2017 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Regional Water Stress Analysis with Hydrogen Production at Scale

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SA039

Overview

Timeline

- Start: April 2013
- End: Determined by DOE
- % complete (FY17): 70%

Barriers to Address

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

Budget

- Funding for FY16: $175K
- Funding for FY17: $175K

Partners/Collaborators

- Duke University
- U.S. Bureau of Reclamation
- U.S. Army Corps of Engineers
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

Relevance/Impact

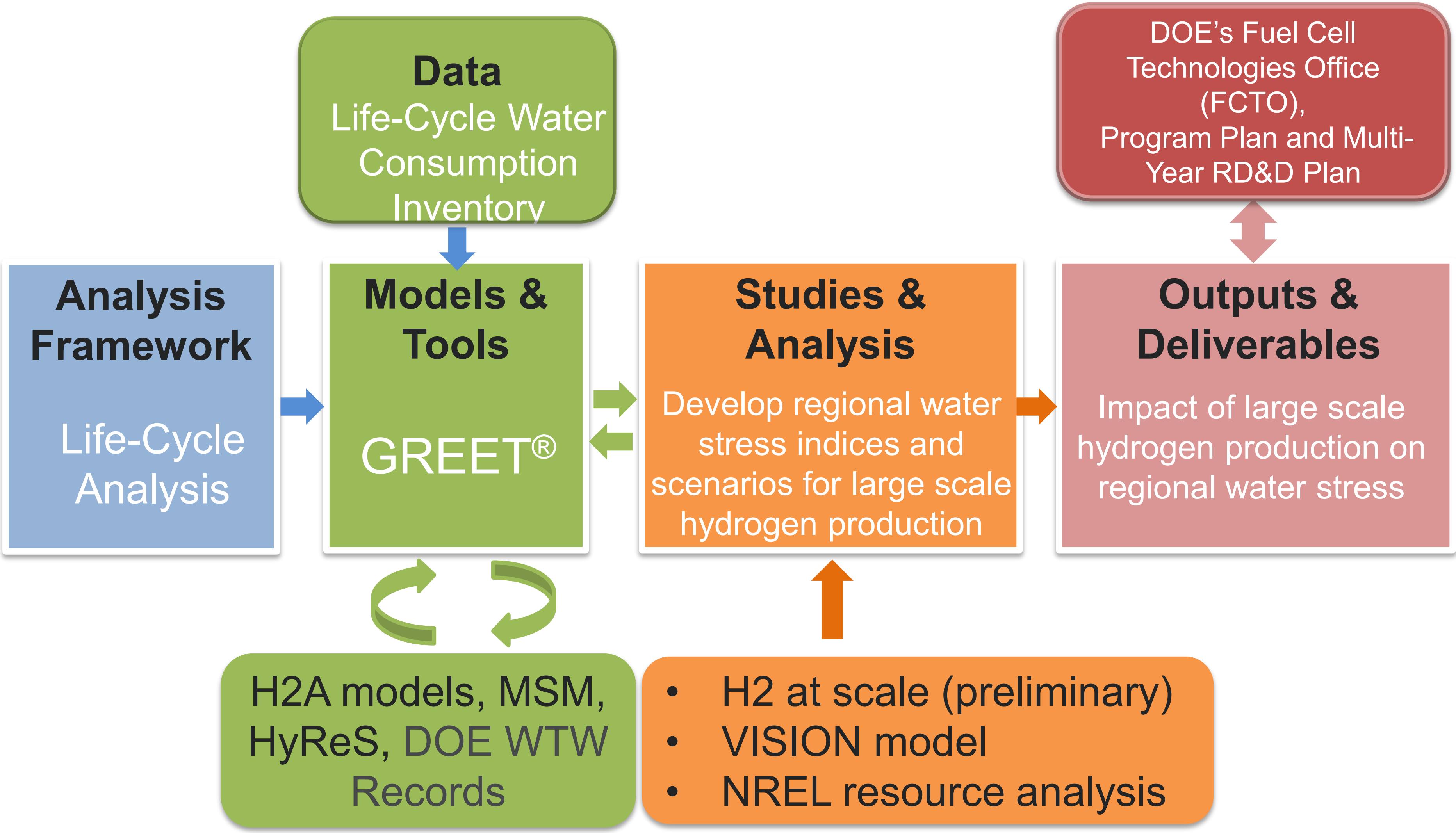
Objective: Evaluate impact of large scale hydrogen production on regional water stress considering local water supply and demand

- **Why Hydrogen?** Hydrogen is a zero-carbon energy carrier that can be produced from various domestic feedstock sources, and is important for fuel cell electric vehicles and the processing and upgrading of other fuels.

- **Evaluation of life-cycle water consumption:** Life-cycle analysis (LCA) provides a consistent accounting of freshwater consumption for the production of various fuels along their supply chain.
  - Life cycle water consumption needs to be evaluated for hydrogen pathways for comparison with other fuel pathways (e.g., biofuels and electricity for plug-in electric vehicles).

- **Developing water stress indices for regional impact analysis of large scale H_2 production:** The impact of hydrogen production on water stress in different regions is important for evaluating the sustainability of large scale H_2 production and use in various applications.

LCA of water consumption for hydrogen production pathways and regional impact analysis – Relevance



GREET is used to evaluate life-cycle water consumption and its regional impacts – Approach

- GREET accounts for freshwater consumption for various vehicle/fuel systems along the supply chain of fuel production from its feedstock source.
- FCTO supported water LCA of hydrogen and baseline fuels production pathways.

GREET

Life-cycle Inventory

- Evaluate water consumption factors by region for alternative fuel technologies, including hydrogen production technologies.

