2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review

Life-Cycle Analysis of Water Consumption for Hydrogen Production

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SA039

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Overview

Timeline

- Start: April 2013
- End: Determined by DOE
- % complete (FY16): 70%

Barriers to Address

- Stove-piped/siloed analytical capability for evaluating sustainability
- Inconsistent data, assumptions and guidelines
- Insufficient suite of models and tools

Budget

- Funding for FY15: $250K
- Funding for FY16: $175K

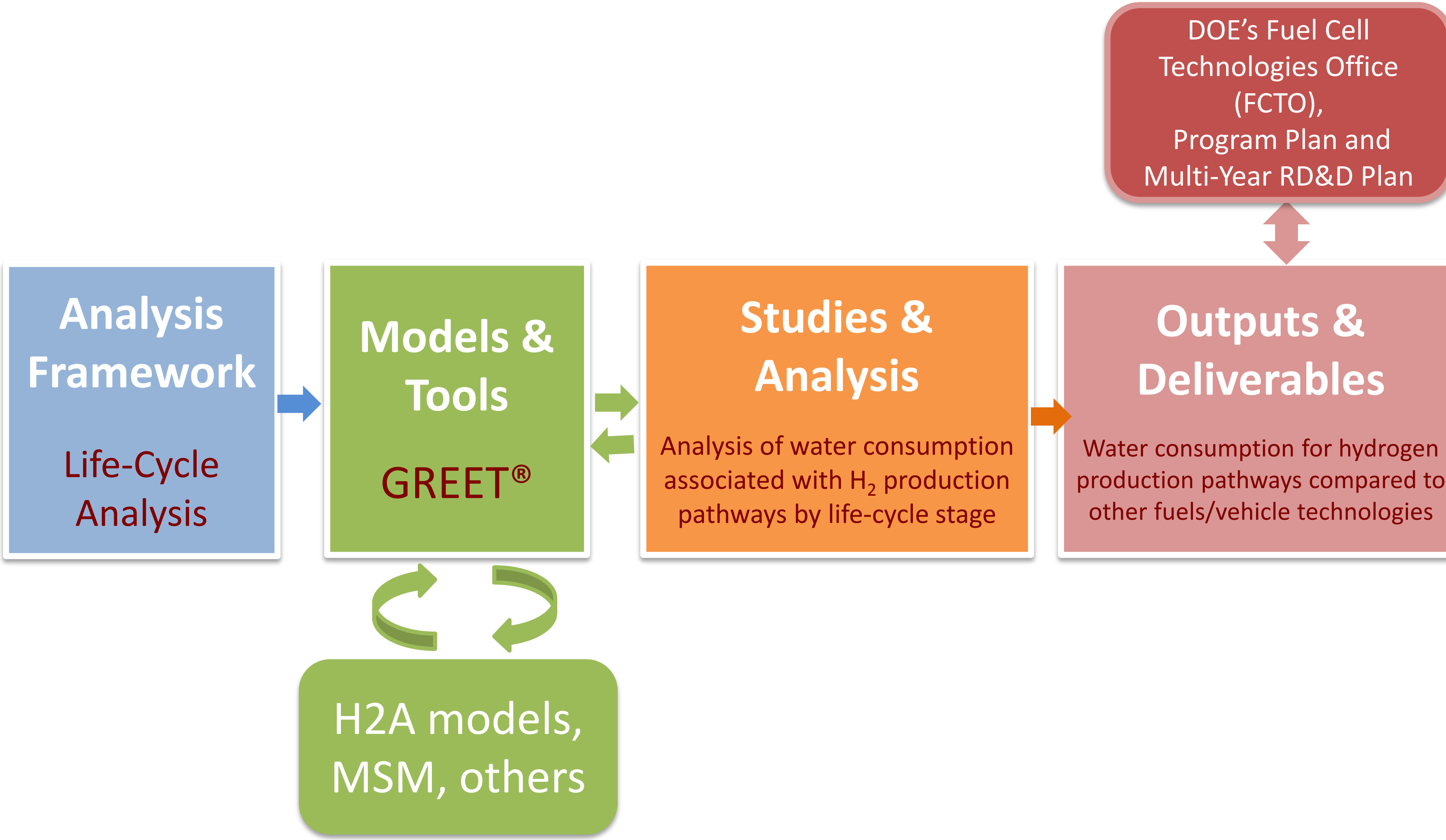
Partners/Collaborators

- Jacobs® Consultancy
- Other industry stakeholders

Relevance/Impact

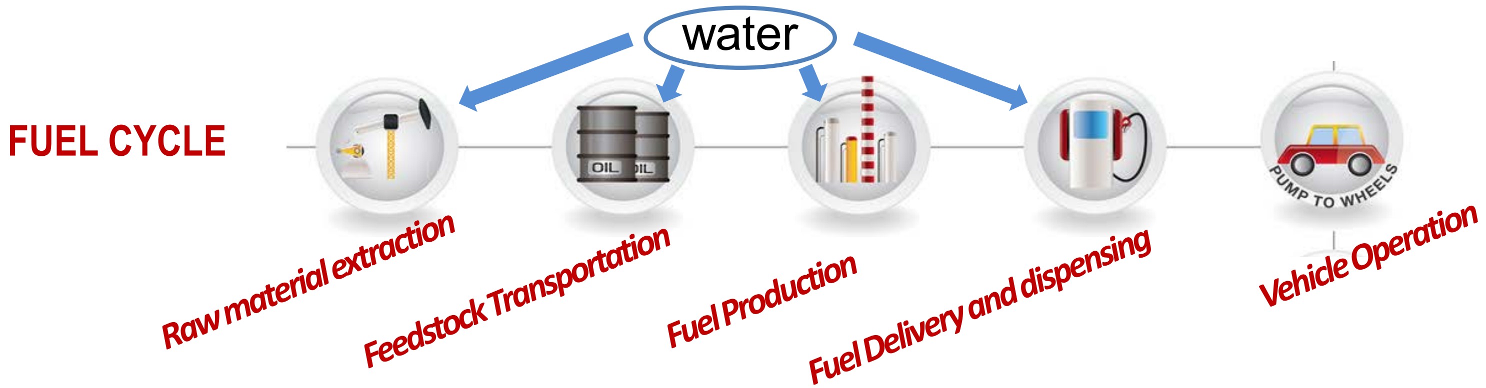
- Life-cycle analysis (LCA) estimates water consumption along supply chain of different transportation fuels
  - Life-cycle water consumption includes both direct and indirect freshwater consumption embedded in energy products
  - LCA provides a consistent accounting of water consumption associated with the production of transportation fuels (including hydrogen)
- Hydrogen is a zero-carbon fuel with potential for significant reduction of GHG and air pollutant emissions
  - Water consumption, together with energy use and air emissions 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 and refining heavy crude to produce fuels
  - Hydroprocessing of biofuels (e.g., plant oils, pyrolysis oil, waste oils)

LCA of water consumption for hydrogen production pathways – Relevance



Expanded GREET to include water consumption – 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 or incorporated into the product)
    - Discharged water needs to be evaluated with expanded system boundary to account for its fate



- FCTO, VTO, and BETO supported incorporation of water consumption in GREET
- FCTO supports evaluation of life-cycle water consumption for hydrogen and baseline fuels production pathways
- GREET is expanded to evaluate water consumption factors for various vehicle/fuel systems

