Water Resource Impacts Embedded in the Western US Electrical Energy Trade; Current Patterns and Adaptation to Future Drought

WRRC

University of Arizona

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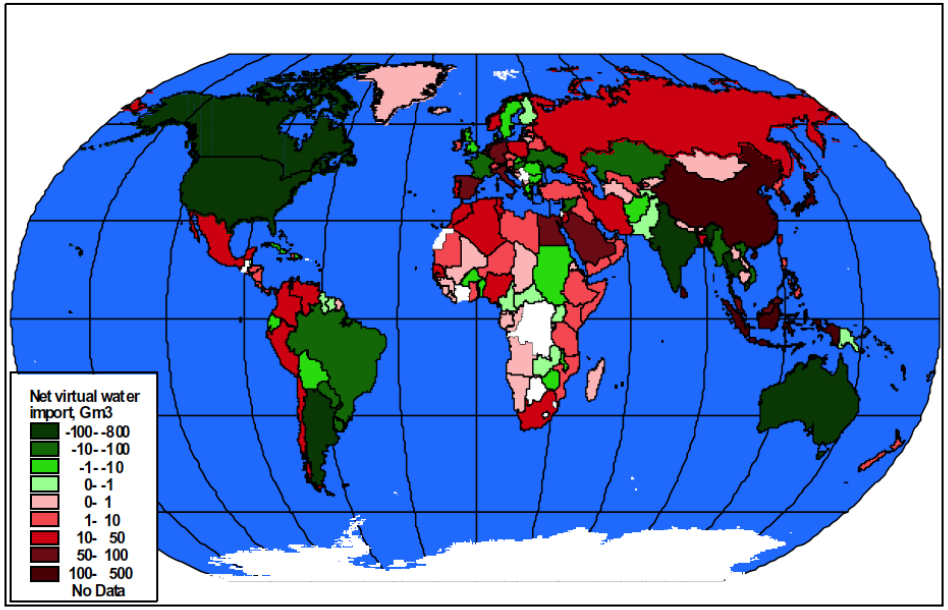
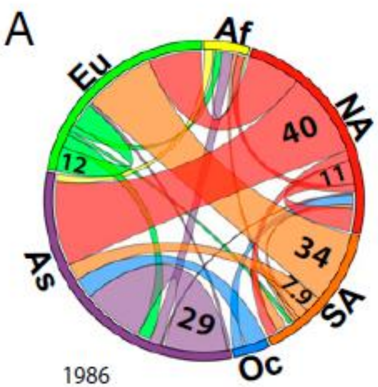
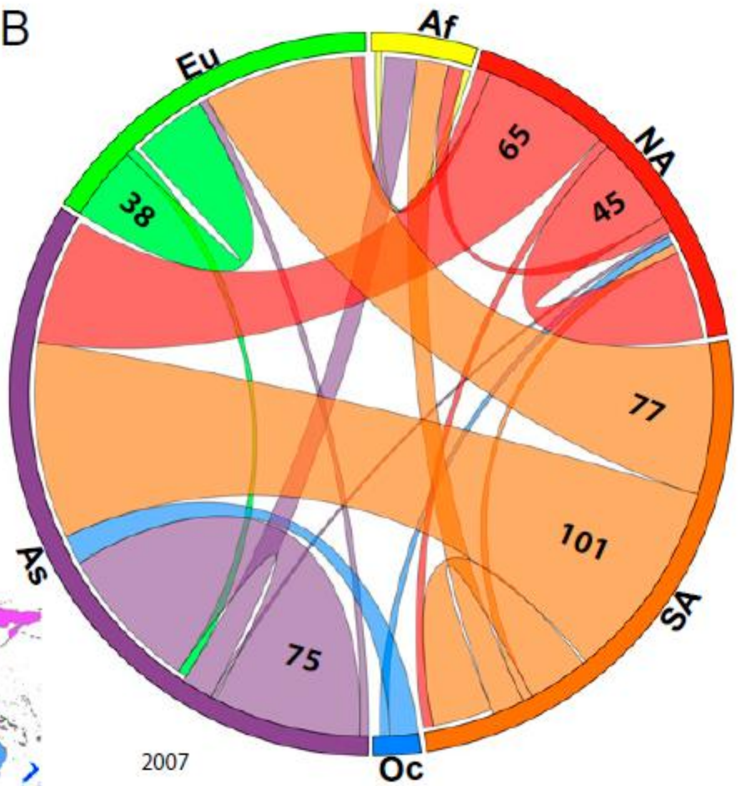
(change in)
Global Virtual Water Trade

A Signature of (increasingly) Complex Water-Economy Interactions



Hoekstra and Chapagain (2007)





Dalin et al., 2012

Virtual Water is THE major adaptive mechanism to water scarcity worldwide… just at trade in products derived with the service of scarce resources is the major adaptive mechanism to ALL types of resource scarcity. This is a hydrologist's way of understanding economic trade.

