2015 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Life-Cycle Analysis of Water Consumption for Hydrogen Production

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Argonne NATIONAL LABORATORY

SA039

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Overview

Timeline

- Start: April 2013
- End: Determined by DOE
- % complete (FY15): 70%

Barriers to Address

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

Budget

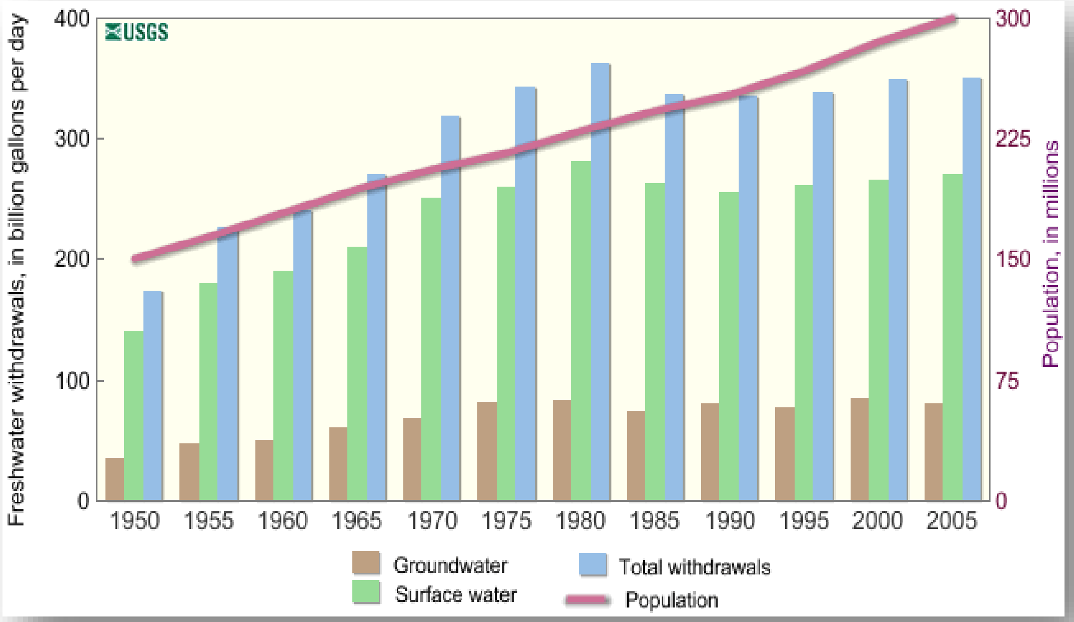
- Funding for FY14: $175K
- Funding for FY15: $250K

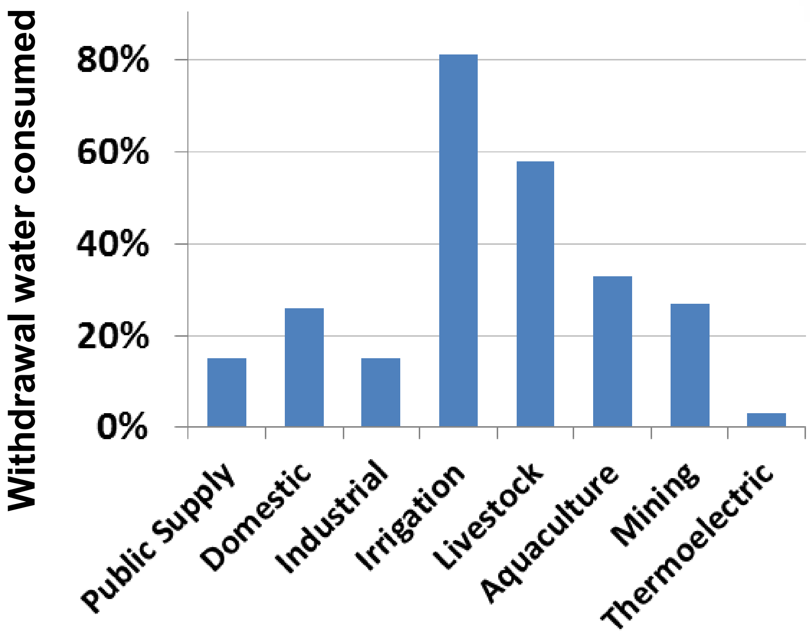
Partners/Collaborators

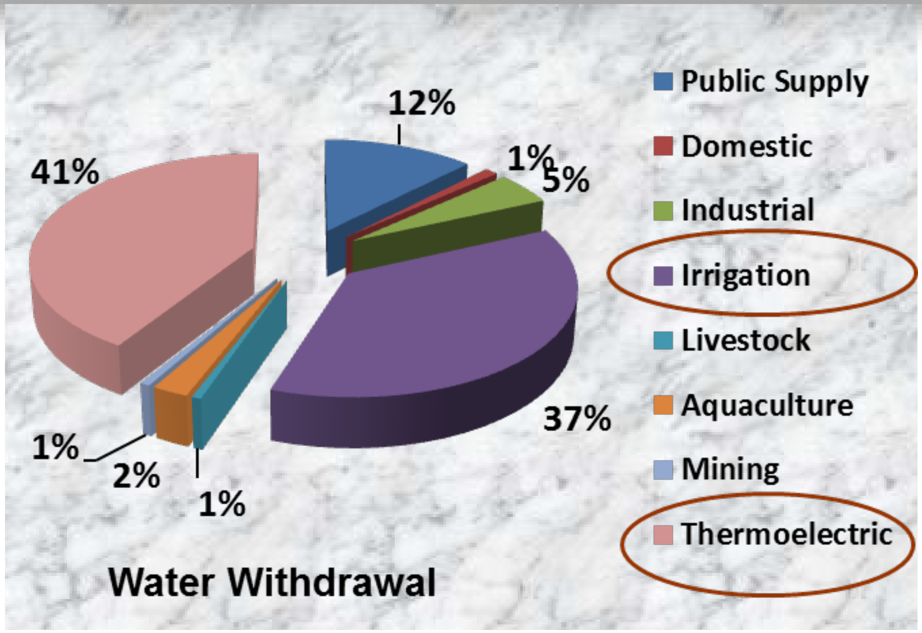
- Industry stakeholders

Relevance/Impact

- Water consumption is the withdrawn amount, not returned to the immediate environment
- Water consumption is an important sustainability metric for evaluating the production of alternative fuels