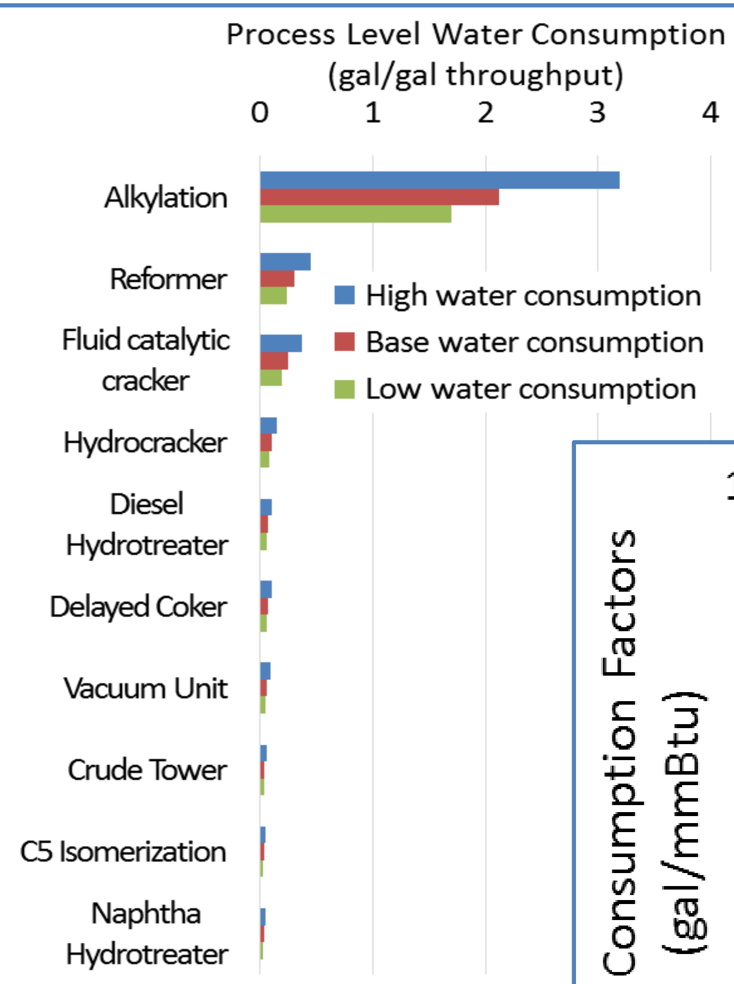
Life-cycle stages and data sources for GREET expansion – Approach

- 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
  - Open literature
    - Peer-reviewed reports and papers: EPRI (2013), Choi et al. (2009), Spath et al. (2005)
    - Public database: EPA's Clean Watersheds Needs Survey (2012)
  - Industrial sources
  - Modeling of physical processes
    - Refinery water analysis model by Jacobs® Consultancy
    - H2A models
  - Water footprint database and assessment tools developed at Argonne
  - National Agricultural Statistics Service (NASS), part of USDA and USGS

Continued incorporation of water consumption in GREET in FY16 – Approach

- Review and update water consumption for baseline fuels and hydrogen production technologies
  - ✓ Petroleum fuels production
  - ✓ Natural gas SMR and electrolysis for hydrogen production
    - ❖ Evaluate fate of discharged water
  - ✓ Biomass gasification
- Examine impact of various cooling technologies and cooling water source in thermoelectricity generation
  - ✓ Single loop vs. recirculating
  - ✓ Tower vs. pond
  - ✓ Freshwater vs. saline, brackish water or wastewater
- Address outstanding water consumption issues for hydrogen production
  - ✓ Allocation of water consumption by multipurpose hydropower
  - ✓ Regional variations in water consumption factors of power generation

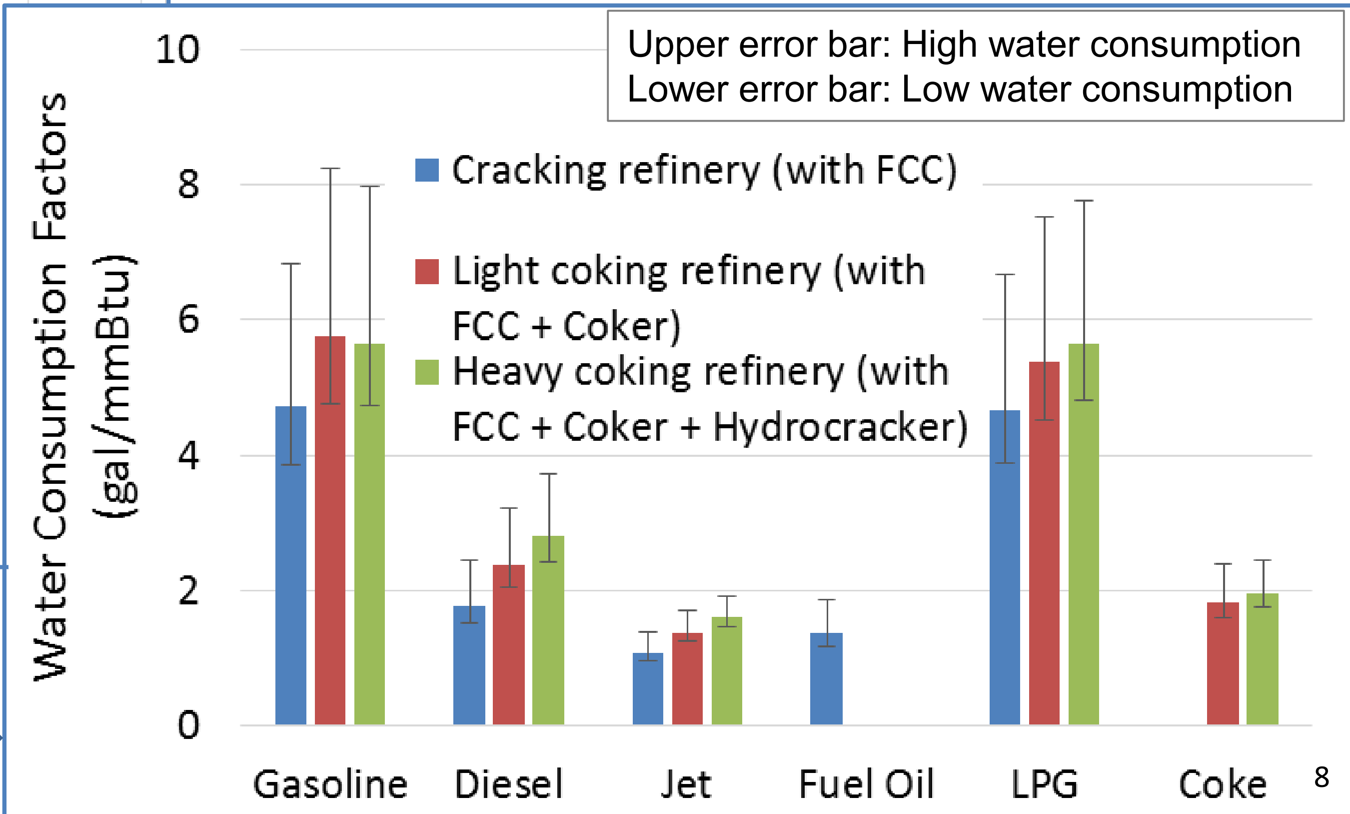
Updated water consumption factors (WCF) for petroleum products using detailed refinery water analysis model – Accomplishment



- Gasoline and LPG consume more water than the other products because their production involves water-intensive processes
- More complex refineries are more water-intensive in general
- Water consumption correlates well with energy consumption