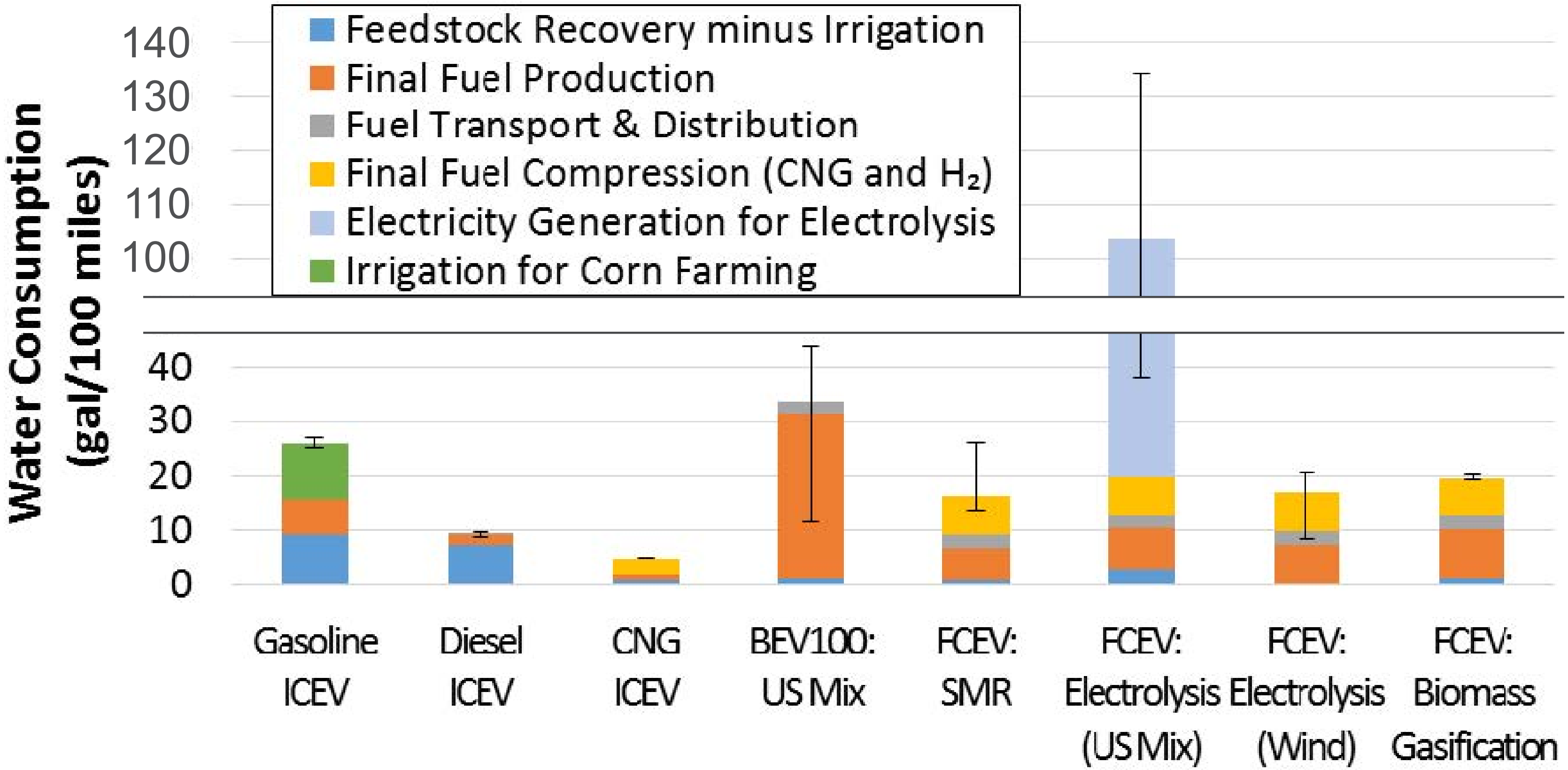
Regional Water Consumption

- Examine large scale hydrogen production scenarios leading to additional regional water consumption

Impact Analysis

- Develop a baseline, county-level, water stress index that includes water supply and demand.
- Evaluate impact of large scale hydrogen production on the regional water stress.

Life-cycle water consumption of various transportation fuels is dominated by electricity use – FY16 Accomplishment



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

Source: https://www.hydrogen.energy.gov/pdfs/review16/sa039_elgowainy_2016_o.pdf

What if H_2 is deployed at scale in various region? Impact analysis on water resources – Approach

Water consumption for H_2 production (process-level)

- Water consumed by electrolysis and steam methane reforming
- Upstream water consumption

Regional baseline water supply and demand

- Surface /groundwater supply
- Water demand (human and environmental water demand)

Regional water consumption for H_2 production at scale

Regional water impact analysis

Regional H_2 demand scenarios for fuel cell vehicles

- H_2 Fuel cell vehicle deployment scenarios by region
- Fuel economy

H_2 production technologies by region

- Resource availability (natural gas / wind / solar / nuclear)

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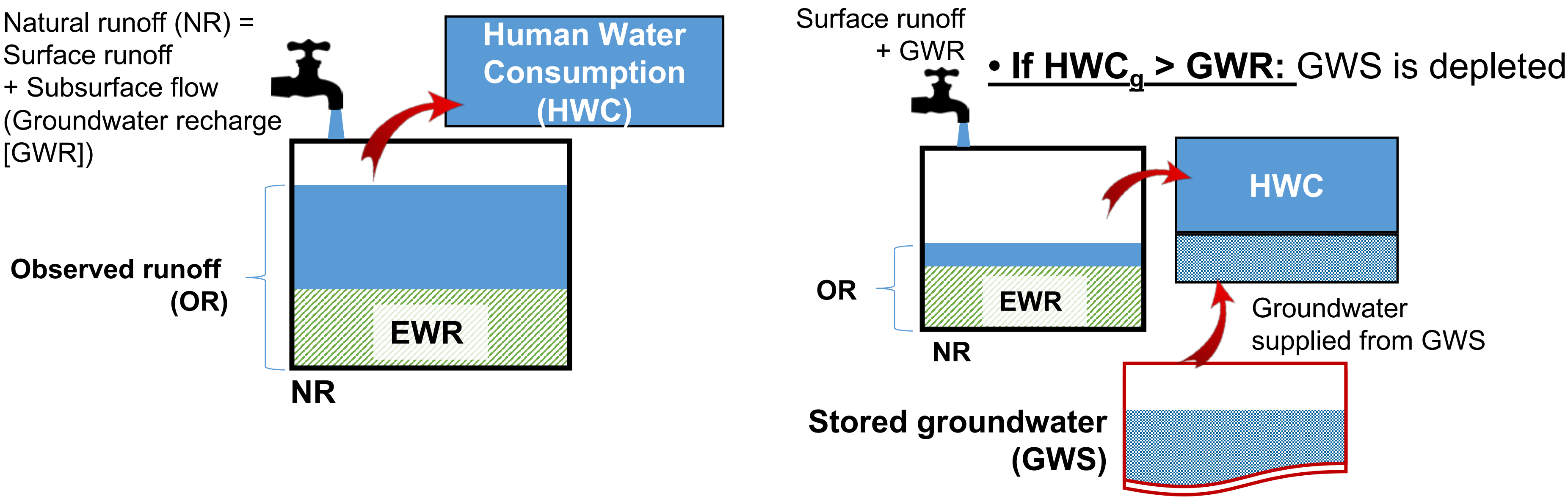
Definitions of water supply and demand – Approach