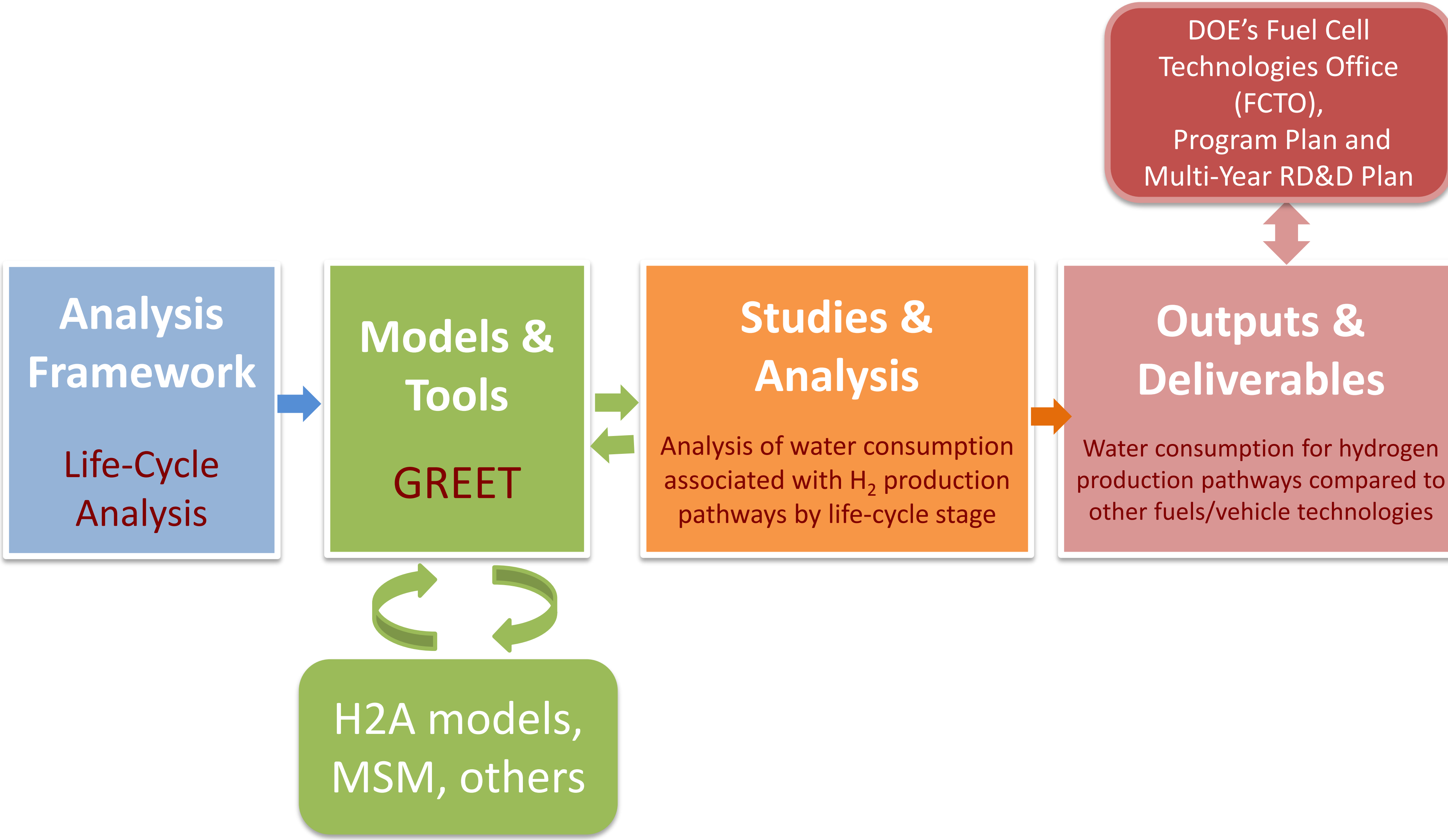


Source: USGS http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf

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 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 and refining heavy crude to produce fuels
  - Hydroprocessing of biofuels (e.g., plant oils, pyrolysis oil, waste oils)

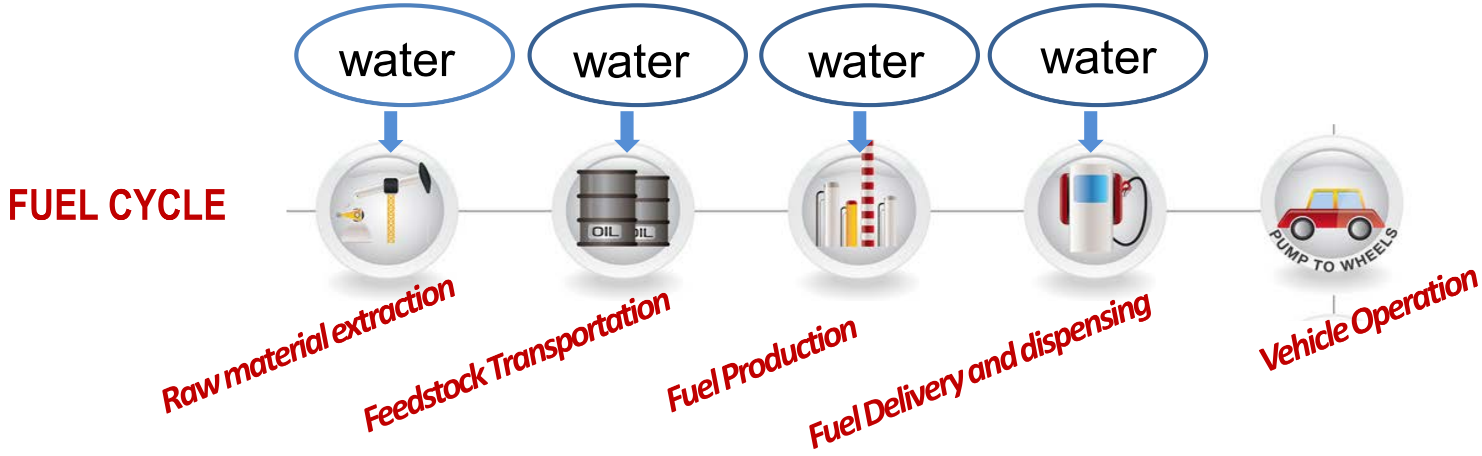
LCA of Water Consumption for Hydrogen Production Pathways – Relevance



Expanded GREET to include Water Consumption – Approach

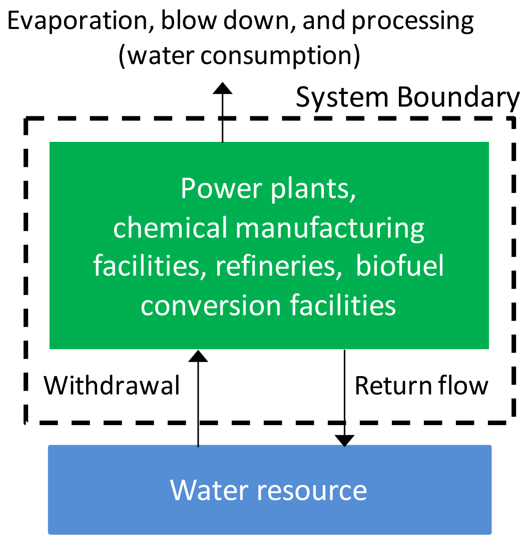
- Water LCA of a fuel: accounts for fresh water consumption along the pathway of producing the fuel from its feedstock

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

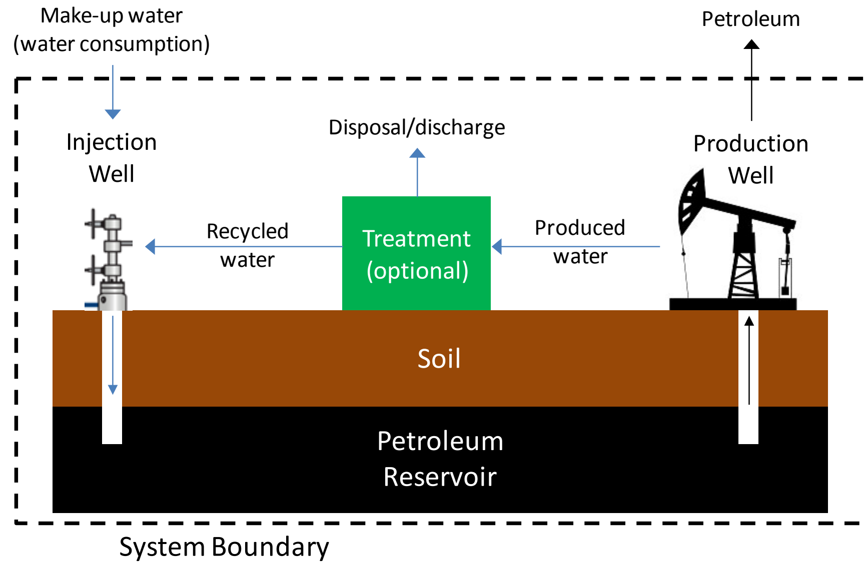


- FCTO, BETO and VTO supported incorporation of water consumption in GREET
- FCTO supports evaluation of life-cycle water consumption for hydrogen production pathways
- GREET is expanded to evaluate water consumed per MJ of fuel and per mile for various vehicle/fuel systems