Embedded Resource Impact Accounting (ERA): A network theory for complex CNH's (Liu et al., 2007)

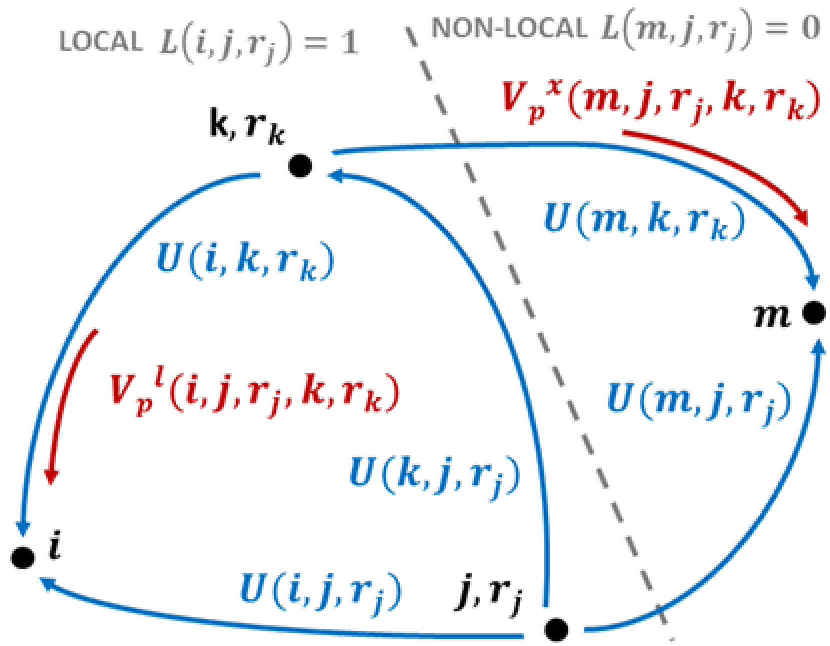
Net Systemic Impact (footprint) of a Process, E: the sum of the Direct (U) and indirect (V) network impacts of a process on a stock of interest, conditioned on a local/external (*l/x*) boundary

$$E = U^l + U^x + V_{IN}^l - V_{OUT}^l + V_{IN}^x - V_{OUT}^x$$

"Virtual Water" (Allan, 1993) is a special single-type network case of ERA. ERA is related to Input-Output and Life Cycle Analysis, which are also network concepts.

The foundation of ERA is the *partial embedded resource impact* V_p; the sum across intermediaries k and r_k is the net indirect impact V

$$V_p(i,j,r_j,k,r_k) = \frac{U(i,k,r_k)}{\sum_n U(n,k,r_k)} * U(k,j,r_j)$$



Western Power Grid: State Level Data

	Water Intensity (gal/MWh)	Price ($/MWh)
New Mexico	437.25	$103.56
Utah	411.77	$81.35
Wyoming	384.17	$85.57
Colorado	352.66	$100.26
Nevada	349.23	$80.10
Montana	297.32	$81.57
Arizona	183.81	$86.23
California	129.69	$125.26
Idaho	83.31	$62.91
Oregon	82.04	$67.65
Washington	52.52	$61.65

Water intensities calculated using *Sandia National Laboratory Energy/Water Nexus Group* data, for year 2009, of total electricity production reported by plants and estimated net water consumption at each power plant within each state (Tidwell et al. 2012, EPA 2010, EIA 2005, Kenny et al. 2009, Macknick et al. 2011, Solley et al.1995)

Prices are 2009 averages of retail electric utility prices for all utilities within each state obtained from US Energy Information Administration (EIA 2011a)