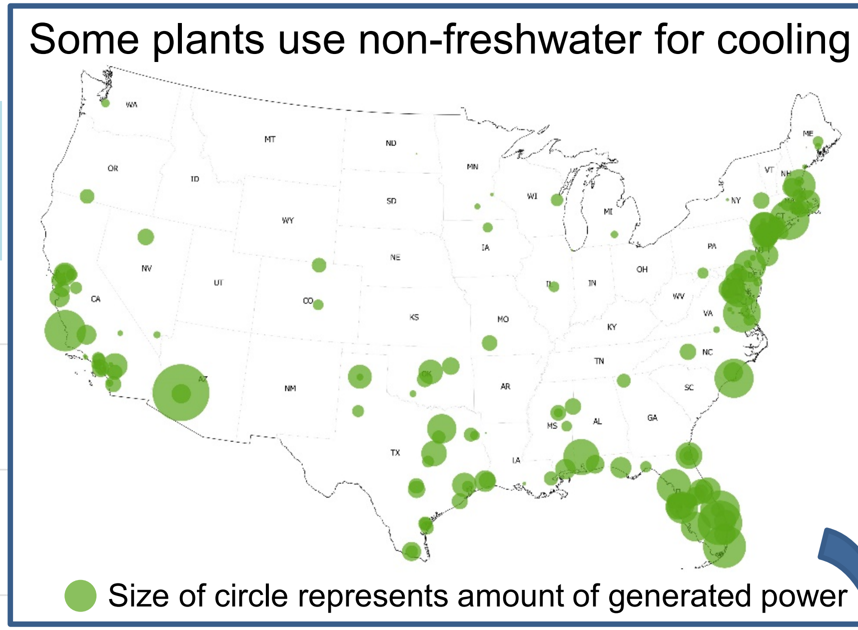
By refining process

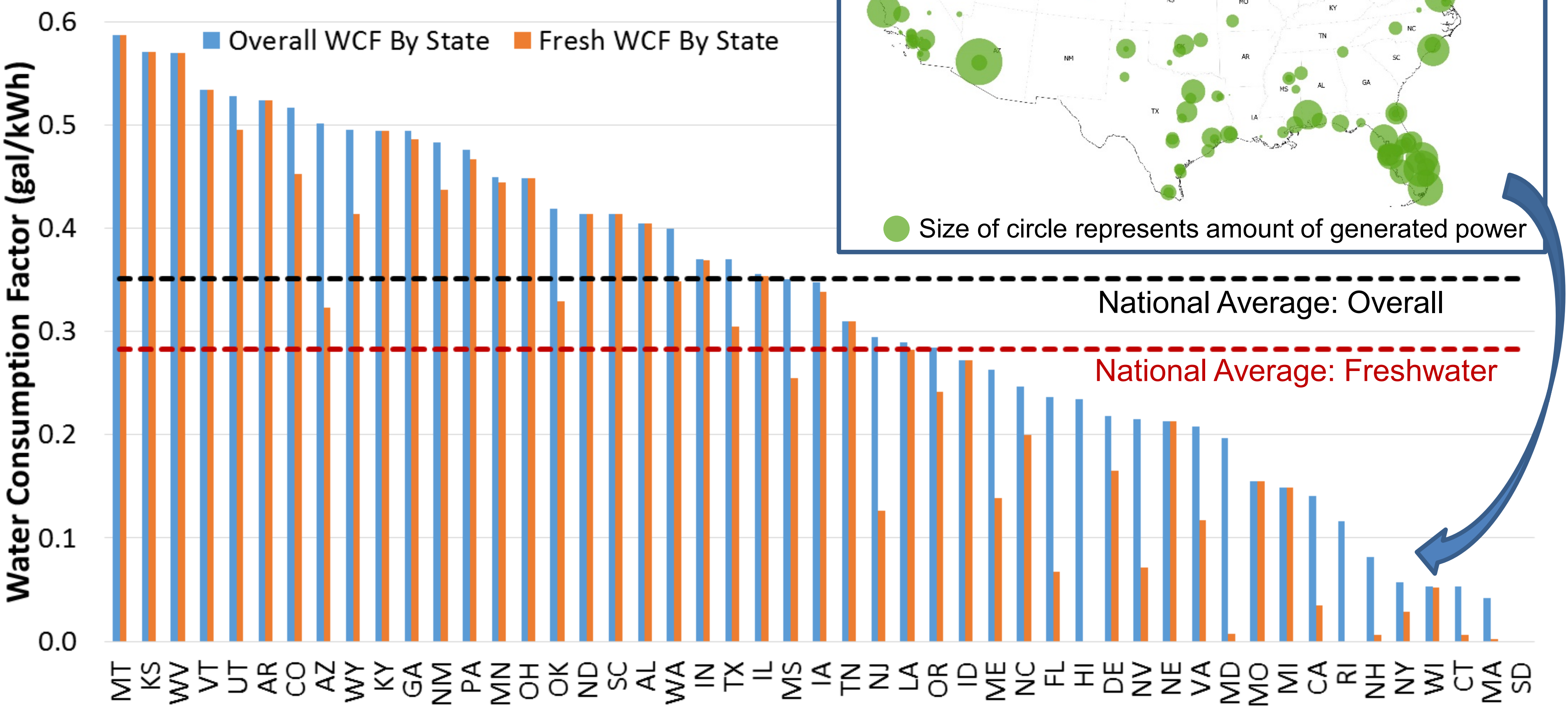
By refinery product



Developed cooling WCF of thermoelectric generation by region – Accomplishment

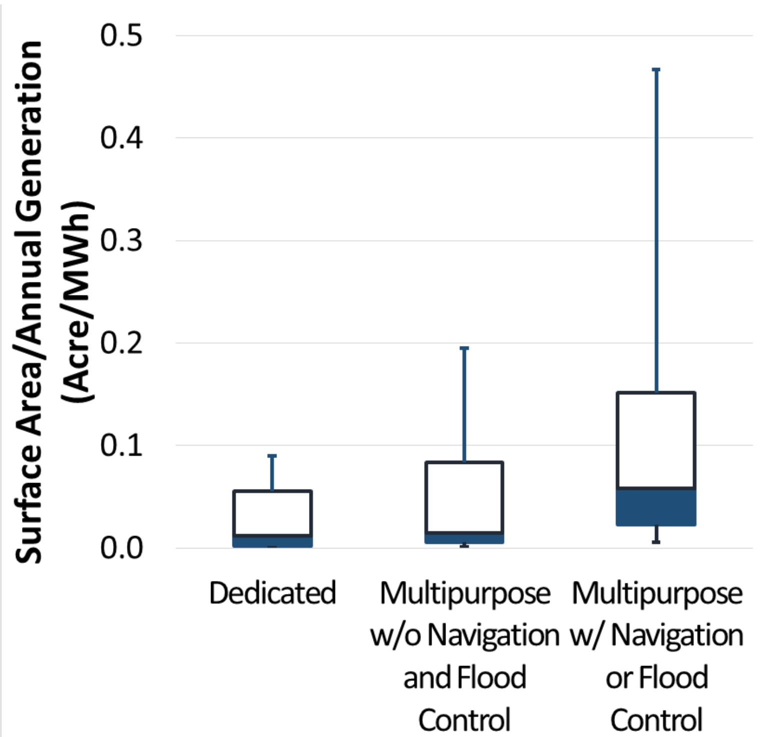
Freshwater usage can be reduced by using saline, brackish water or treated wastewater