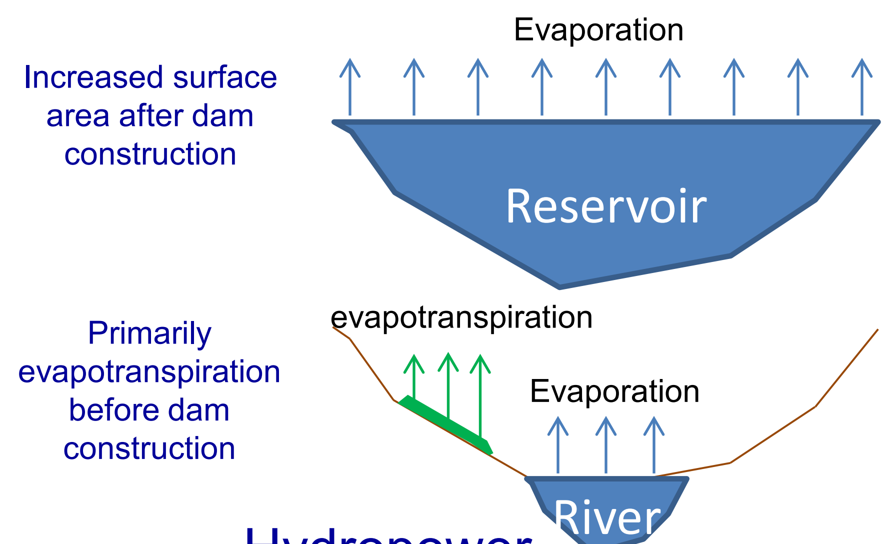
Water Consumption Accounting –*Approach*



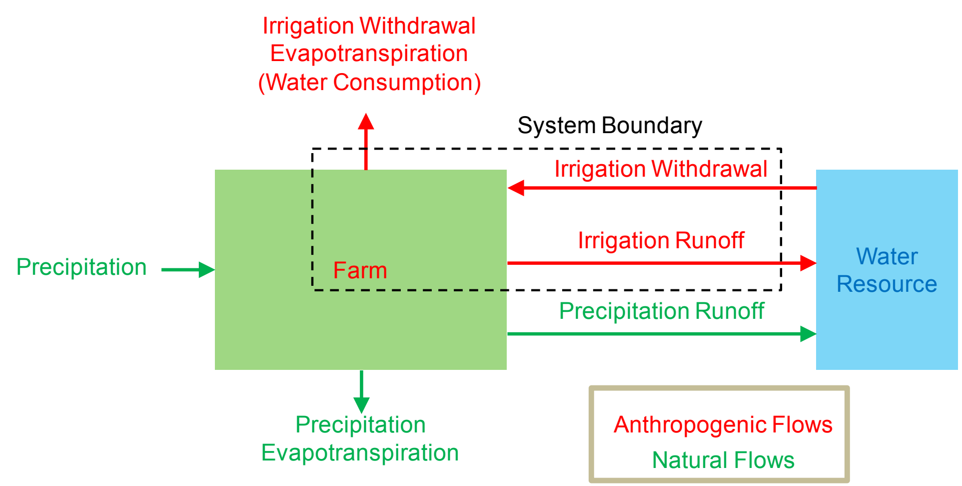
Energy Conversion Facilities



Petroleum Recovery



Hydropower



Agricultural Processes

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
  - Industrial sources
  - Modeling of physical processes
  - H2A models
  - Water footprint database and assessment tools developed at Argonne
  - National Agricultural Statistics Service (NASS), part of USDA and USGS

Strategy for Incorporating Water Consumption in GREET – Approach

Phase I: Incorporate water consumption for current fuel production pathways (completed in FY14)

- ✓ 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 (also serve CNGVs and LNGVs)
  - ❖ Electricity → requires coal, NG, nuclear, and biomass for upstream (also serve PHEVs and BEVs)
  - ❖ Hydrogen from SMR and electrolysis (also serves FCEVs)

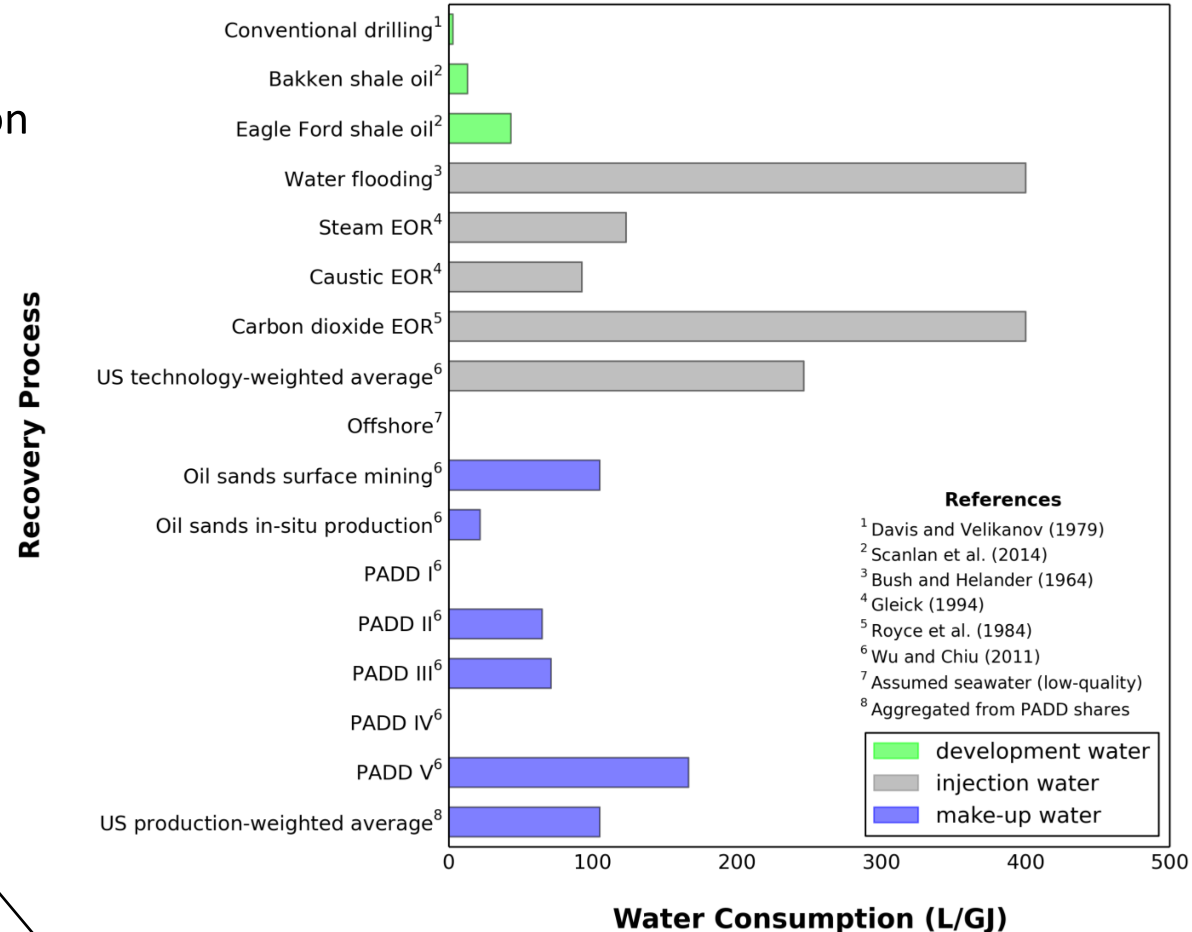
Continue Incorporation of Water Consumption in GREET in FY15 – Approach