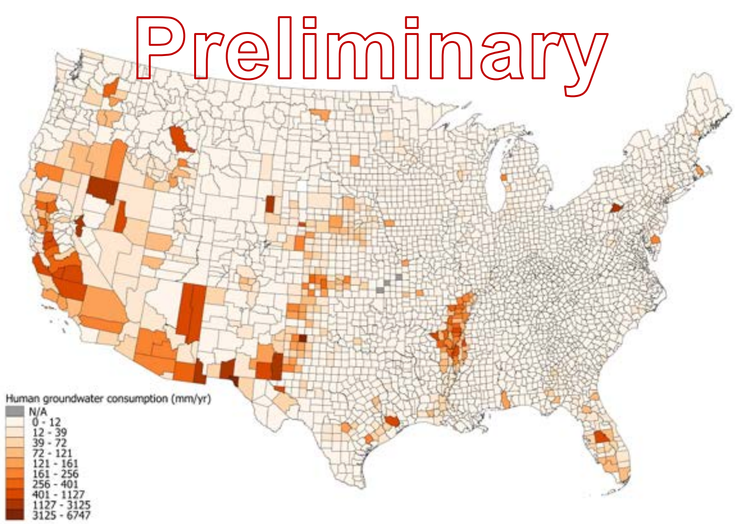


- Definitions for water supply and demand (unit: mm/year)
  - HWC: Human water consumption for irrigation, public water supply, and power generation, etc.
    - ✓ HWC_g = the portion of HWC supplied from groundwater (GWR and GWS)
  - NR: water supply which is sustainably available for HWC and EWR
    - ✓ NR = observed runoff + HWC
    - ➢ NR = observed runoff + HWC – (HWC_g – GWR) → in arid regions for indexing purposes where (HWC_g – GWR) is supplied from GWS (not sustainable)
  - EWR: Environmental water requirement (to maintain freshwater ecosystems)
- Stored (fossil) groundwater (GWS) can be depleted → it is not a sustainable resource for water supply

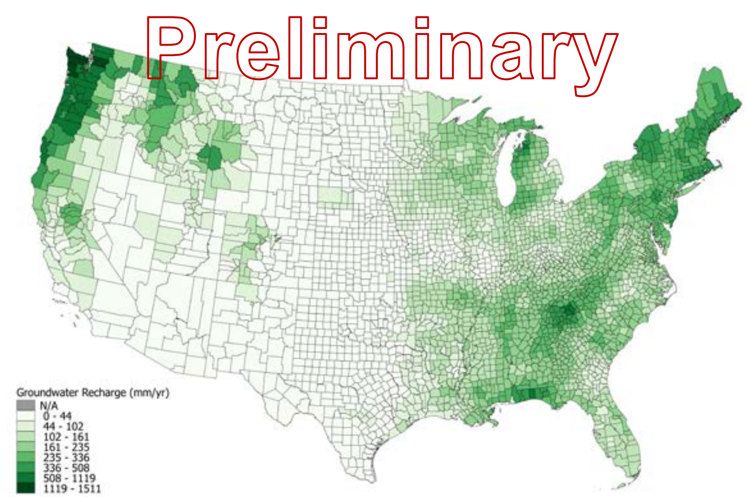
Evaluated groundwater supply and demand – Accomplishment

- GWR is estimated as a fraction of NR
- Groundwater is excessively used where NR-EWR-HWC < 0
- Groundwater recharge (renewable groundwater) and demand do not regionally match, which depletes stored groundwater when HWC_g > GWR

Human groundwater consumption (HWC_g)	Groundwater recharge (GWR) – Renewable groundwater



Based on USGS water use data



Fractions of mean annual runoff (1951-1980) (Wolock 2003, Gebert et al. 1987)

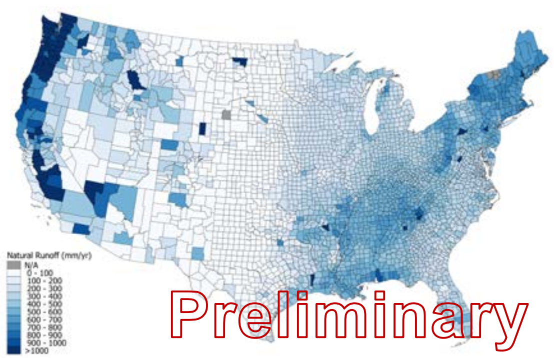
Evaluated remaining available water resources by region using measured data – Accomplishment

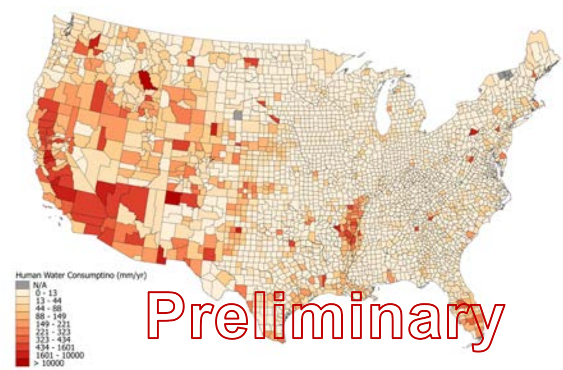
- Remaining water (rechargeable water supply – demand) in each county shows relative water-stress characterized by AWARE index

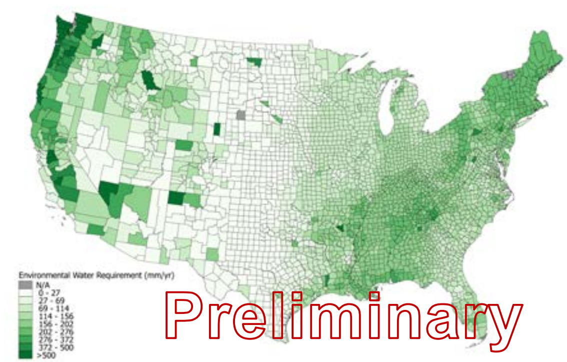
$$\text{AWARE index}^{*} = \frac{1}{\text{Remaining water available}} = \frac{1}{(\text{NR} - \text{HWC} - \text{EWR})}$$

* Normalized for each county by HWC weighted U.S. average

Supply	Demand	
Natural runoff (NR)	Human water consumption (HWC)	Environmental water requirement (EWR)







Estimated using USGS reported HUC-8 level observed runoff and county level HWC data (annual average using monthly data from 1970 to 2015).