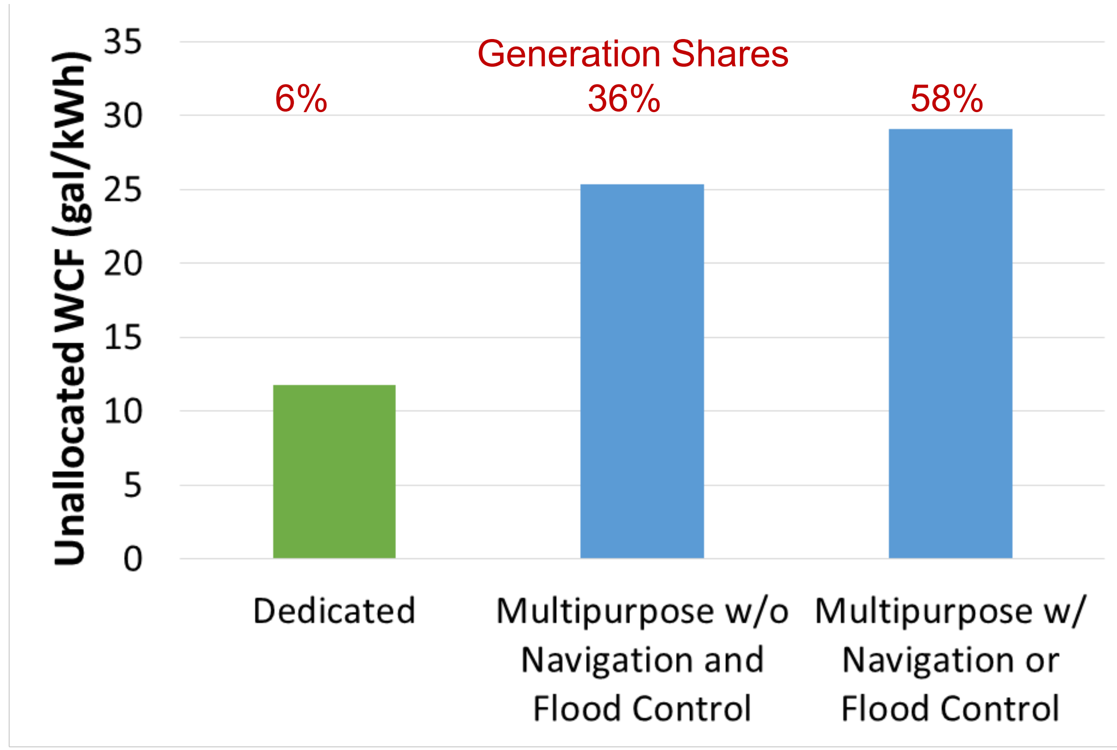




Source: US EIA (EIA-923 and EIA-860)

Significant variability/uncertainty exist with hydropower WCF – Accomplishment

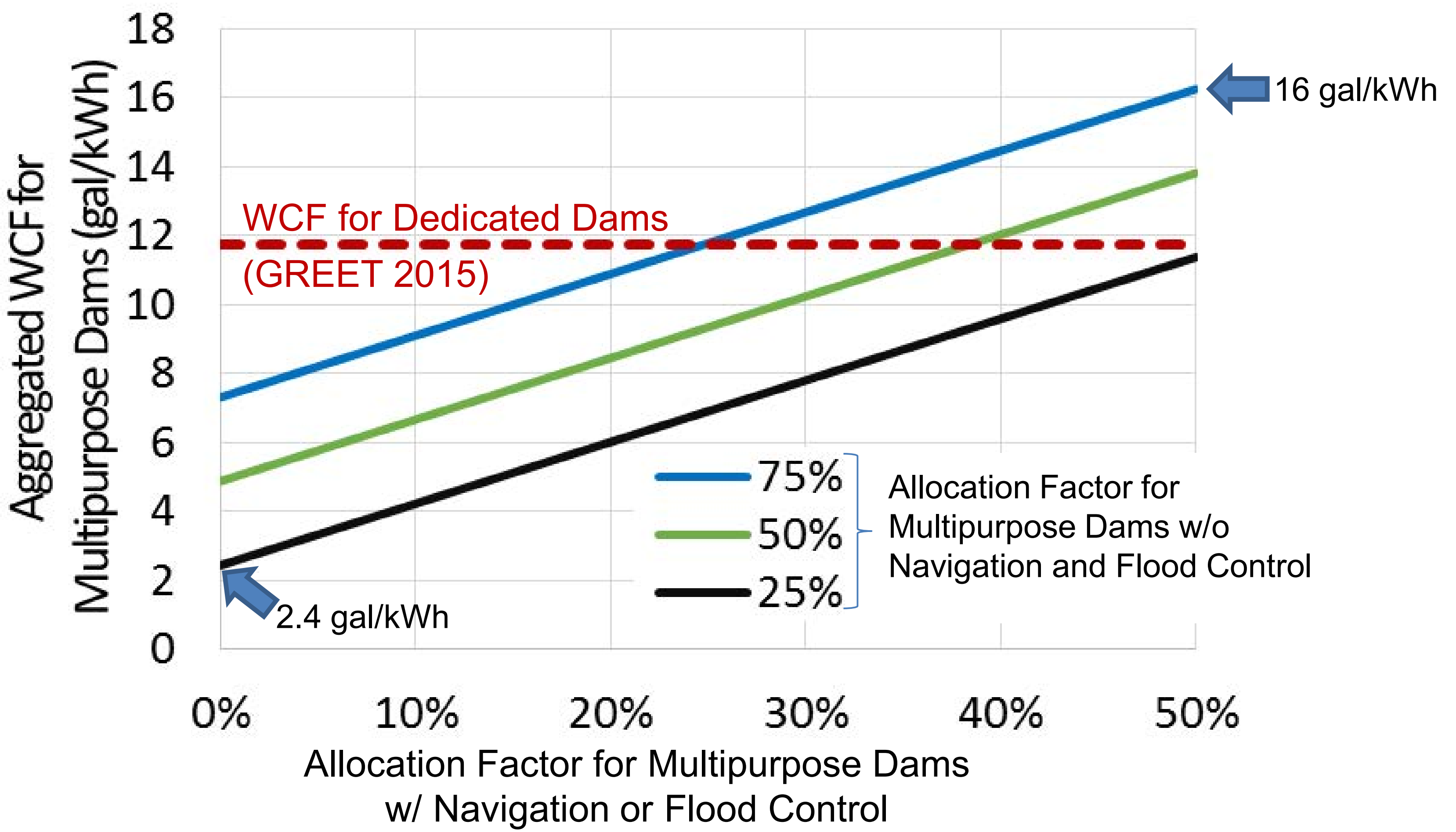




Source: eGRID (US EPA) and National Inventory of Dams (US Army Corps of Engineers)

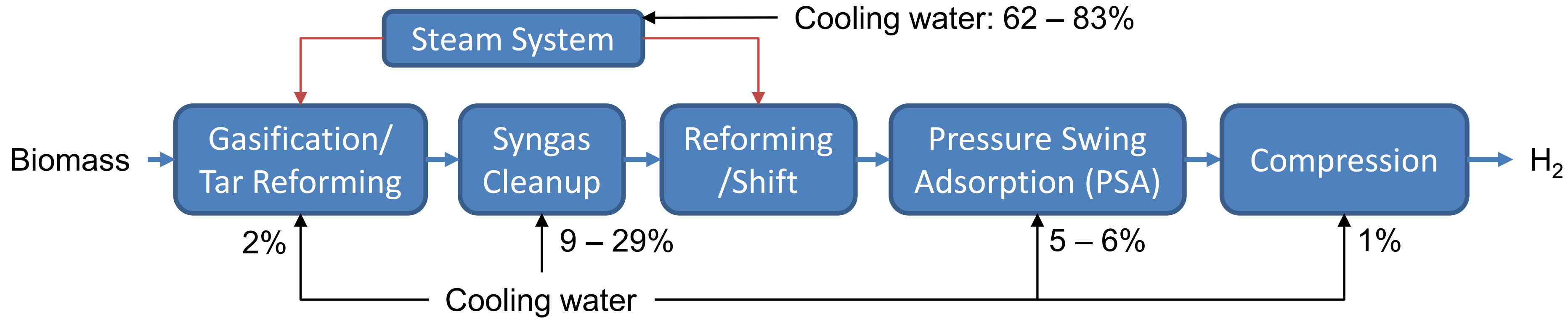
- ❑ Multipurpose dams dominate hydropower generation and consume (or evaporate) a large amount of water due to their larger surface area
- ❑ Allocation of water consumptions for these multipurpose dams is a key issue
- ❑ Two different allocations could be used for these multipurpose dams (by purpose)
  - ❑ With navigation or flood control: Large surface area, mainly for navigation and flood control
  - ❑ Without navigation and flood control