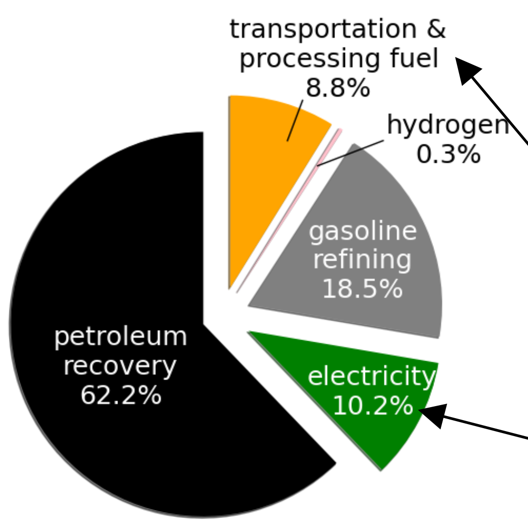
Phase II:

- Review and update water consumption for baseline fuels and current hydrogen production technologies
  - ✓ Petroleum fuels production
  - ✓ Natural gas SMR and electrolysis for hydrogen production
- Incorporate water consumption for other hydrogen production pathways
  - ✓ Biomass gasification
  - ✓ Biogas purification and reforming
- Address outstanding water consumption issues for hydrogen production
  - ✓ Impact of water treatment for SMR and electrolysis
  - ✓ Indirect water consumption associated with hydropower electricity generation (for electrolysis pathway)
- Examine impact of various cooling technologies
  - ✓ Wet cooling vs. dry cooling

Updates to Petroleum Pathway – Accomplishment

- ❑ Water consumption depends on well age/recovery technology
- ❑ Large difference between recovery technologies
- ❑ Updates to refinery water consumption estimates from linear programming model





Gasoline Lifecycle Water Consumption
46 gal water per mmBtu

Electricity and process fuels important to life-cycle water consumption

✓ previous studies only considered recovery and refinery water consumption

Updated Water Consumption of SMR – Accomplishment

Reforming: $CH4 + H2O \overset{\Delta}{\rightleftharpoons} CO + 3H2$

Shift: $CO + H2O \rightarrow CO2 + H2$

Net: $CH4 + 2H2O \overset{\Delta}{\rightleftharpoons} CO2 + 4H2$ Steam/carbon ratio (S/C) =2

Stoichiometry: 1.2 gal_{water} per kg_{H2} for SMR with (S/C=2)

- In practice, S/C ratio of ~ 2.5 - 3 is used to maximize methane conversion
  - ✓ 1.5 -1.8 gal_{water}/kg_{H2}

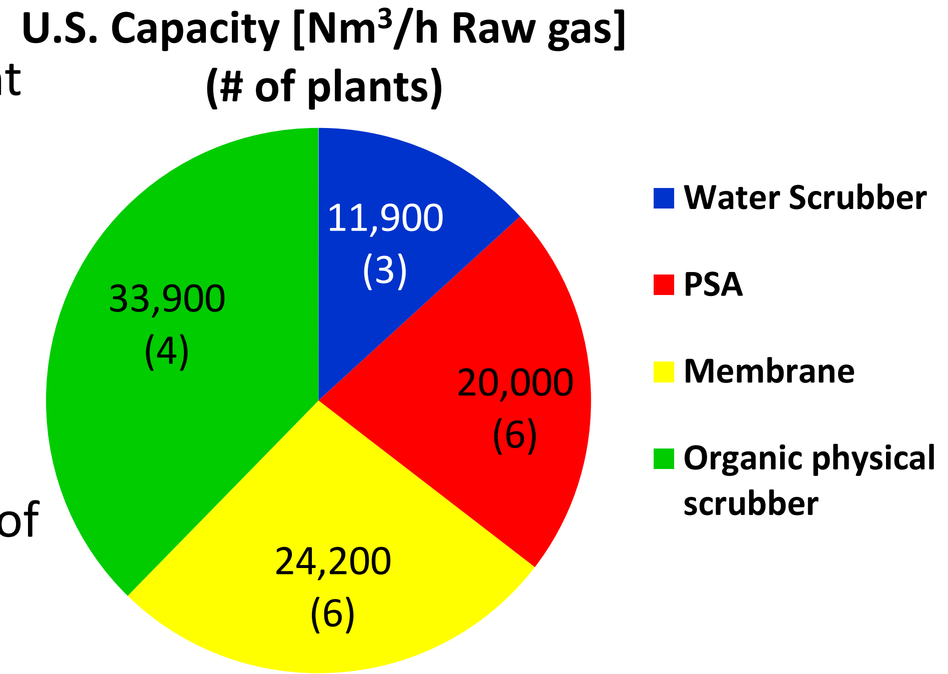
Industry Sources:

- ❑ Central production
  - 3.9 - 4.2 gal_{water} / kg_{H2} without accounting for recycling
  - 1.6 gal_{water} / kg_{H2} with recycling of steam and condensate
- ❑ Distributed production
  - 5 gal_{water} / kg_{H2} without condensate recycling
  - 2.4 - 3 gal_{water} / kg_{H2} (S/C = 4 - 5) with condensate recycling

Water consumption factor for SMR is 1.6 gal/kg_{H2} for central production and 2.5 gal/kg_{H2} for distributed production

Water consumption by biogas upgrading is 9.3 gal per mmBtu of biogas – Accomplishment

- Four major technologies for contaminant removal from biogas
  - ✓ Water scrubber uses water as an absorption agent, and consumes a large amount of water
  - ✓ Water scrubber technology for biogas upgrading accounts for 13% of total upgrading capacity in the U.S.