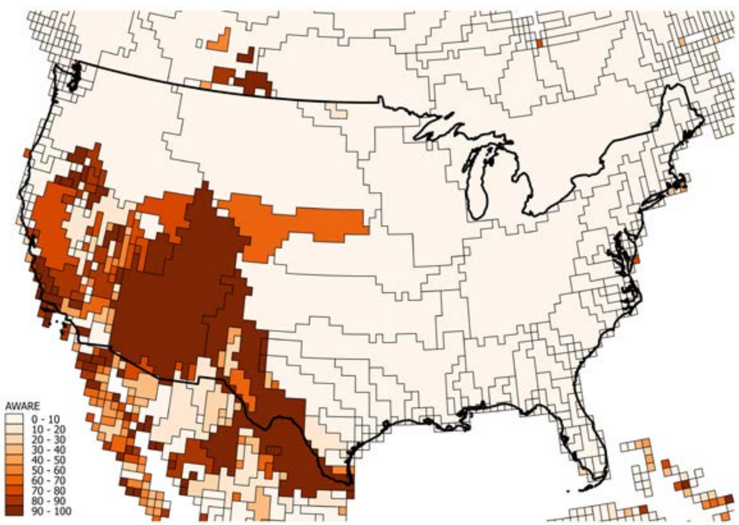
Calculated using USGS 2010 water withdrawal data applying consumption % average 1980-1995)

Estimated as a monthly fraction of average NR (Pastor et al. 2014; Moore et al. 2015), aggregated to annual

AWARE: Available WAter Remaining

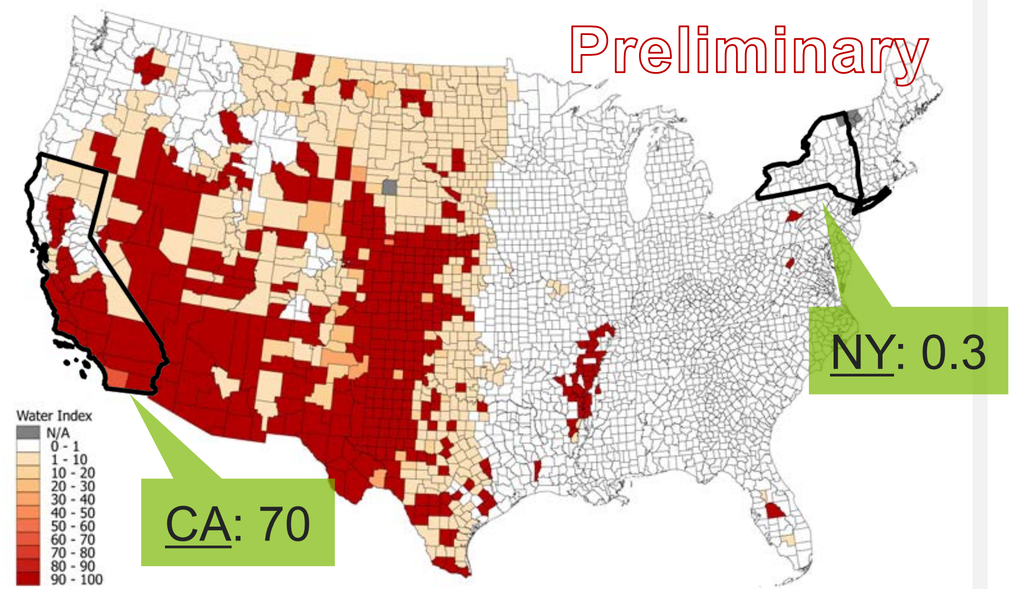
Evaluated a county-level baseline stress-based water index for the impact analysis – Accomplishment

Current AWARE index



- Calculated based on water-balance simulation model
- Low resolution (watershed level)
- Normalized by world average

Water index by ANL



- Based on measured data
- Better resolution (county level)
- Normalized by HWC weighted U.S. average

✓ **Any marginal increase in water demand in high water index - regions (e.g., CA) will magnify its impact on water stress -**

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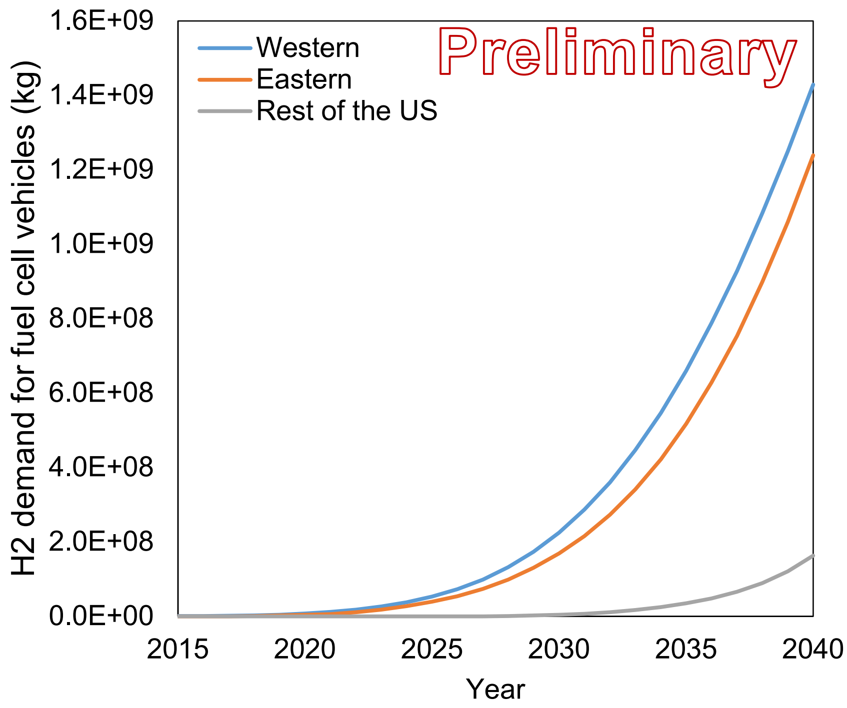
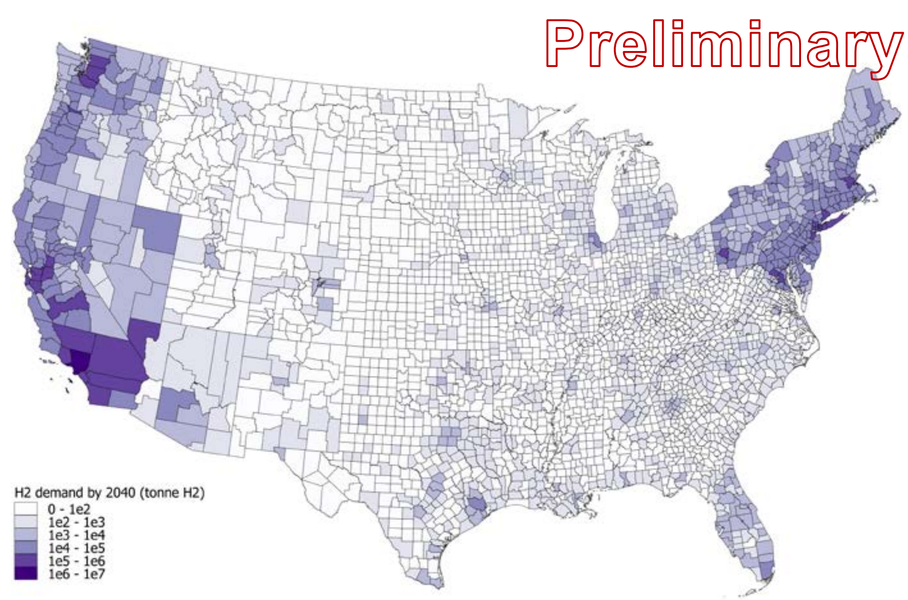
Developed H_2 demand scenarios for fuel cell vehicles by 2040 – Accomplishment