- High prices = high demand, limited supply, high costs of electricity generation
- Low water consumption intensity = water scarcity/conservation

Western Power Grid: Interstate Trade Estimation

	Net Interstate Trade, (MWh)	Gross Export, (MWh)	Gross Export Coefficient, (%)
Arizona	31,685,245	31,685,245	31.3%
Montana	5,775,543	5,775,543	5.7%
New Mexico	15,700,958	15,700,958	15.5%
Nevada	1,65[illegible]	[illegible]	[illegible]
Oregon	5,07[illegible]	[illegible]	[illegible]
Utah	12,38[illegible]	[illegible]	[illegible]
Washington	2,117,039	2,117,039	2.1%
Wyoming	26,882,529	26,882,529	26.5%
		Gross Import, (MWh)	**Gross Import Coefficient, (%)**
California	(84,137,000)	84,137,000	83.1%
Colorado	(4,815,000)	4,815,000	4.8%
Idaho	(12,333,000)	12,333,000	12.2%

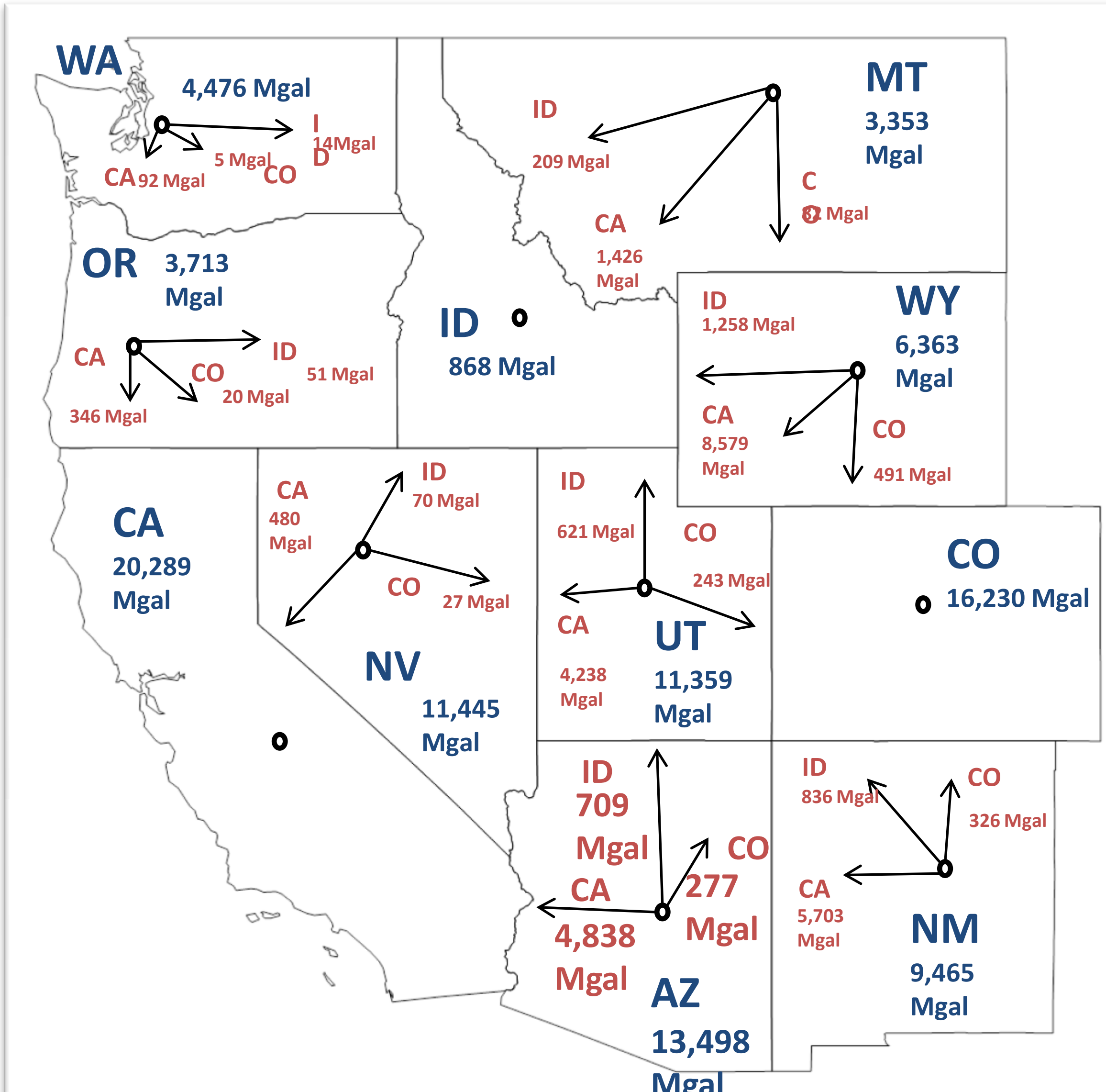
Scott and Pasqualetti (2010) Reported Gross export of electricity from Arizona = 30,750,700 MWh.