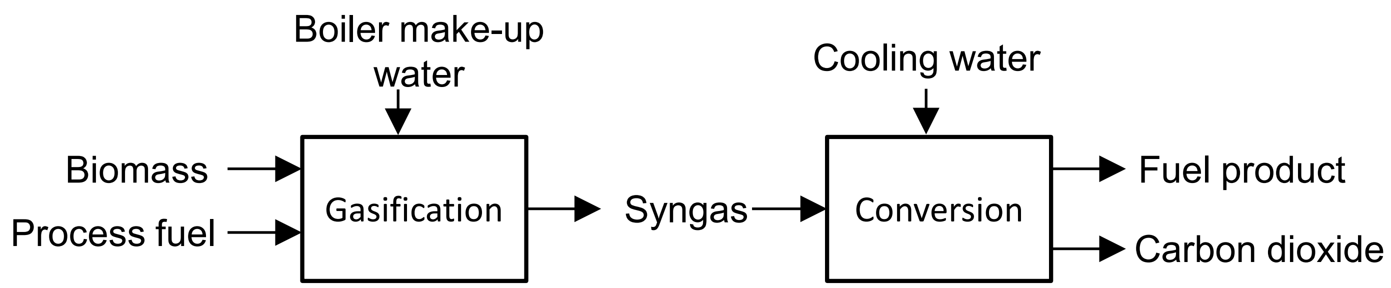


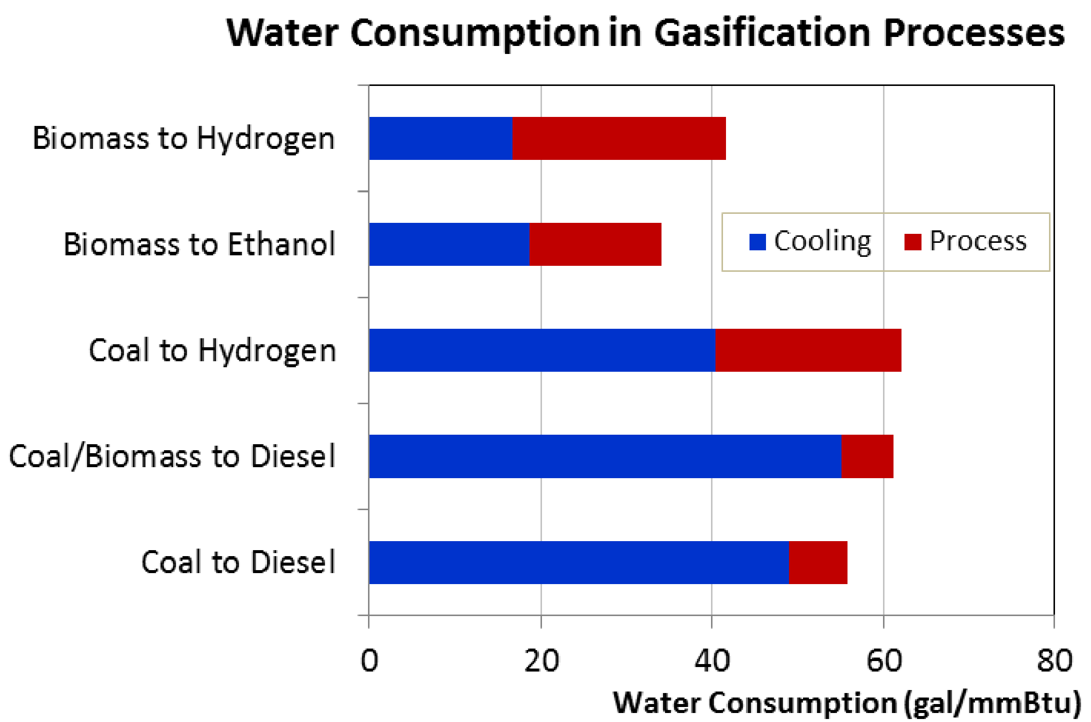
- ➢ Water consumption by water scrubbers is 59 gal/mmBtu
  - ✓ Range: 2 – 192gal/mmBtu
- ➢ Water consumption by other biogas contaminant removal technologies is small
  - ✓ Similar to that of fossil NG processing (1.7 gal/mmBtu)

Average water consumption for total biogas upgrading in the US is 9.3 gal/mmBtu
- ✓ **Range: 2 – 27 gal/mmBtu**

http://www.sgc.se/ckfinder/userfiles/files/SBGF610408.pdf

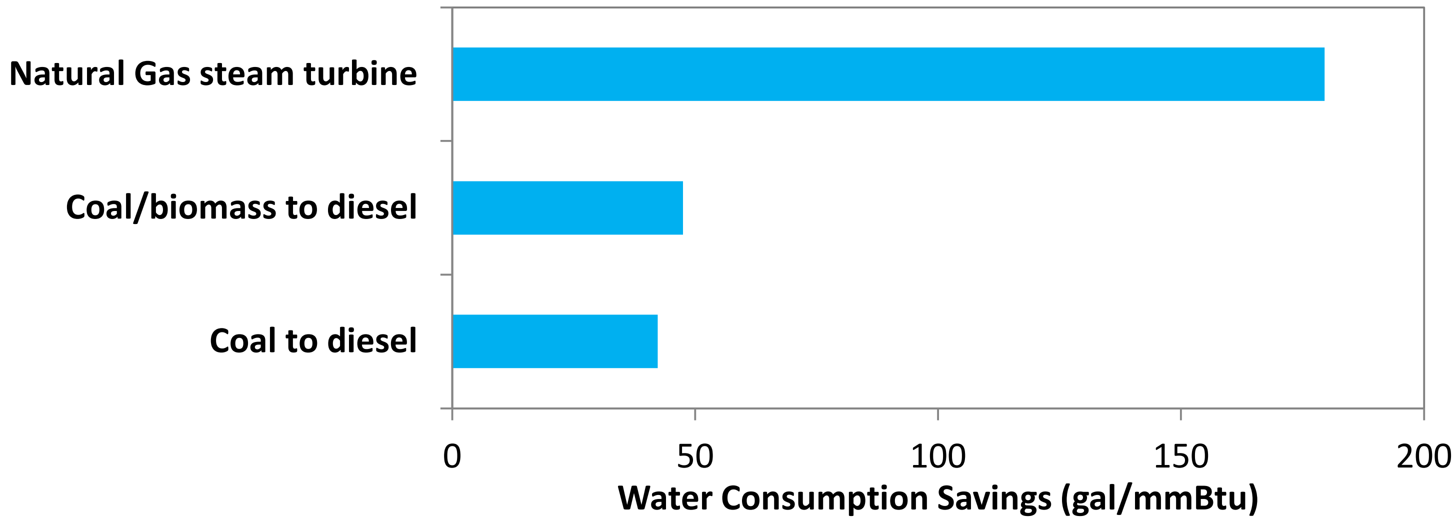
Gasification Water Consumption for Various Fuels Vary by Employed Cooling Technology – Accomplishment

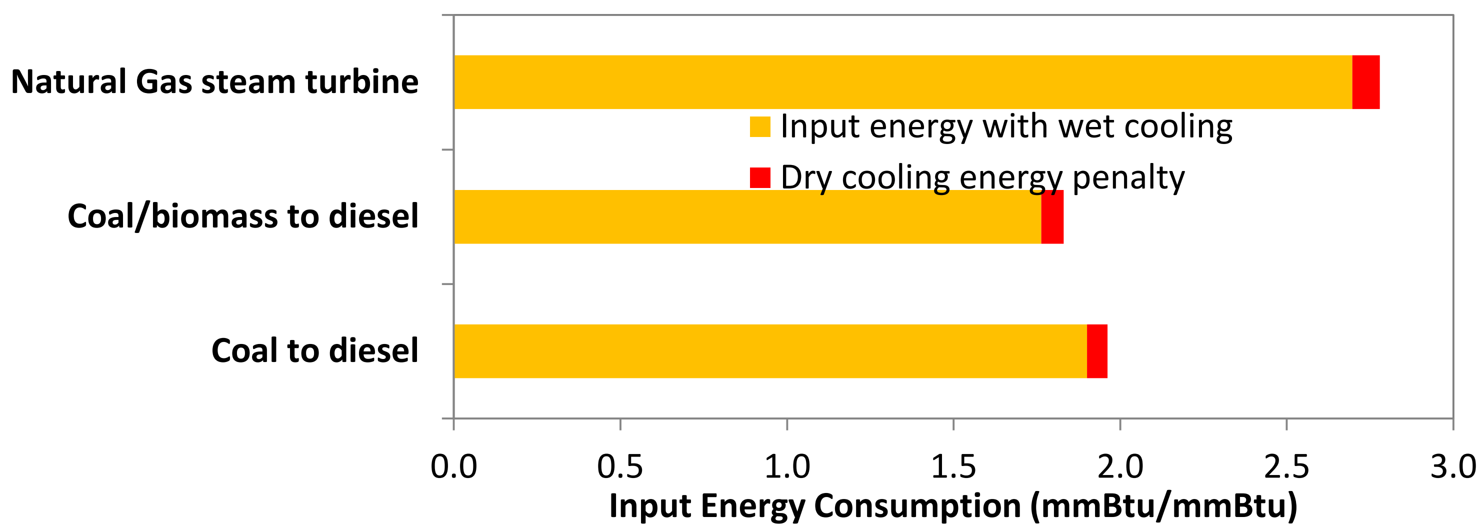




Efficiency of feedstock to fuel conversion determines water consumption factors for various gasification pathways

Dry Cooling Technologies Save Water but with Energy Consumption Penalty – Accomplishment