- H_2 demand scenarios for fuel cell vehicles by state by 2040 (VISION model)
  - Deployment of H_2 fuel cell vehicles may vary by region
  - Fuel economy is expected to be improved over time
- Disaggregated H_2 demand from state level to county-level based on population

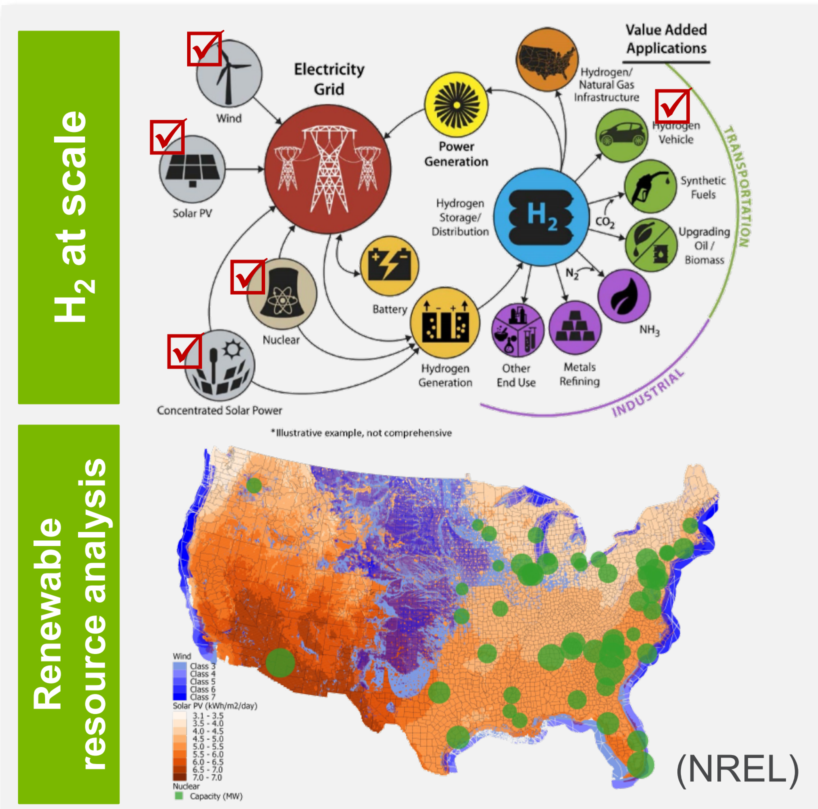


Total H_2 demand by 2040

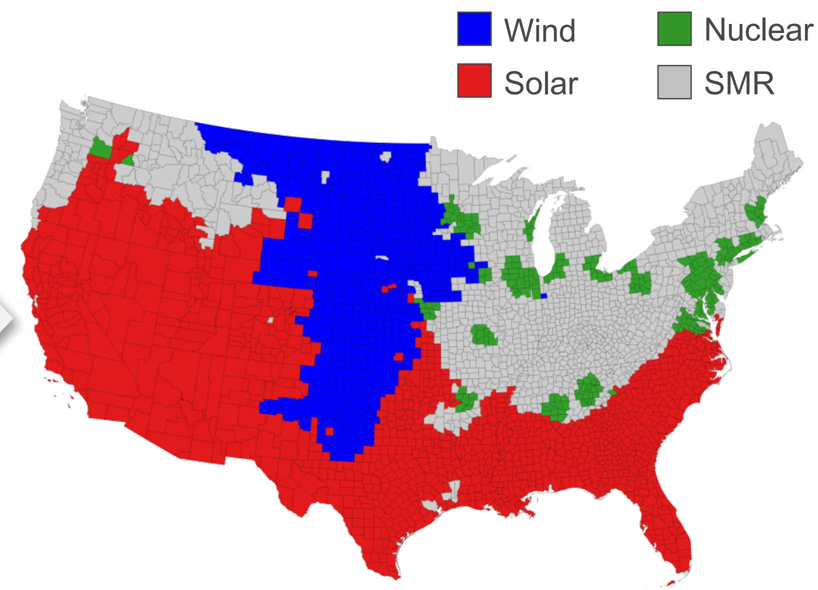


Developed H_2 production scenarios based on H_2 at scale and NREL resource analysis – Accomplishment

- Electricity (wind/solar/nuclear) is used for renewable H_2 production
- Steam methane reforming (SMR) of natural gas is used where renewable resources are not available



H_2 production scenarios



- H_2 production scenarios are generated - based on the resource availability and demand -

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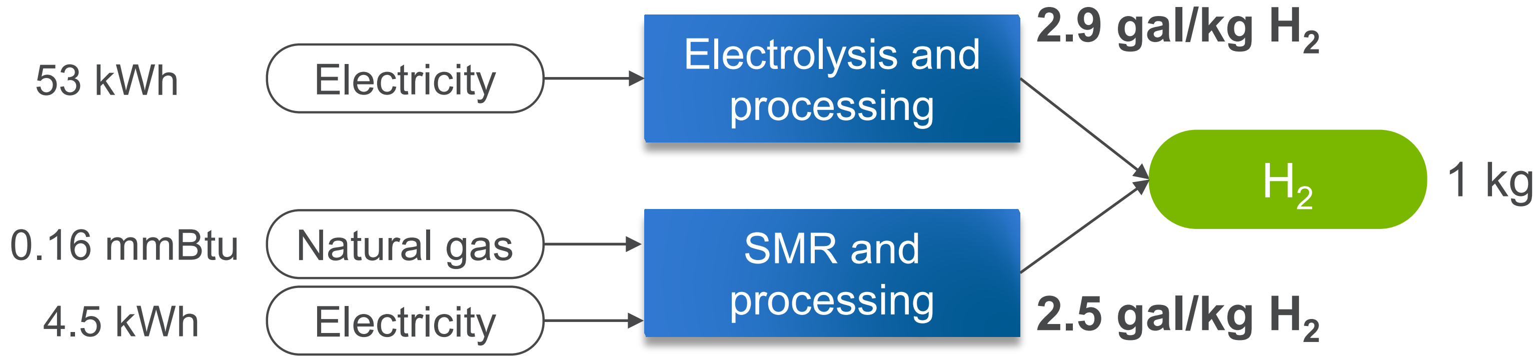
Evaluated life-cycle water consumption for H_2 production pathways – FY16 Accomplishment