- Trade data is for 2009 using EIA data tables
- Net Trade is taken as **production – consumption** within each state
- Total exports must equal total imports summed across network
- Assumed 1% reduction in exports due to export to neighboring grid(s)

(EIA 2011a, EIA 2011b)

Transfer quantities between states = (Exporting state Net Trade) * (Importing state Import Coeff)

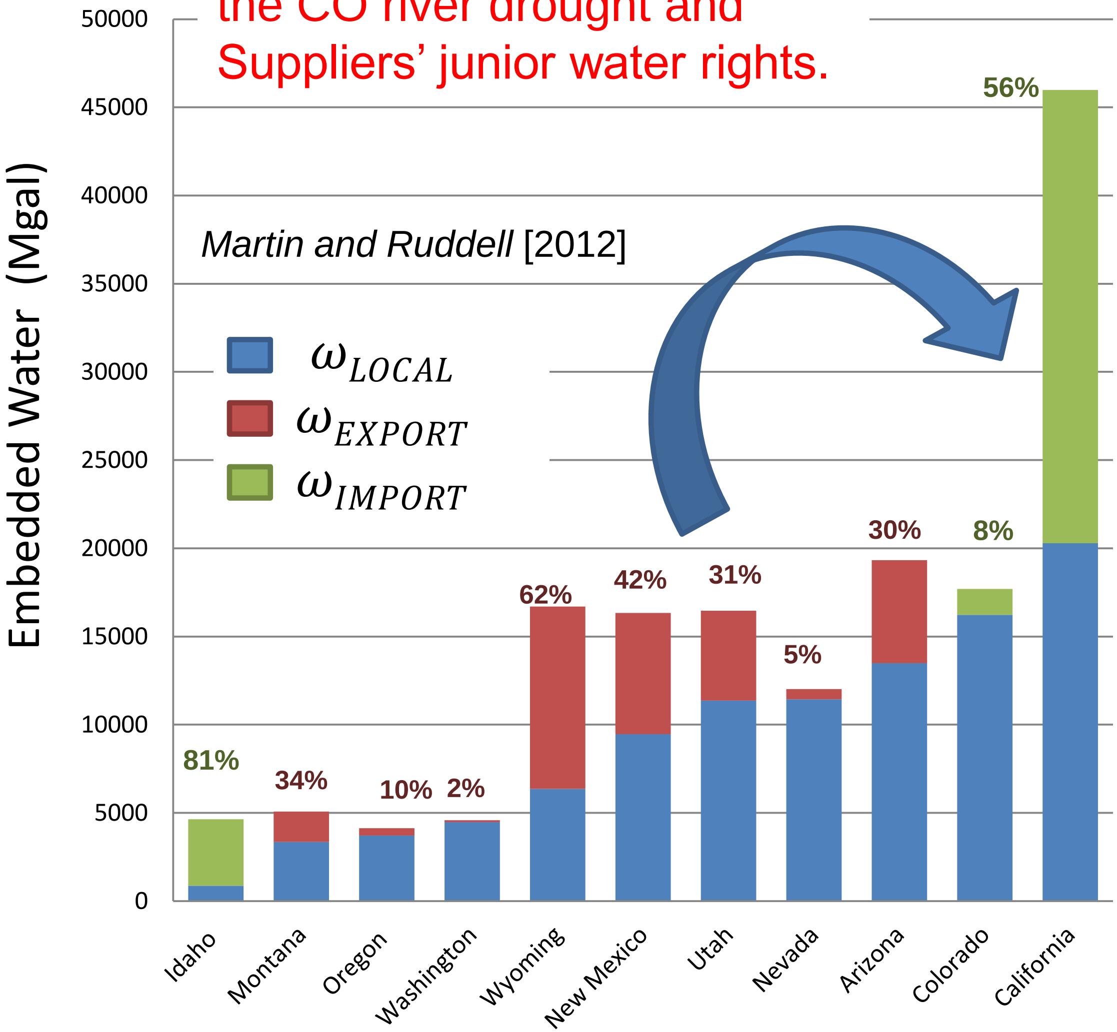
Virtual Water Embedded in the Electrical Power Grid in the Western USA: Outsourcing Water Impact via Power