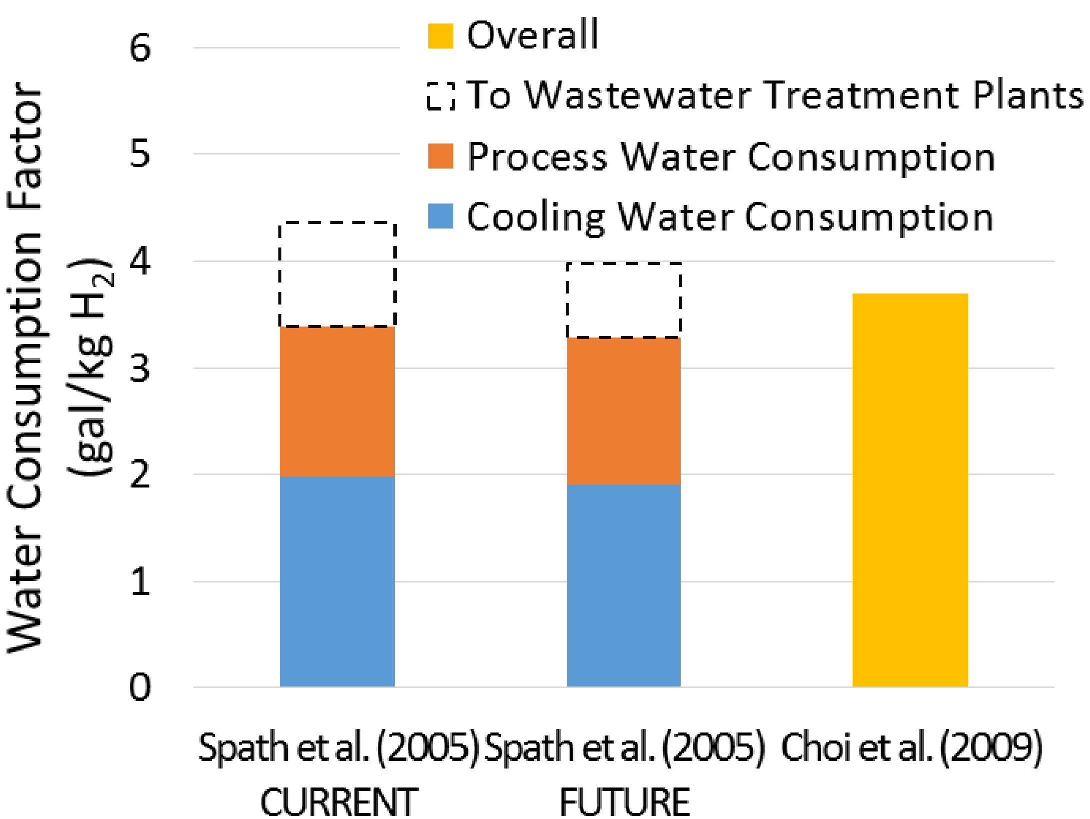
WCF for multipurpose dams varies by allocation factor approach – Accomplishment



- Pasqualetti and Kelley (2008) allocated 55% of water consumption by Glen Canyon Dam in Lake Powell (multipurpose w/o navigation and flood control) to hydropower using the revenue from four principal uses (hydropower, recreation, irrigation and domestic supply)

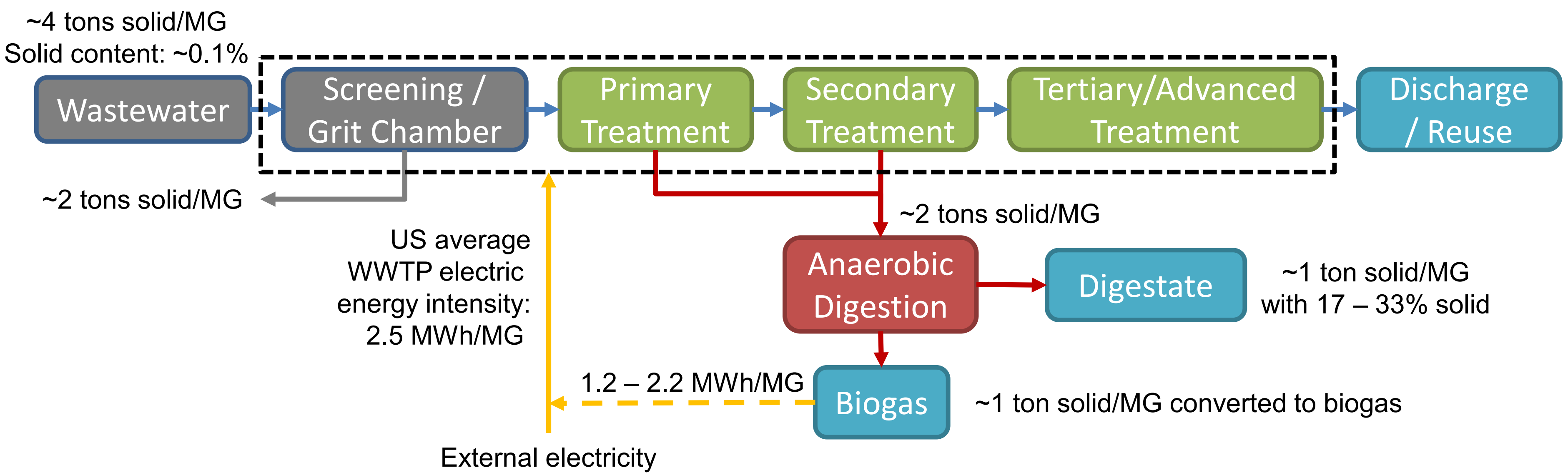
Updated WCF for hydrogen production via biomass gasification – Accomplishment





- WCF of H_2 from biomass gasification: 3.3 – 3.7 gal/kg H_2
- 0.7 – 1.0 gallon of water per kg H_2 is sent to wastewater treatment plants before discharge
- Steam turbine condenser is the largest cooling water consumer, followed by gas clean-up

Examined Wastewater Treatment Plants (WWTP) to evaluate impact of discharged water in WCF calculations – Accomplishment



MG = million gallons

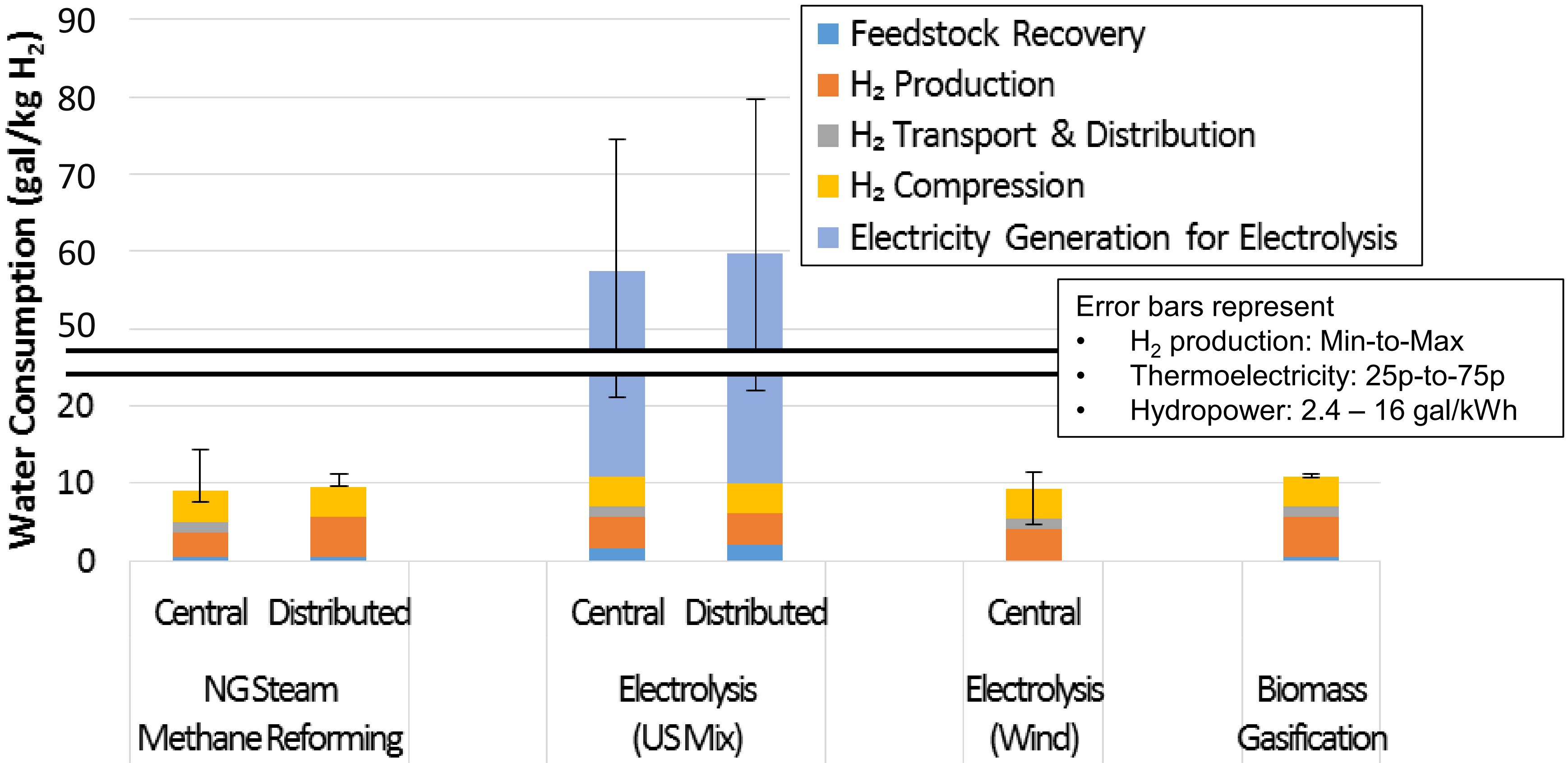
- Water consumption associated with wastewater treatment process electricity
  - ✓ Without CHP: 0.0028 MG/MG (or 0.28%)
  - ✓ With CHP: 0.0003 – 0.0015 MG/MG (or 0.03 – 0.15%)
- Water consumption by solid disposal: 0.001 – 0.02 MG/MG (or 0.1 – 0.2%)
- Water consumption via evaporation: negligible
- WCF of wastewater treatment **is negligible**
  - Without CHP: **0.38 – 0.48%**
  - With CHP: **0.13 – 0.35%**