- Water consumption for H_2 production



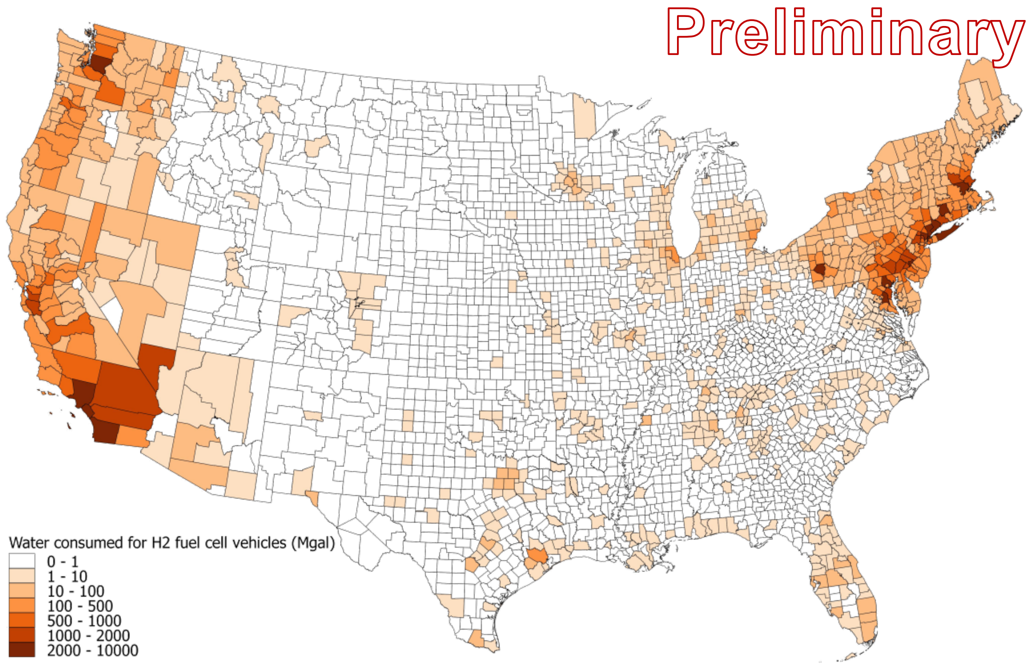
- Upstream water consumption factors

Input energy		WCF
Renewable electricity	Wind	0.001 gal/kWh
	Solar photovoltaics	0.018 gal/kWh
	Nuclear	0.34 gal/kWh
Natural gas		4.7 gal/mmBtu

- WCFs for H_2 production pathways are within a narrow range

Significant regional variation exists for water consumed for fuel cell vehicles – Accomplishment

- The most influential driver for the regional variation is the differences in the number of deployed fuel cell vehicles
  - Types of H_2 production pathways (scenarios) and fuel cell vehicles' fuel economy do not notably change the regional variation trend

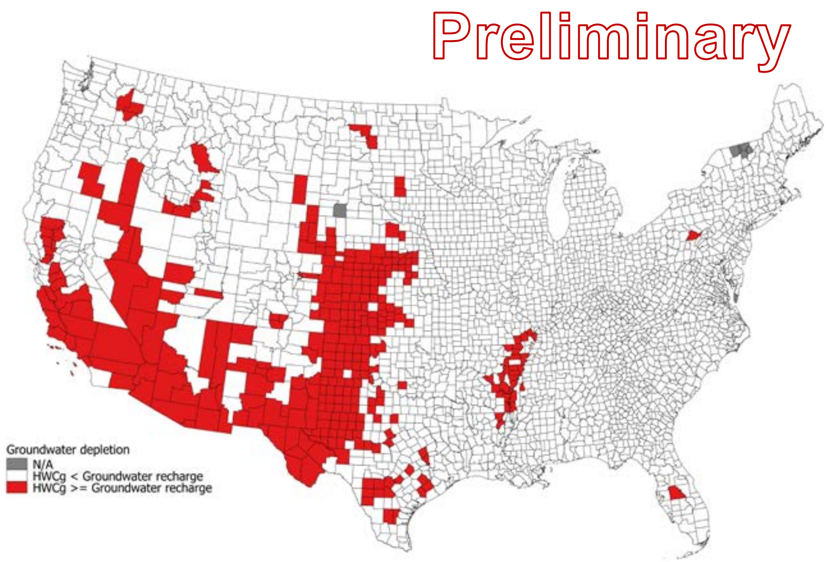


- Water consumed for H_2 production may pose additional burden in water-stressed regions

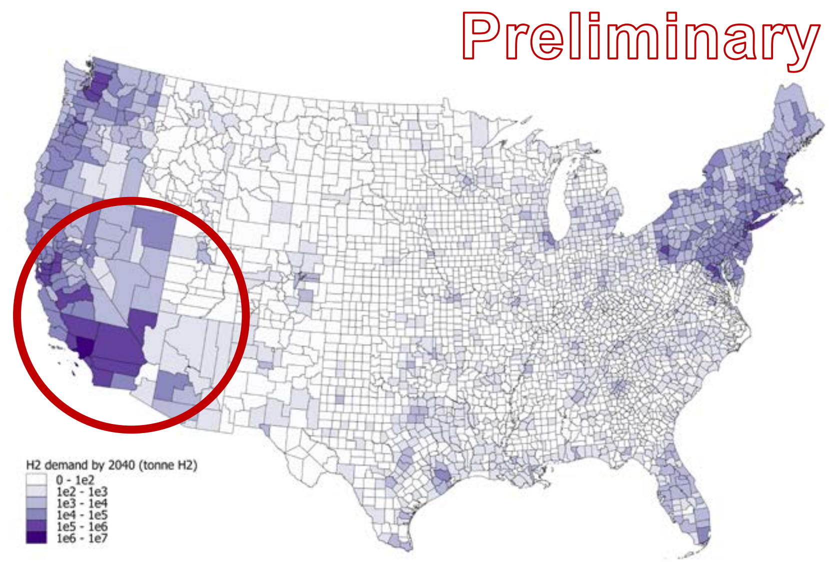
Need hydrogen production pathways with low or no water consumption in water stressed regions – Accomplishment

