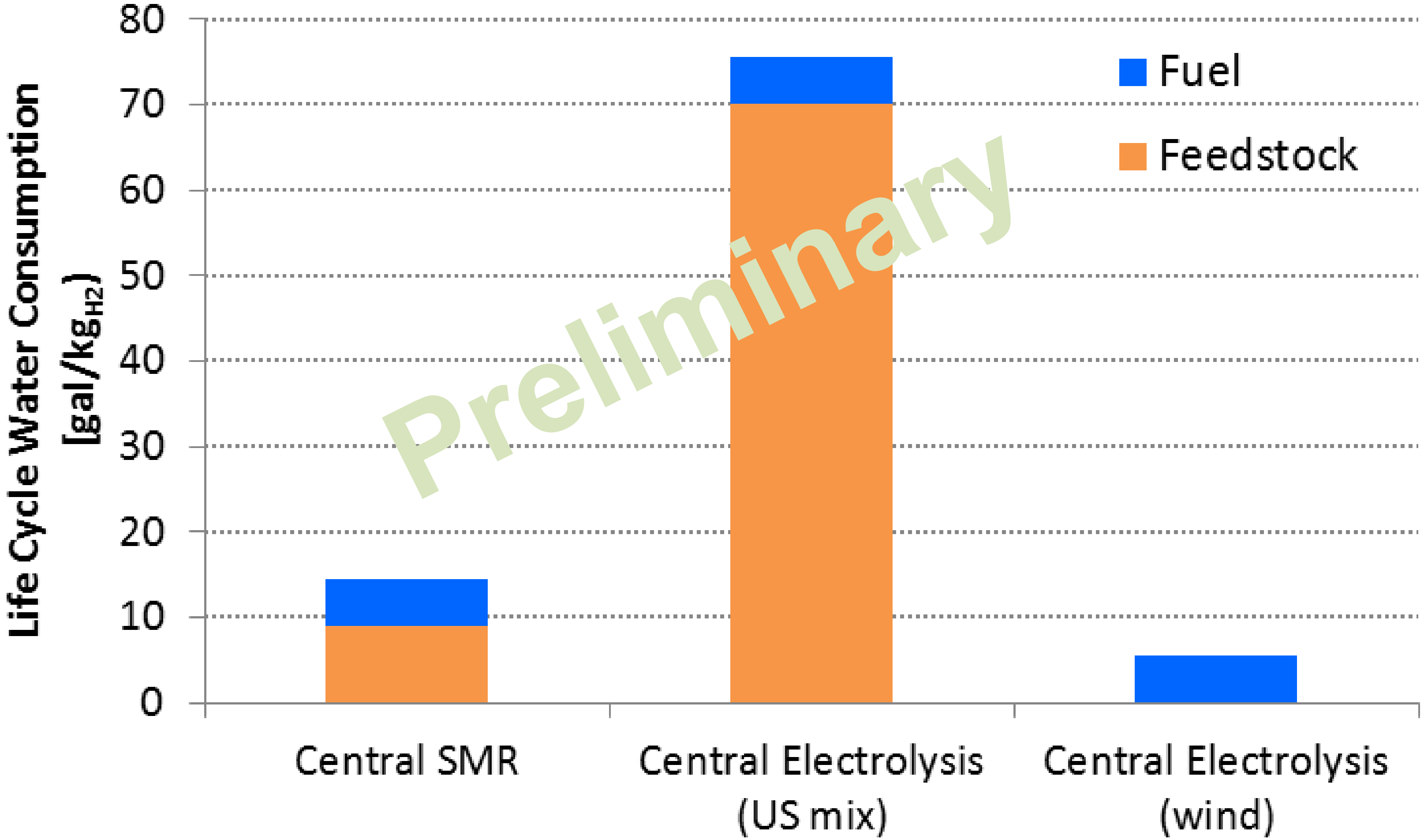
Water consumed to generate electricity in power plant (in gal/kWh)