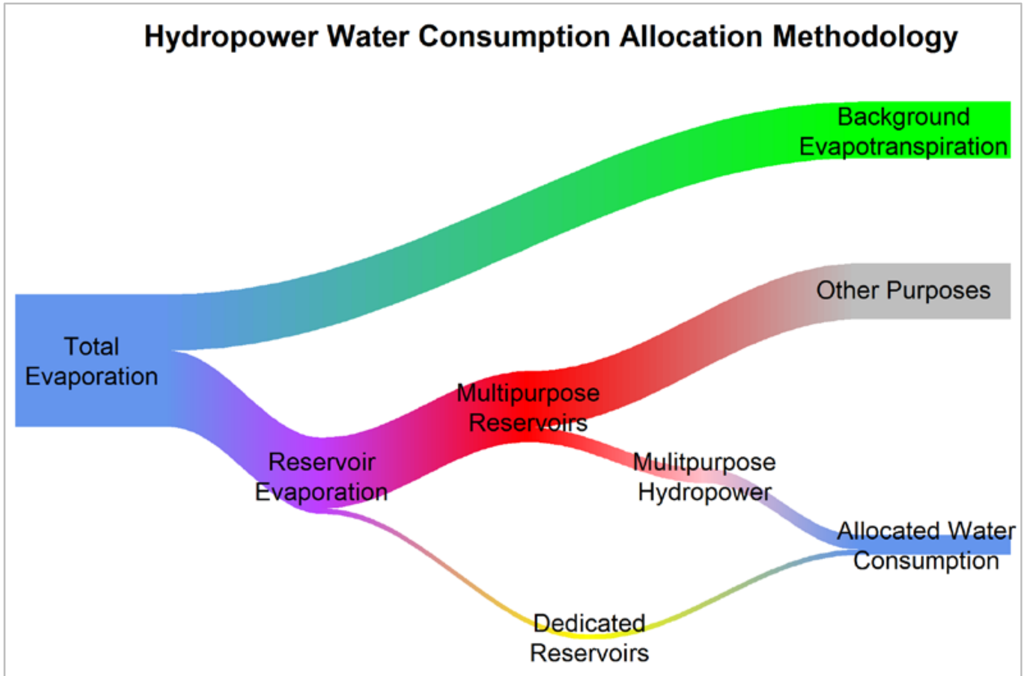


Energy penalty for dry cooling is in the order of 2-3% of total input energy

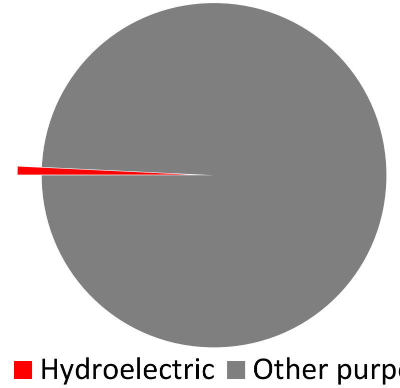
✓ **Environmental and economic implications of energy penalty must be considered**

Developed Hydropower Water Allocation Methodology – Accomplishment

- Merged eGRID and National Inventory of Dams databases
- Most dams exist for purposes other than hydroelectricity generation
- Excluded major navigational water bodies (Great Lakes, Mississippi River, etc.)
- Allocation methodology of reservoir evaporation for hydropower dams:
  1. Estimated gross reservoir evaporation from observed pan evaporation
  2. Calculated and removed background evapotranspiration from gross evaporation
  3. Divided dams into two categories: multipurpose and dedicated hydropower
  4. Allocated water burden in multipurpose reservoirs based on penstock and spillway flows