Revised Water Consumption of SMR and Electrolysis – Accomplishment

	Production Technology				
	SMR			Electrolysis	
Process	Central w/o CCS	Central w/CCS	Distributed	Central	Distributed
~~Water Treatment Process~~	~~0.7~~	~~0.75~~	~~3.3~~	~~3.9~~	~~3.9~~
Production Process	1.7	1.7	2.5	2.9	2.9
Cooling Loss	0.65	1.15	0	1.2	0
Total WCF [gal/kgH_2]	3.1 → **2.4**	3.6 → **2.9**	5.8 → **2.5**	8.0 → **4.1**	6.8 → **2.9**

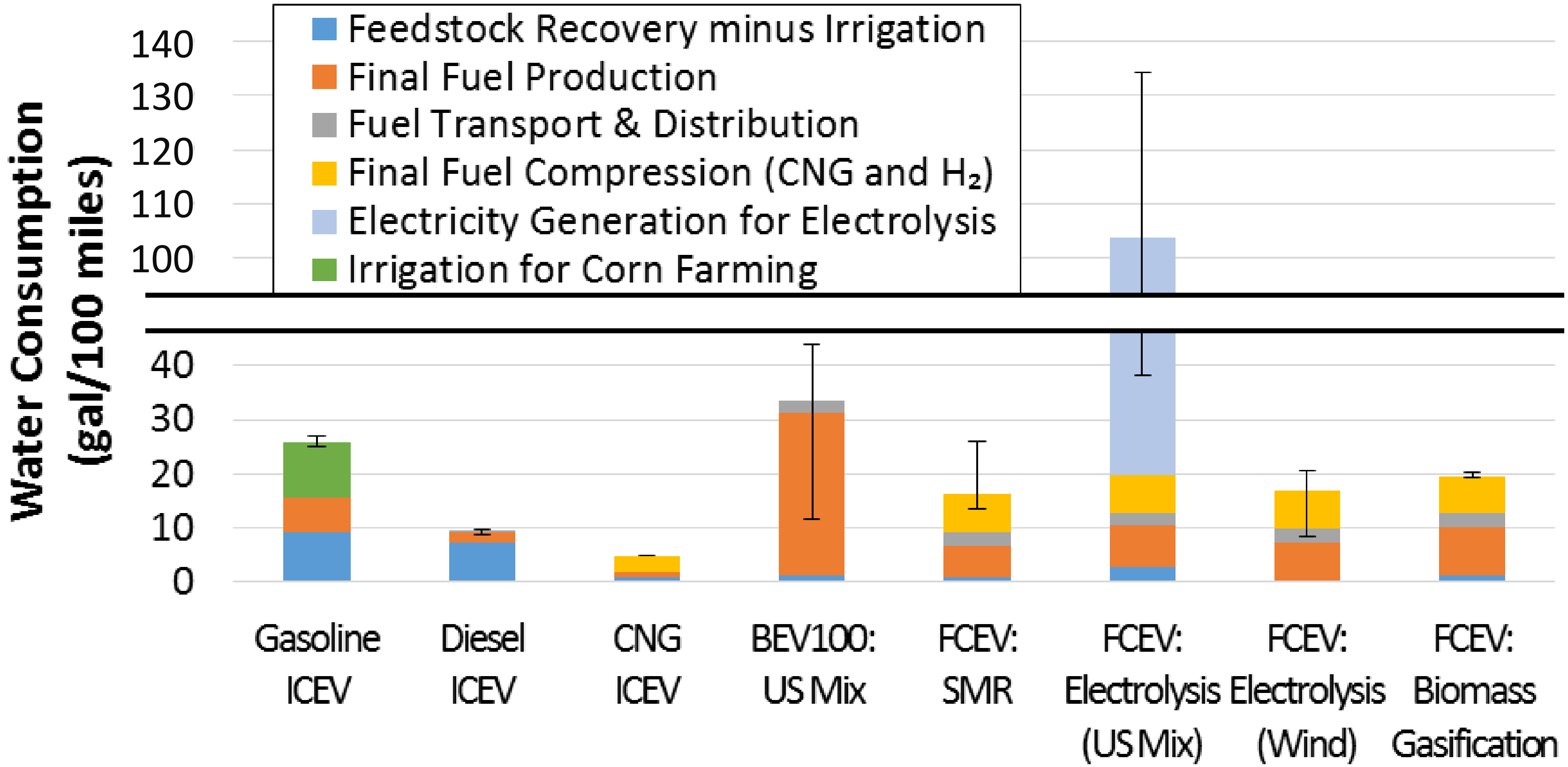
Water consumption factors for SMR and electrolysis were revised after discounting discharged water from being "consumed"

Life-cycle water consumption of hydrogen production varies by feedstock source and conversion process – Accomplishment



- ✓ WCF for electricity strongly impacts water consumption for H_2 production via electrolysis and compression at refueling stations
- ✓ H_2 production and compression are the largest water consumers in the fuel's life cycle

Life-cycle water consumption among various transportation fuels is dominated by electricity use – Accomplishment



Fuel Economy: (MPPGE)	26	31	27	94	55	55	55	55

- FCEVs fueled by H_2 from SMR and biomass gasification consume 37% and 24% less water compared to baseline gasoline (E10) ICEVs, respectively.