	Estimate	Range
U.S. Average Mix	1.6	
Natural Gas	0.21	0.2-0.7
Biomass	0.40	0.1-1.0
Nuclear	0.58	0.4-0.7
Coal	0.52	0.1-1.1
Hydroelectric	18	14-100

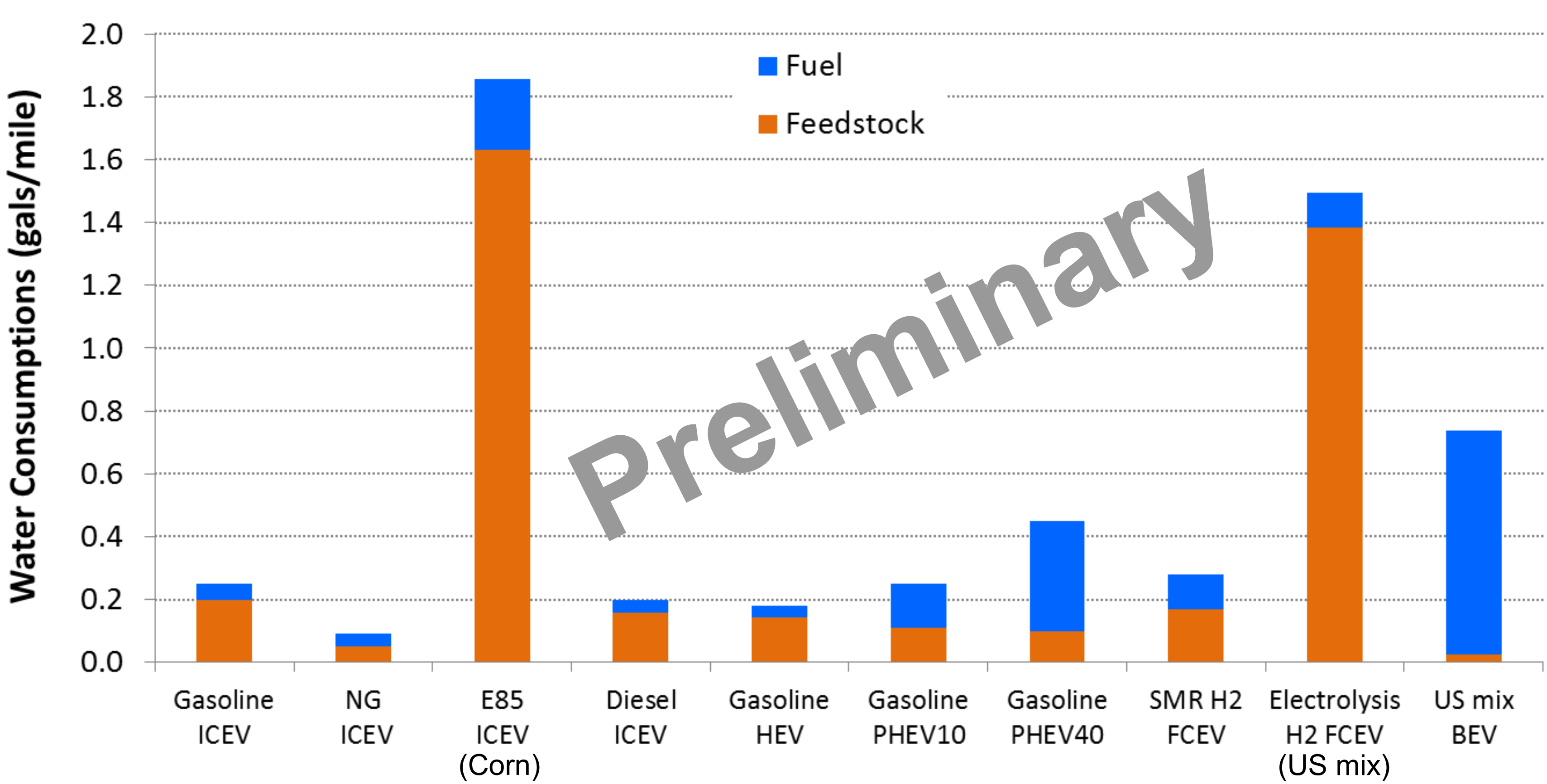
Water consumption: what, where, business as usual