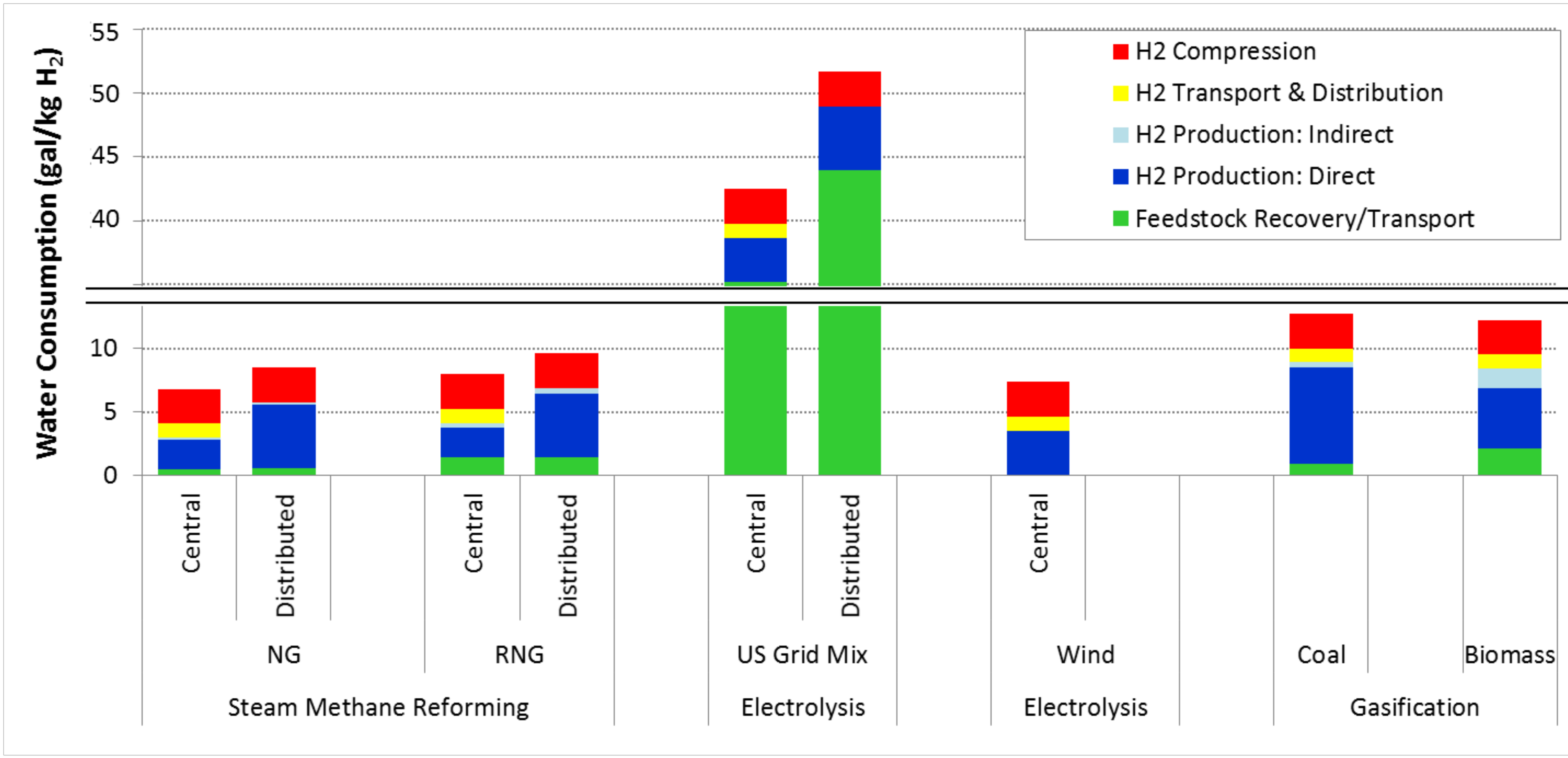


Share of Dams used for Hydroelectricity Generation



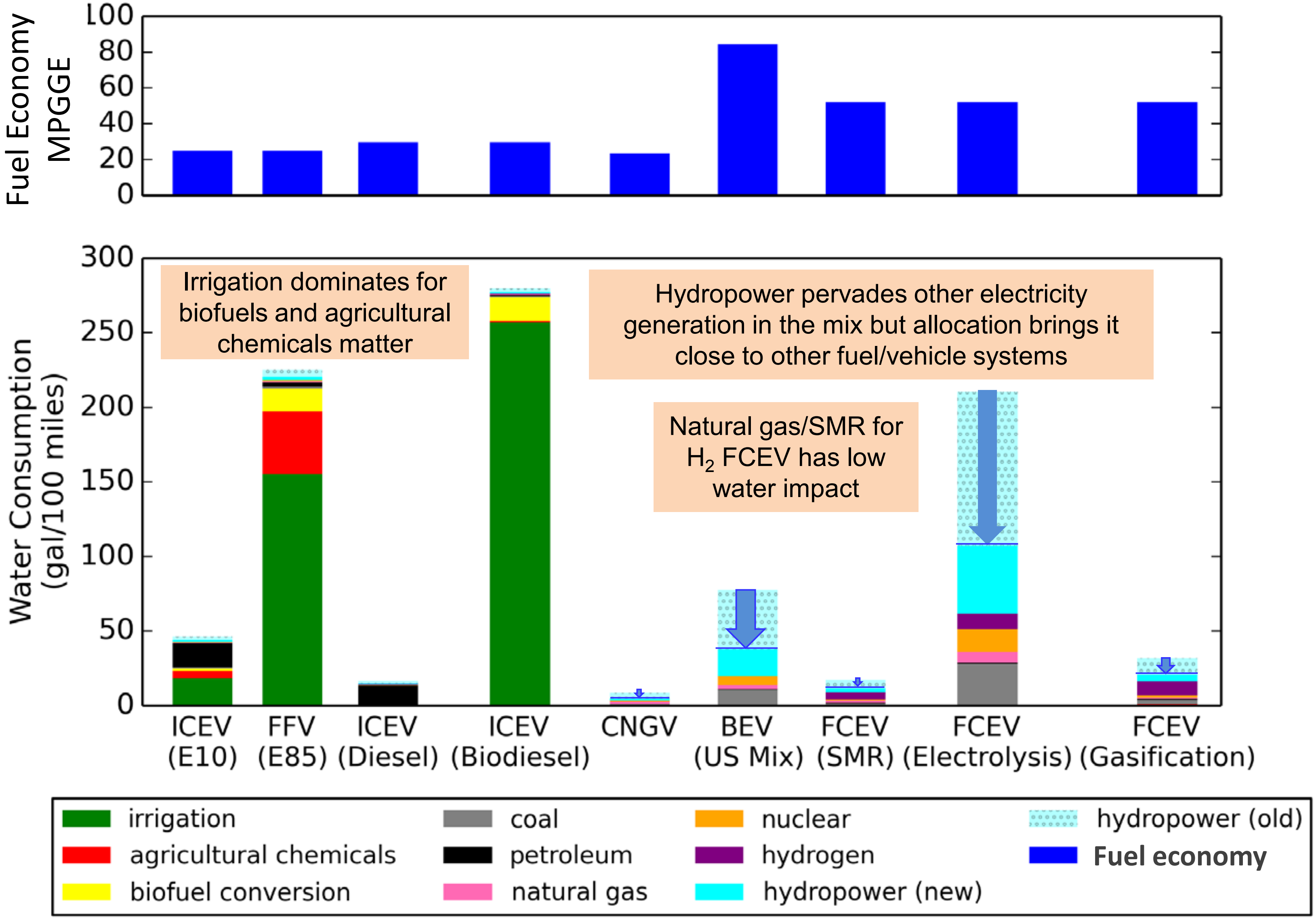
Hydropower generation weighted average net water consumption is 8.2 [gal/kWh]

Life-Cycle Water Consumption of Hydrogen Production Varies by Feedstock Source and Conversion Process – Accomplishment



Electricity use for H_2 production and compression significantly impacts water consumption for H_2

Life-cycle water consumption is dominated by electricity use and irrigation for biofuels – Accomplishment



Summary – Accomplishment

- Developed water consumption factors for hydrogen production from biogas and from coal and biomass gasification
- Updated water consumption factors for hydrogen production via SMR and electrolysis
- Updated water consumption for petroleum pathways
- Developed methodology for allocating water consumption to hydropower generation
- Examined tradeoff between water saving and energy use of dry cooling vs. wet cooling
- Expanded the GREET model to include updated and new water consumption factors
- Compared water consumption per mi for various fuel/vehicle combinations
  - ✓ Water consumption by hydrogen production via SMR (for FCEVs) is lower than gasoline (E10), and much lower than biofuels and electricity
- Documented approach, data, methodology, and analysis in a report

Collaborations and Acknowledgments

– Jeni Keisman, AAA Fellow with DOE (Currently with USGS), shared information on water consumption for various fuel production processes

– Interacted with industrial companies and received water consumption data for large scale SMR

– Interacted with companies producing electrolyzers, who provided field water consumption data for H_2 production via electrolysis

– 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)
- Develop water consumption factors for chemicals and vehicle materials (GREET2)
- Reconcile different water consumption evaluation methods with respect to system boundary and allocation.
- Assess variability of water consumption by region and availability
- Examine energy penalty/cost of alternative water production processes (e.g., desalination)
- Address purification water consumption as a function of water quality and process requirement
- Update GREET model and submit report with new water factors for peer review
- Continue support to DOE and industry stakeholders

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 technologies.
- **Technical accomplishments and progress:**
  - Developed water consumption factors for hydrogen production from biogas and via coal and biomass gasification
  - Updated water consumption factors for hydrogen production from SMR and electrolysis
  - Updated water consumption for petroleum pathways
  - Developed methodology for allocating water consumption to hydropower generation
  - Examined tradeoff between water saving and energy use of dry cooling vs. wet cooling
  - Expanded the GREET model to include updated and new water consumption factors
- **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)
  - Reconcile different water consumption concepts
  - Assess variability of water consumption by region and availability
  - Address purification water consumption as a function of water quality requirement

Argonne NATIONAL LABORATORY

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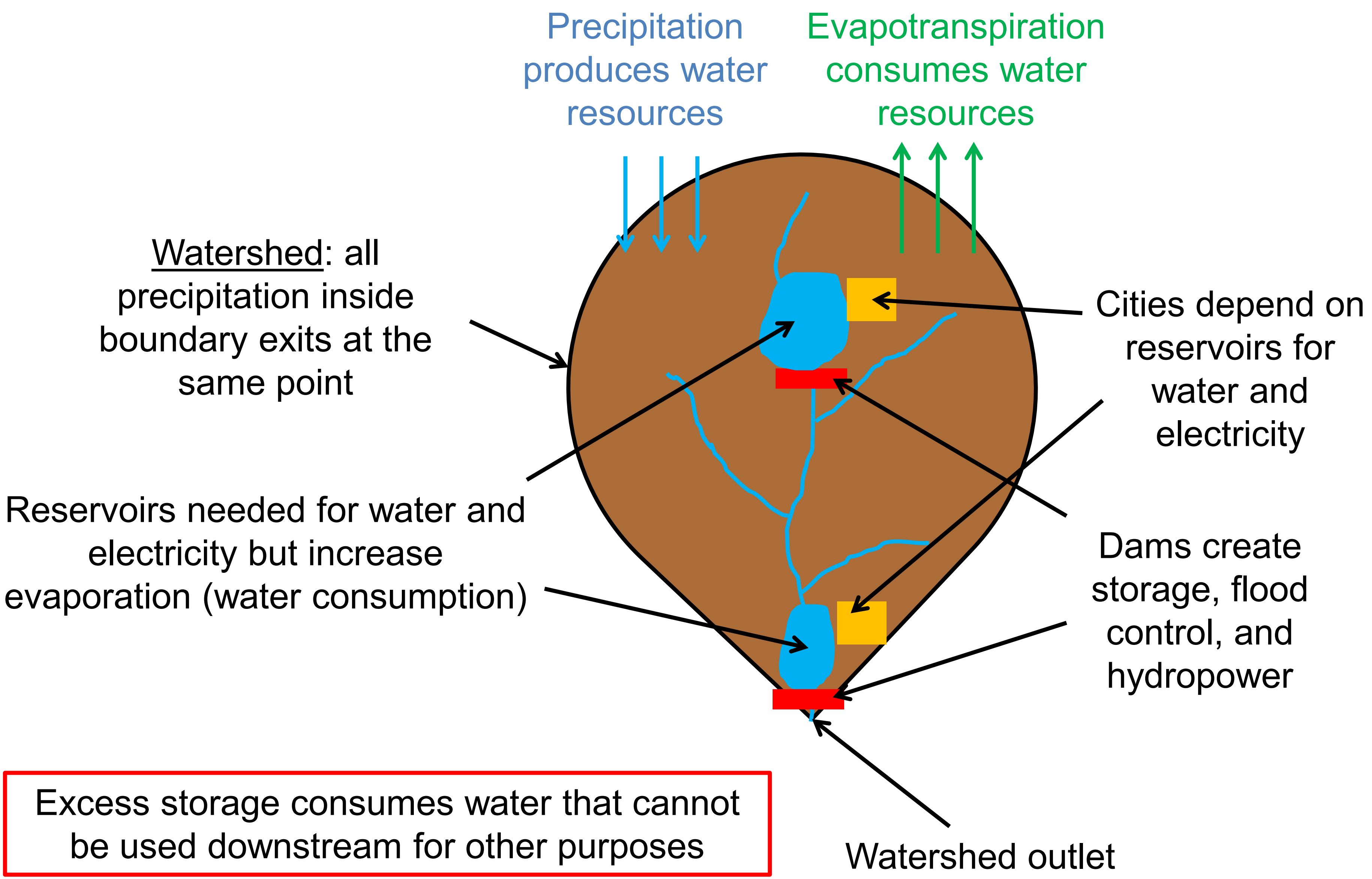
Technical Backup Slides