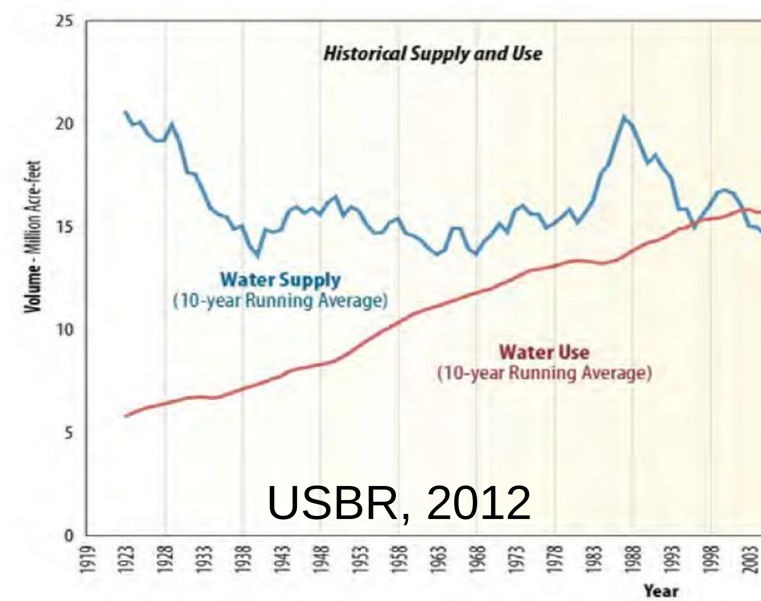


Ruddell et al., in review

A systematic shift of water impacts (and emissions) from California to energy exporters like WY and NM

A risky strategy for CA, given the CO river drought and Suppliers' junior water rights.