- Corn ethanol number is mainly from cornfield; total withdrawal from surface and ground water
- Hydroelectric number is due to evaporation of reservoirs; business as usual evaporation of rivers? Water is not a limiting factor where hydro dams are built
- Water returned to water bodies has different water quality implications
- Confusion still remains; reconciliation of different metrics is needed

Water consumption of hydrogen production pathways depends on feedstock production – Accomplishment



Life cycle water consumption of fuels and vehicle technologies varies by feedstock and fuel production technologies – Accomplishment



	Gasoline ICEV	CNG	E85 ICEV	Diesel ICEV	Gasoline HEV	Gasoline PHEV10	Gasoline PHEV40	H2 FCEV	BEV
Fuel Economy* [mi/gge]	25	25	25	29	35	47 CD 37 CS	82 CD 28 CS	52 52	85

* Midsize vehicle

Summary – Accomplishment

- Completed assessment of water consumption for hydrogen production from SMR and electrolysis
- Expanded the GREET model to include major fuel pathways (petroleum fuels, natural gas, electricity, corn ethanol and hydrogen)
- Compared water consumption per mi for various fuel/vehicle combination pathways
- Irrigation water for farming, cooling water for electricity, and evaporation associated with hydro-power have the greatest impact on water life-cycle
  - ✓ Each has different implications
  - ✓ H2O in different forms and locations and with different impurities has different implications
  - ✓ Water consumption is a complicated topic is going through reconciliation at Argonne and in the broader water LCA and water footprint community

Response to Reviewers' Comments from 2013 AMR

Recommendations for additions/deletions to project scope

Comment

- The project should increase or confirm the scope of work to include a water analysis in GREET for all fuels.

Response

- The major fuel production pathways (petroleum fuels, natural gas, electricity, hydrogen and corn ethanol) have been added to GREET. The water analysis for the remaining pathways will be added to complete the implementation of water consumption evaluation in GREET.

Collaborations and Acknowledgments

Collaborators:

- Jeni Keisman, DOE AAA Fellow (Currently with USGS)
- Three industrial companies for actual water consumption data on large scale SMR
- Three industrial companies for actual water consumption data on forecourt electrolysis

Future Work

- Evaluate other hydrogen pathways (e.g., biomass gasification, reforming of biogas and other HC fuels)
- Complete implementation of additional pathways in GREET
- Reconcile different water consumption concepts (form, location, resource availability, etc.)
- Assess variability of water consumption associated with various production technologies and by region
- Address purification water consumption as a function of water quality and process requirement
- Develop water factors for vehicle materials
- Develop for future technologies and pathways

Project Summary

- **Relevance:** Develop water consumption as a new sustainability metric for evaluating the production of energy products . Life cycle analysis (LCA) is needed to estimate water consumption to provide a consistent accounting of water consumption of transportation fuels (including hydrogen).
- **Approach:** Expand the GREET model to assess life-cycle water consumption along the pathways of producing transportation fuels from various feedstock sources.
- **Collaborations**: Collaborated with experts from the industry who provided water consumption information needed for the simulations and received valuable input on various production technologies.
- **Technical accomplishments and progress:**
  - Completed assessment of water consumption for hydrogen production from SMR and electrolysis
  - Expanded the GREET model to include major fuel pathways (petroleum fuels, natural gas, electricity, corn ethanol and hydrogen)
- **Future Research**:
  - Evaluate other hydrogen pathways (e.g., biomass gasification, reforming of biogas and other HC fuels).
  - Complete implementation of additional pathways in GREET.
  - Reconcile different water consumption concepts (form, location, resource availability, etc.)
  - Assess variability of water consumption associated with various production technologies and by region.
  - Address purification water consumption as a function of water quality and process requirement.