Acronyms

- ANL: Argonne National Laboratory
- BD: Biodiesel
- BETO: Biomass Energy Technologies Office
- BEV: Battery Electric Vehicles
- CHHP: Combined Heat, Hydrogen and Power
- CNGV: Compressed natural Gas Vehicle
- DOE: Department of Energy
- E10: 10% ethanol by volume blended in gasoline
- eGRID: Emissions & Generation Resource Integrated Database
- EOR: Enhanced Oil Recovery
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- FFV: Flexible Fuel Vehicle
- FY: Fiscal Year
- Gal: Gallon
- GHG: Greenhouse Gases
- GGE: Gallon of gasoline equivalent
- GREET: Greenhouse gases, Emissions, and Energy use in Transportation
- H_2: Hydrogen
- ICEV: Internal Combustion Engine Vehicle
- LCA: Life-Cycle Analysis
- LNG: Liquefied Natural Gas
- mmBtu: Million British Thermal Unit
- MPGGE: Miles Per Gallon of Gasoline Equivalent
- MSM: Macro-Systems Model
- NG: Natural Gas
- PADD: Petroleum Administration for Defense Districts
- PHEV: Plug-in Hybrid Electric Vehicle
- RD&D: Research, Development, and Demonstration
- S/C: Steam-to-Carbon ration (mol%)
- SMR: Steam Methane Reforming
- 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

Hydropower Water Consumption



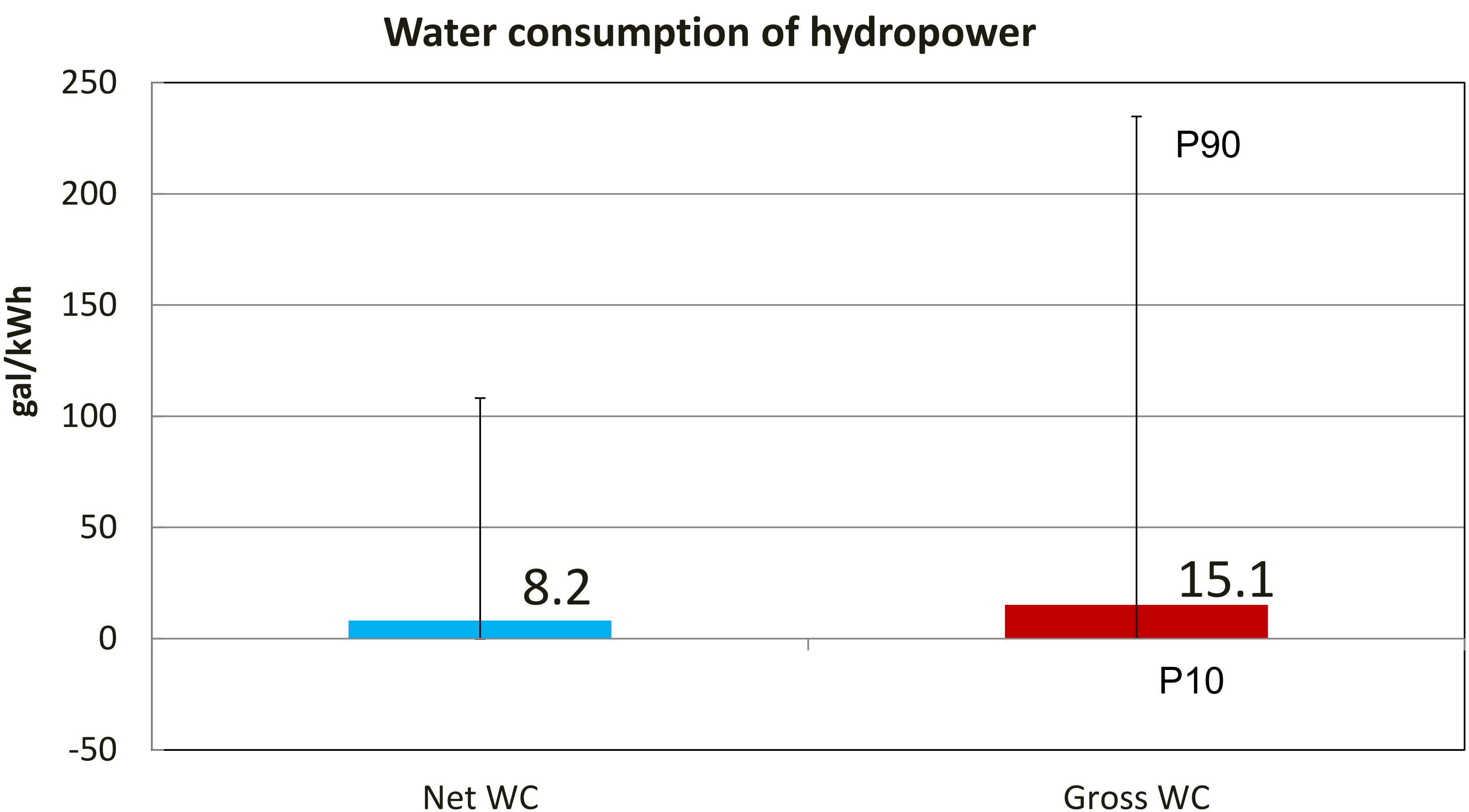
Excess storage consumes water that cannot be used downstream for other purposes

Net water consumption of 356 dedicated hydropower plants was estimated

- We focuses on dedicated hydropower plants
  - Allocation schemes for determining water consumption from multipurpose reservoirs can significantly influence reported water consumption values
- Most (94%) dedicated hydropower dams (totaling 356) have reservoirs
  - Most (83%)dedicated plants are small hydropower plants with a <30 MW capacity (small plants ~ 21% of total capacity of dedicated dams for hydropower)
  - Representing 10% of the total hydropower capacity and 15% of total generation
  - Sizes of reservoirs vary significantly
- Multiple-station measurement of state-specific pan evaporation was used to estimate gross evaporation from reservoirs
  - Adjusting pan evaporation by a 75% correction factor
  - Gross (corrected) evaporation ranges from ~11 to ~251 inches a year
- State-specific land evapotranspiration (ET)
  - A climate variables-dependent regression formula developed by USGS was used to estimate the ET to precipitation ratio
  - ✓ ET ranges from ~12 to ~42 inches a year across states

Sanford and Selnick, 2013, J Amer. Water Res. Assoc.

Hydropower generation weighted average net water consumption is 8.2 gal/kWh



✓ Previous estimate was 18 gal/kWh