- Groundwater depletion is expected where groundwater consumption is greater than recharge
  - H_2 production in these regions incur additional groundwater depletion using current H_2 production pathways

HWC_g > GWR



H2 demand



- Possible H_2 production pathways with low freshwater consumption (e.g., tri-generation CHHP system)

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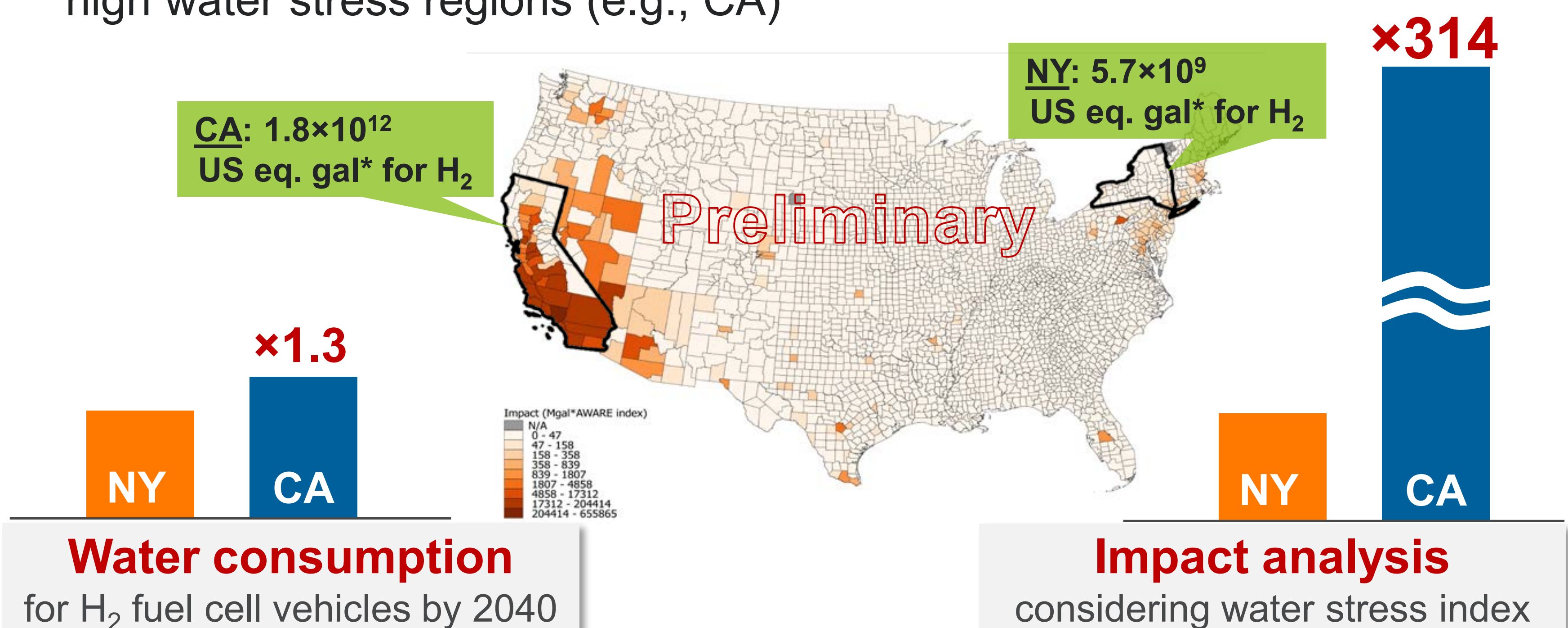
Need to minimize additional water consumption in water-stressed regions – Accomplishment

- Water consumption for large scale deployment of H_2 fuel cell electric vehicles is marginal compared to HWC (CA: 0.046%, NY: 0.038%)
- Two scenarios:
  1. Water for H_2 FCEVs displaces water for gasoline ICEVs → no impact on water stress (see slide 6)
  2. Water for H_2 FCEVs is additional to water for gasoline ICEVs → impact in high water stress regions (e.g., CA)



* US eq. gal = marginal water consumption in a region x regional water index

Summary – Accomplishment

- **Updated AWARE model with U.S. measured water runoff and ground water data at the county level**
  - Developed a version of AWARE that is U.S. centric for regional water stress impact analysis associated with major deployment of fuel/vehicle Systems
- **Evaluated county-level water index for regional impact analysis**
  - Evaluated surface and ground water supply and demand
  - Evaluated relative water stress by region using calculated remaining water (supply – demand) in each county, normalized by U.S. average
- **Estimated H_2 demand and associated water consumption for H_2 fuel cell vehicles by 2040**
  - Examined process-level water consumption factors for H_2 production
  - Developed scenarios for fuel cell vehicles deployment by region
  - Developed regional H_2 demand scenarios using VISION
  - Estimated county-level water consumption for H_2 fuel cell vehicles based on previous ANL water inventory analysis and NREL's energy resource analysis
- **Performed water stress impact analysis associated with large scale deployment scenarios of H_2 fuel cell vehicles**
- **Any increase in marginal water demand in high water index regions (e.g., CA) will magnify its impact on water stress**

Collaborations and Acknowledgments

- Allocation of water consumption for multipurpose reservoirs
  - Bureau of Reclamation (David Raff, Kenneth Nowak, Clark Bishop, and Max Spiker), Oak Ridge National Laboratory (Rocio Uria Martinez), U.S. Army Corps of Engineers (Chandra Pathak) provided critical guidance for allocating water consumption of multipurpose reservoirs to hydropower

- H_2 demand for fuel cell vehicles
  - ANL's VISION model (Joann Zhou and Anant Vyas) supported to estimate H_2 demand for fuel cell vehicles by 2040

- Water index development
  - Duke University (Jesse Daystar) evaluated environmental water requirement
  - PNNL (Andre Coleman) provided weighting factors by sector/region used to disaggregate annual human water consumption into county level