Argonne NATIONAL LABORATORY

Amgad Elgowainy
aelgowainy@anl.gov
Project AN39

Acronyms

- ANL: Argonne National Laboratory
- AW: Animal Waste
- BAU: Business As Usual
- BD: Biodiesel
- BETO: Biomass Energy Technologies Office
- BEV: Battery Electric Vehicles
- CD: Charge Depleting
- CNGV: Compressed natural Gas Vehicle
- CS: Charge Sustaining
- DI: Deionization
- DME: Di-Methyl Ether
- DOE: Department of Energy
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- FTD: Fischer Tropsch Diesel
- GHG: Greenhouse Gases
- GGE: Gallon of gasoline equivalent
- GREET: Greenhouse gases, Emissions, and Energy use in Transportation
- H2: Hydrogen
- HEFA: Hydrotreated esters and fatty acids
- LCA: Life Cycle Analysis
- LFG: Landfill Gas
- LNG: Liquefied Natural Gas
- MSW: Municipal Solid Waste
- NG: Natural Gas
- PHEV: Plug-in Hybrid Electric Vehicle
- RD&D: Research, Development, and Demonstration
- RO: Reverse Osmosis
- SMR: Steam Methane Reforming
- SWG: Switchgrass
- US Mix: US electricity grid mix
- VTO: Vehicle Technologies Office

Technical Backup Slides

Table 19. Onsite Natural Gas Steam Methane Reforming (Near Term)

Consumption	E3database	H2A	Japan
Natural Gas	48.0 kWh/kg-H2	46.4 kWh/kg-H2	46.6 kWh/kg-H2
	LHV 12.5 kWh/kg	LHV 13.1 kWh/kg	LHV 13.6 kWh/kg
Electricity	3.30 kWh/kg-H2	3.73 kWh/kg-H2	4.14 kWh/kg-H2
Process Water	7.9 litter/kg-H2	22.7 litter/kg-H2	11 litter/kg-H2
Plant Capacity	1,211 kg-H2/day (560 Nm3/h)	1,500 kg-H2/day	1,071 kg-H2/day (500 Nm3/h)
Operating	68.5%	70%	54% (13 h/d)
Efficiency	LHV 65%	LHV 66.4%	LHV 65.7%
Capital Investment	$5,334,000	$3,225,000	$3,667,000
Operating cost	2.33% of Capital Investment	6.15% of Capital Investment	3.8% of Capital Investment
	88MPa	43MPa	40MPa

Extracted from IEA HIA Task 23 report on small scale reformers

Table 25. Reformer cost comparison

Hydrogen production Capacity	**Nm3/h**	**50**	**50**	**100**	**100**	**200**	**300**	**500**
	Kg/h	4.495	4.495	8.99	8.99	17.98	26.97	44.95
Natural Gas	kWh/kg – H2	46.33	49.00	45.96	49.00	45.08	TBC	47.72
Low heating value	kWh/kg	13.78	11.67	13.78	11.67	13.78	TBC	14.68
Electricity	kWh/kg-H2	1.45	2.69	1.33	2.69	1.22	TBC	1.09
Process water	litter/kg-H2	33.37	38.80	33.37	38.80	33.37	TBC	10.00
Plant capacity	Kg-H2 per day	107.9	107.00	215.8	214.00	431.5	647.28	1080.00
Efficiency	LHV %	72	70	72	70	74	70.00	80.00
Capital investment	$ (and currency exchange date) \95/$	684,000	450,000	947,000	900,000	1,630,000	1,895	2,730,000

Extracted from IEA HIA Task 23 report on small scale reformers