Summary – Accomplishment

- Updated water consumption for petroleum products
- Evaluated impact of various cooling technologies and cooling water source in thermoelectricity generation
- Examined impact of methodology for allocating water consumption to hydropower generation from multipurpose reservoirs
- Examined WWTP to evaluate impact of discharged water in water consumption factor calculations
- Revised water consumption factors for hydrogen production via biomass gasification, SMR and electrolysis
- Expanded the GREET model to include updated and new water consumption factors
- Compared water consumption on per mi basis for various fuel/vehicle combinations

Collaborations and Acknowledgments

- Jacobs® Consultancy developed a detailed refinery water analysis model to estimate WCF of petroleum products
- Jason Turgeon, US EPA Region 1 Energy and Climate Unit, and LouAnn Unger, EPA Region 5 Water Division, provided critical information on WWTPs operation and regulations
- Meltem Urgun-Demirtas, Principal Environmental Engineer in ANL, shared information on energy and water consumption in WWTPs
- Received water consumption data for large scale SMR plants from industrial gas companies
- Reached out to individual organizations and U.S. DRIVE Partnership technical teams for guidance and input

Future Work

- Continue development and implementation of water consumption factors of other hydrogen and alternative fuel pathways in GREET
- Examine hydrogen pathways with low or no water consumption (e.g., tri-generation CHHP systems)
- Reconcile different water consumption evaluation methods with respect to system boundary and allocation.
- Assess variability of water consumption by region and availability
- Develop probability distribution functions for WCF of various processes
- Develop water consumption factors for chemicals and vehicle materials (GREET2)
- Examine energy penalty/cost of alternative water production processes (e.g., desalination)
- Update GREET model and submit report with new water factors for peer review

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**: Sought data and guidance from the industry experts who provided guidance and valuable input on various production and water treatment technologies.
- **Technical accomplishments and progress:**
  - Updated water consumption for petroleum products
  - Evaluated impact of various cooling technologies and cooling water source in thermoelectricity generation
  - Examined impact of methodology for allocating water consumption to hydropower generation from multipurpose dams
  - Examined WWTP to evaluate impact of discharged water in water consumption calculations
  - Revised water consumption factors for hydrogen production via biomass gasification, SMR and electrolysis
- **Future Research**:
  - Examine hydrogen pathways with low or no water consumption (e.g., tri-generation CHHP systems)
  - Develop water consumption factors for vehicle materials (GREET2)
  - Assess variability of water consumption by region and availability
  - Develop probability distribution functions for WCF of various processes

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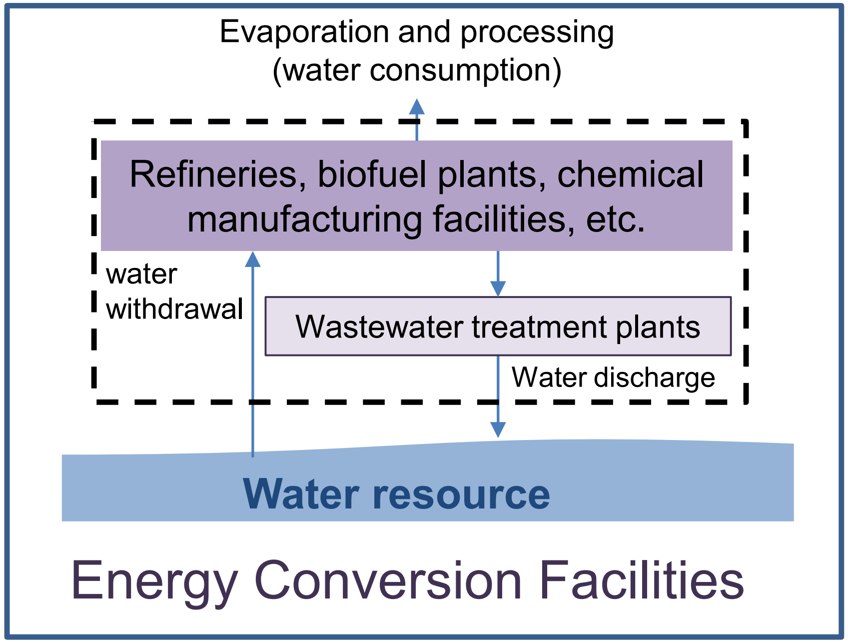
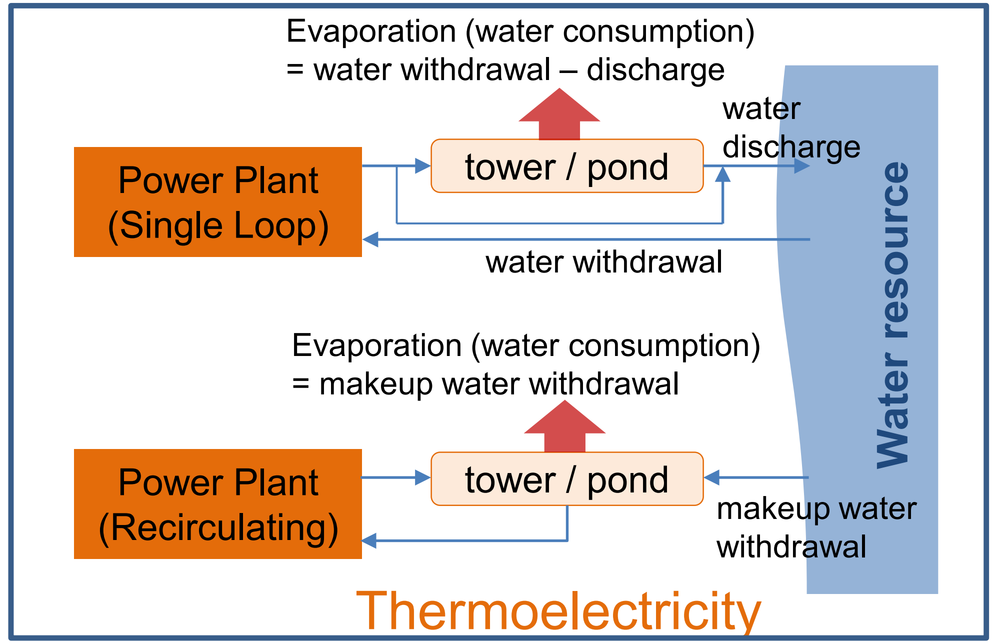
Acronyms

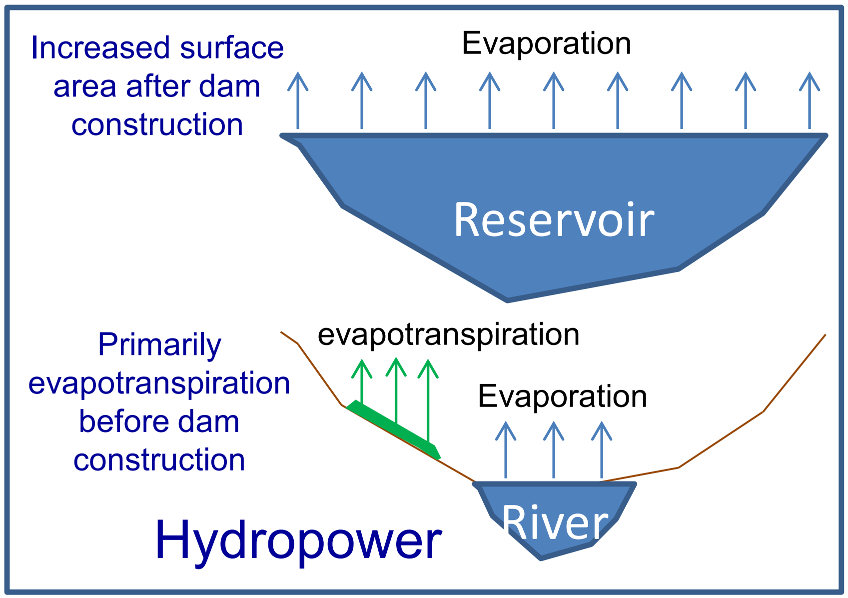
- ANL: Argonne National Laboratory
- BETO: Biomass Energy Technologies Office
- BEV: Battery Electric Vehicles
- CHP: Combined Heat and Power
- CNG: Compressed Natural Gas
- DOE: Department of Energy
- E10: 10% ethanol by volume blended in gasoline
- EIA: Energy Information Administration
- EPA: Environmental Protection Agency
- EPRI: Electric Power Research Institute
- FCC: Fluid Catalytic Cracking
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- FY: Fiscal Year
- Gal: Gallon
- GHG : Greenhouse Gases
- GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- H_2: Hydrogen
- H2A: Hydrogen Analysis
- ICEV: Internal Combustion Engine Vehicle
- LCA: Life-Cycle Analysis
- LPG: Liquefied Petroleum Gas
- MCFC: Molten-Carbonate Fuel Cells
- MG: Million Gallons
- MPGGE: Miles Per Gallon of Gasoline Equivalent
- MSM: Macro-Systems Model
- NG: Natural Gas
- PAFC: Phosphoric Acid Fuel Cells
- PSA: Pressure Swing Adsorption
- RD&D: Research, Development, and Demonstration
- SMR: Steam Methane Reforming
- U.S. DRIVE: United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability
- USDA: United States Department of Agriculture
- USGS: United States Geological Survey
- US Mix: US electricity grid mix
- VTO: Vehicle Technologies Office
- WCF: Water Consumption Factor
- WWTP: Wastewater Treatment Plants