Future Work

- Expand life-cycle water consumption inventory
  - Continue development and implementation of regional water consumption factors of other hydrogen and alternative fuel pathways in GREET
  - Revisit previously studied baseline fuel production pathways to consider regional variation (e.g., petroleum and natural gas recovery and refineries)
  - Examine alternative hydrogen pathways with low or no water consumption (e.g., tri-generation CHHP systems)
  - Develop water consumption factors for chemicals and vehicle materials (GREET2) for full LCA
- Address outstanding regional and water stress indexing issues
  - Impact analysis for existing baseline fuels (non-marginal)
  - Evaluate uncertainty of key parameters impacting water stress index calculations, including possible double-counting from displaced products
- Document data and analysis in peer-reviewed publication
- Develop a regional module in GREET with county level water index data to evaluate impact of large scale deployment of alternative fuel/vehicle systems
- Release updated GREET model and publications to public for broader utilization of the deliverables of this project

Project Summary

- **Relevance**: The impact of hydrogen production on water stress in different regions is important for evaluating the sustainability of large scale H2 production and use in various applications.
- **Approach**: Develop water consumption factors for various hydrogen production pathways, and develop regional water stress index using water supply and demand at the county level for impact analysis
- **Collaborations**: Sought data and guidance from the experts (national labs/ government agencies/ academia/ US DRIVE technical teams)
- **Technical accomplishments and progress**:
  - Developed water consumption factors for various hydrogen production pathways
  - Developed a U.S. centric version of AWARE model with measured data for water stress indexing at the county level
  - Developed scenarios for regional demand for H_2 fuel cell vehicles and calculated associated freshwater consumption
  - Examined regional water stress impacts for large scale H_2 production scenarios
- **Future Research**:
  - Expand life-cycle water consumption inventory
  - Address outstanding regional and water stress indexing issues (non-marginal and uncertainties)
  - Expand GREET with regional data and document analysis in peer-reviewed publications

Acronyms

- AMR: Annual Merit Review
- ANL: Argonne National Laboratory
- AWARE: Available WAter REmaining
- CA: California
- CF: Characterization Factor
- CHHP: Combined Hydrogen, Heat and Power
- DOE: Department of Energy
- EIA: Energy Information Administration
- EPA: Environmental Protection Agency
- EWR: Environmental Water Requirement
- FCTO: Fuel Cell Technologies Office
- FY: Fiscal Year
- GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportaiton
- H_2: Hydrogen
- H2A: Hydrogen Analysis
- HUC: Hydrologic Unit Code
- HWC: Human Water Consumption
- LCA: Life-Cycle Analysis
- MSM: Macro-System Model
- NR: Natural Runoff
- NREL: National Renewable Energy Laboratory
- NY: New York
- ORNL: Oak Ridge National Laboratory
- PNNL: Pacific Northwest National Laboratory
- SMR: Steam Methane Reforming
- US eq. gal: U.S. equivalent gallon
- USACE: United States Army Corps of Engineers
- USGS: United States Geological Survey
- WCF: Water Consumption Factor

Technical Backup Slides

Analyzed regional life-cycle water consumption for electricity generation – Approach

Previous studies on water for electricity

- Facility-level
- National-level
- by technology types

Current project

Regional water consumption

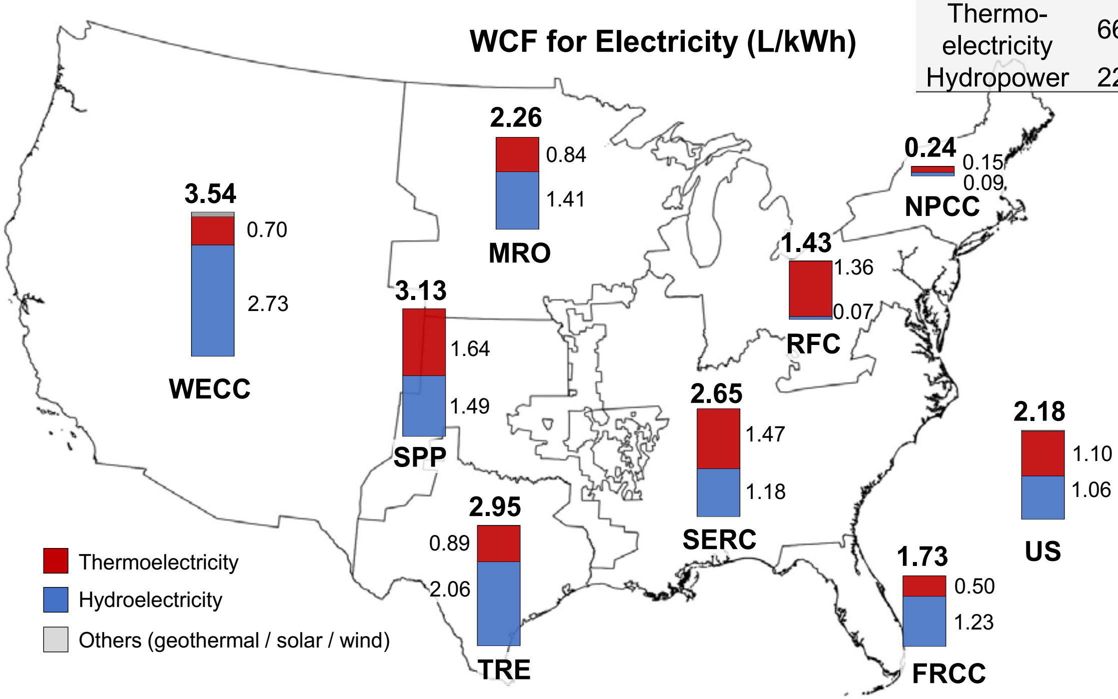
- Water supply and demand balance are of regional concern
- Evaluated regional water consumption factors for hydro and thermal electricity generation
  - Parameters: climate and geographical conditions, competing uses, and employed technologies influenced by policy, economy, and available resources
  - Data Sources: Open literature, EPA, EIA, USGS, USACE, Modeling of physical processes

Evaluated regional WCF for electric power generation – Accomplishment

- Hydroelectricity contributes 50% of water consumption for electricity generation, while it generates only 6.3% of electricity in the U.S.
- Water-stressed regions have relatively low thermoelectricity WCF even with high recirculating cooling share (high efficiency / non-freshwater use)
- WCF depends on electricity generation share and WCF for each region

NERC	WECC	MRO	SPP	TRE	NPCC	RFC	SERC	FRCC	US
Thermo-electricity	66%	77%	82%	90%	83%	96%	96%	98%	87%
Hydropower	22%	5.2%	1.8%	0.2%	13%	1.1%	3.4%	0.7%	6.3%

Power Generation Share



Valuable information for regional analysis of various fuel production pathways