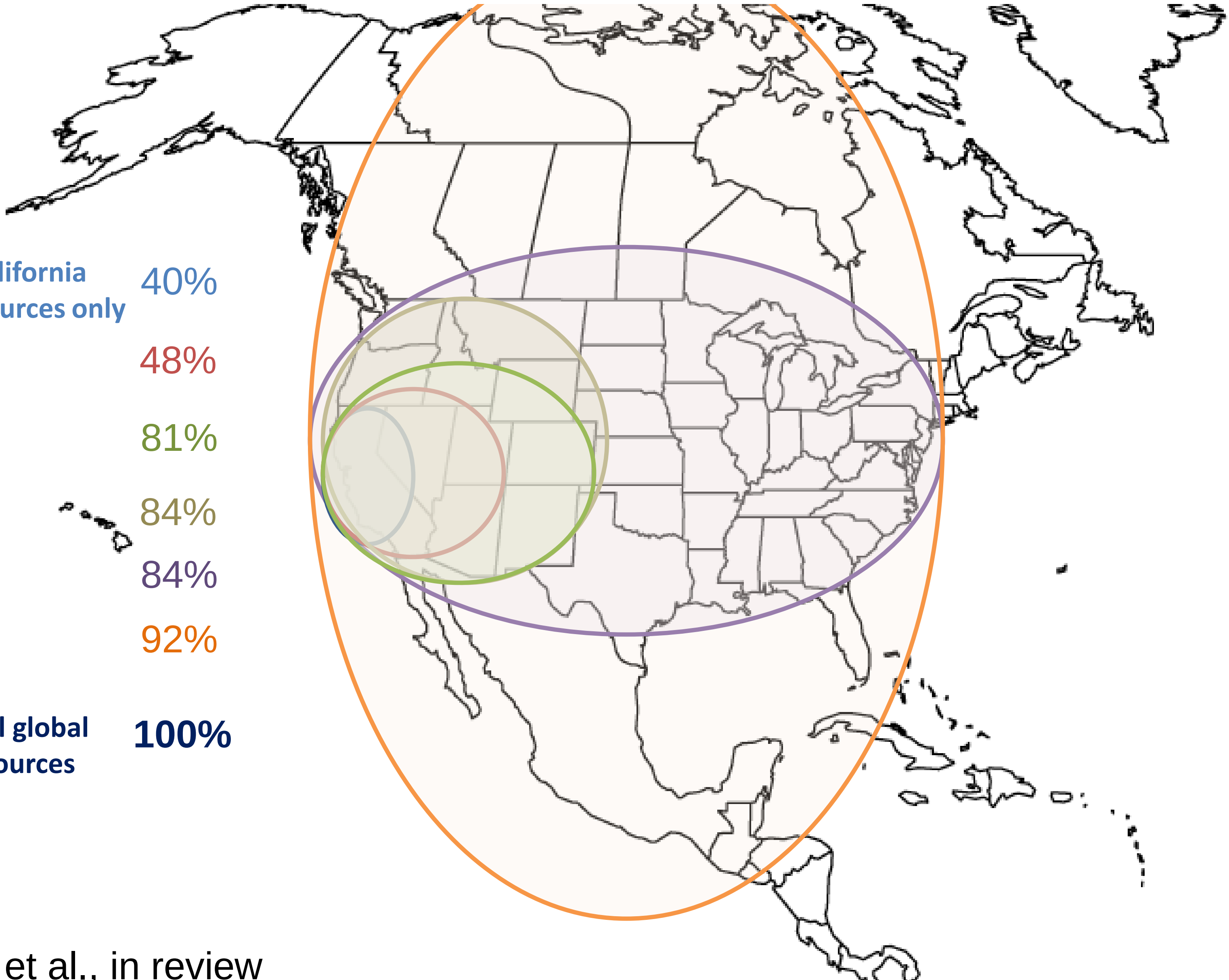




Water Savings through trade in electricity on the power grid

	U (Mgal) Actual	V (Mgal) Actual	E (Mgal) U + V	U' (Mgal) If-local	RS (Mgal) U' - E	RS (%) RS/U'
Arizona	19322	-5824	13498	13498	0	0
California	20289	25703	45992	31200	-14792	-47%
Colorado	16230	1471	17701	17928	227	1%
Idaho	868	3768	4636	1896	-2740	-145%
Montana	5070	-1717	3353	3353	0	0
New	16330	-6865	9465	9465	0	0
Nevada	12023	-578	11445	11445	0	0
Oregon	4129	-417	3713	3713	0	0
Utah	16461	-5102	11359	11359	0	0
Washington	4587	-111	4476	4476	0	0
Wyoming	16690	-10328	6363	6363	0	0
System	**132000**	**0**	**132000**	**114695**	**-17304**	**-15%**

How does the water footprint of California's energy use change as the network boundaries change?



Q=1 for California water resources only 40%

48%

81%

84%

84%

92%

Q=1 for all global water resources **100%**

Adams et al., in review

Making Sense of Multitype CNH Networks (or, Why Does Virtual Water Flow?)

hint: it's not gravity…

A derivative of ERA, Dollar Intensities, DI, are defined by the intersection of three types of networks at a node in the process network:

- Economic Trade in a Good or Service (input/output)
- Exchange of Currency (Dollars) for said Goods and Services
- Water Resource Consumption

$$DI = \left(\frac{USD\$_{consumer}}{MWh_{consumer}}\right) \times \left(\frac{MWh_{producer}}{gal_{producer}}\right) = \left(\frac{USD\$_{consumer}}{gal_{producer}}\right)$$

This gives systemic impacts (*E*) and indirect socio-economic valuation of outsourced impacts (*DI*) using multitype CNH network analysis

Imagine other types of CNH intersections, like the production of a social benefit or value instead of electricity…

What Explains This Virtual Flow: Dollar Intensity

(exists where money flow, trade flow, and resource flow networks connect at a node in a multitype CNH network)

$$\left(\frac{USD\$_{consumer}}{MWh_{consumer}}\right) \times \left(\frac{MWh_{producer}}{gal_{producer}}\right) = \left(\frac{USD\$_{consumer}}{gal_{producer}}\right)$$

Retail electricity price. Function of the economic market.