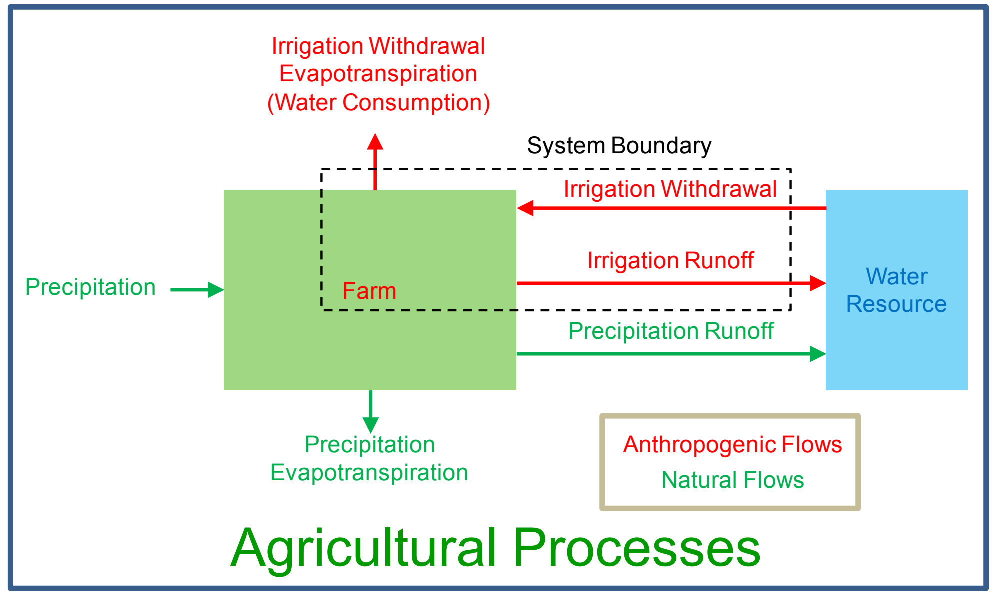
Technical Backup Slides

Water consumption accounting –*Approach*

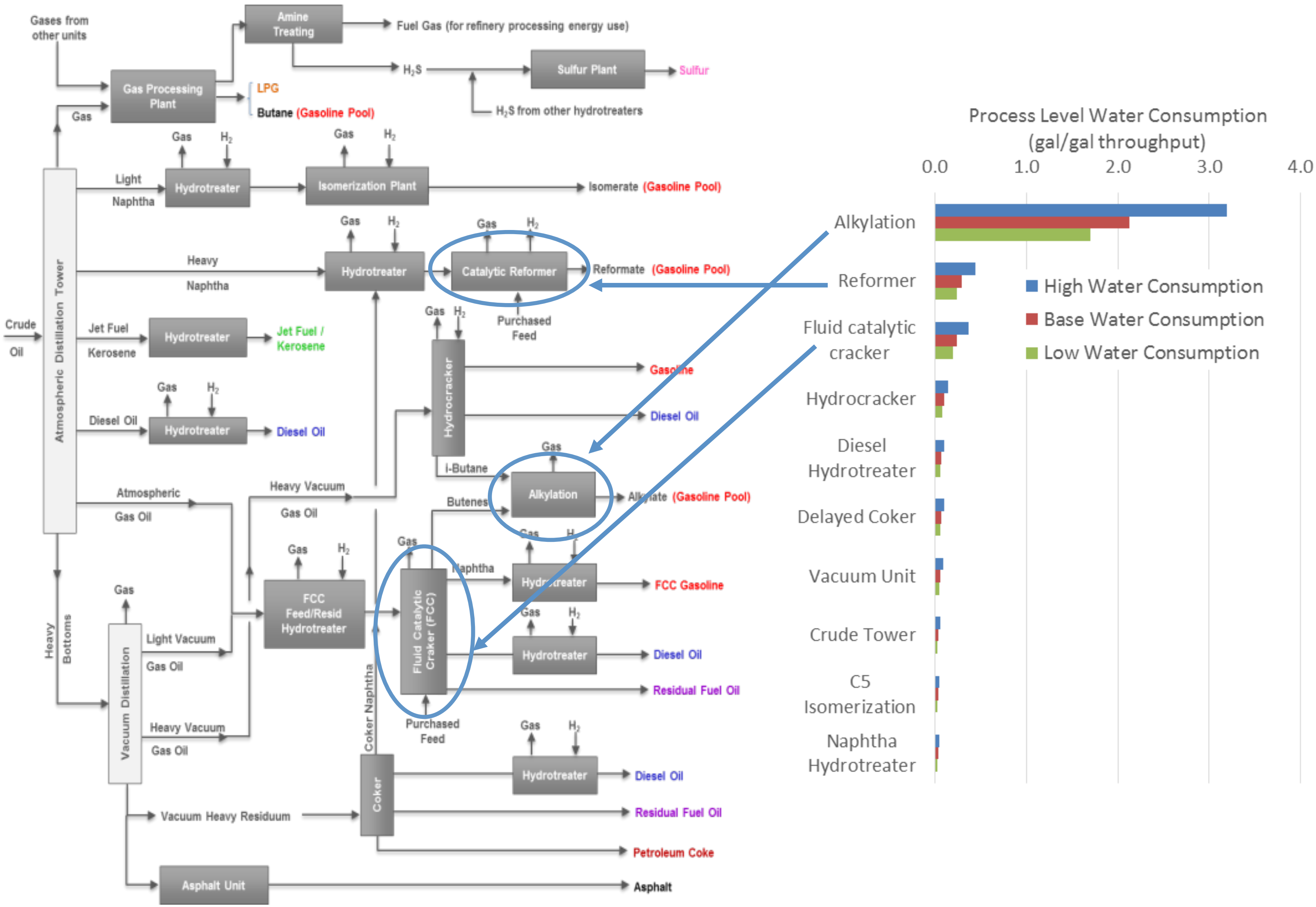








Estimated WCFs for petroleum products using detailed refinery water analysis model– Accomplishment



Collected data on electricity and water consumption in WWTPs – Accomplishment

	Flow Rate (MGD)[a]				Electrical Energy Intensity (kWh/MG)[b]
	Municipal		Industrial		
	w/o Reuse	w/ Reuse	w/o Reuse	w/ Reuse	
Primary	229	166	11	18	750
Secondary	6,437	133	758	3	2,080
Tertiary/Advanced	9,476	1,249	1,317	116	2,690
Total	**16,142**	**1,548**	**2,086**	**137**	**2,424**

[a] EPA's Clean Watersheds Needs Survey (2012); MGD = Million gallons per day
[b] EPRI's Electricity Use and Management in the Municipal Water Supply and Wastewater Industries (2013); MG = Million gallons

- Approximately 8.5 % of wastewater treated in WWTPs is reused
- With pumping energy, total electricity energy intensity is 2.5 MWh/MG
  - ✓ Electric energy intensity for pumping in WWTP is 1.3 MWh/MG
- With electricity WCF of 1.13 gal/kWh, WCF of wastewater treatment is **0.0028 gal/gal** (without biogas CHP)