Water efficiency of electricity generation. Function of the current technology.

Dollar intensity of the embedded water

(Virtual) water flows uphill toward value, in this case $$$

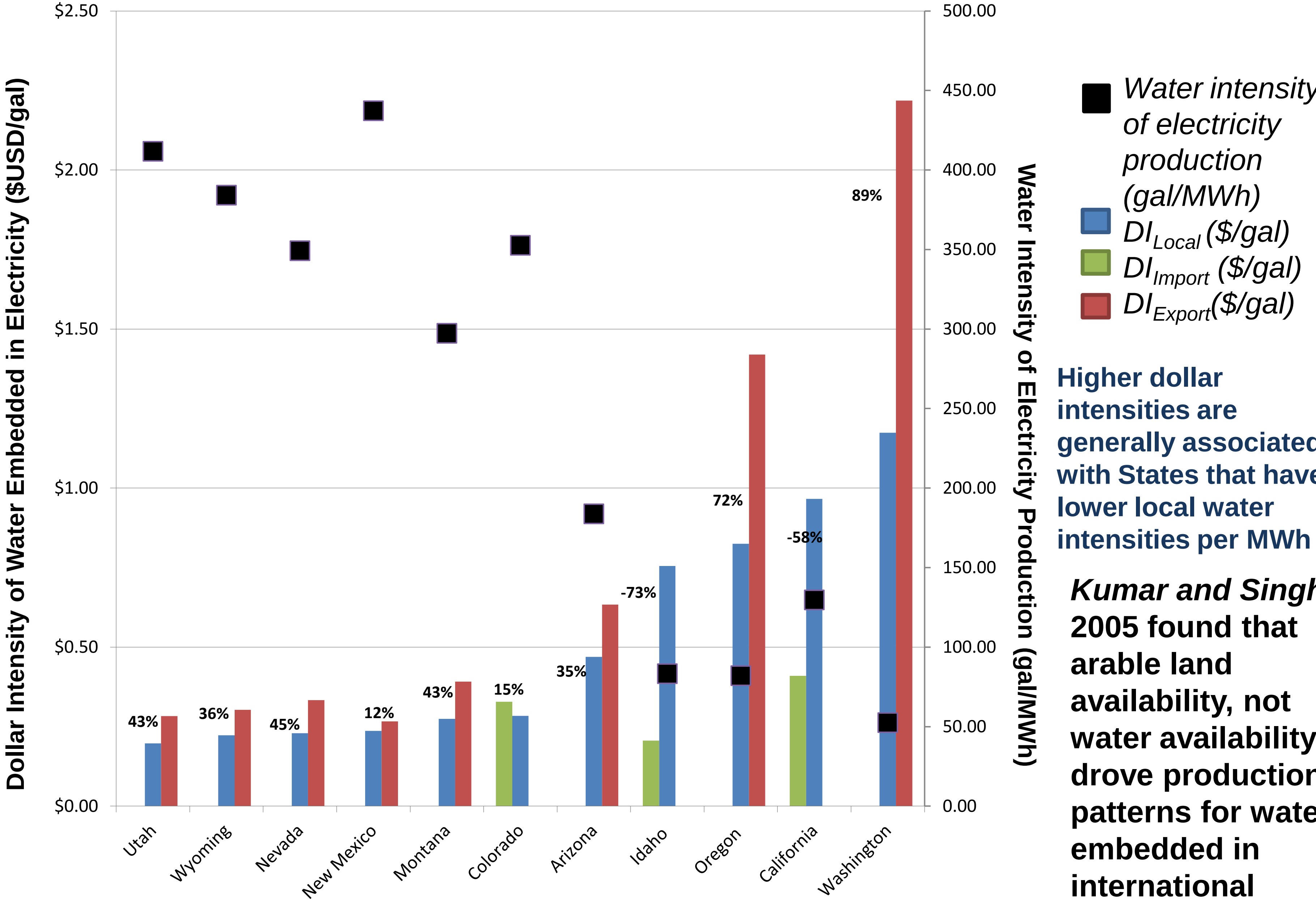


Figure adapted from *Martin and Ruddell* [2012]

Higher dollar intensities are generally associated with States that have lower local water intensities per MWh

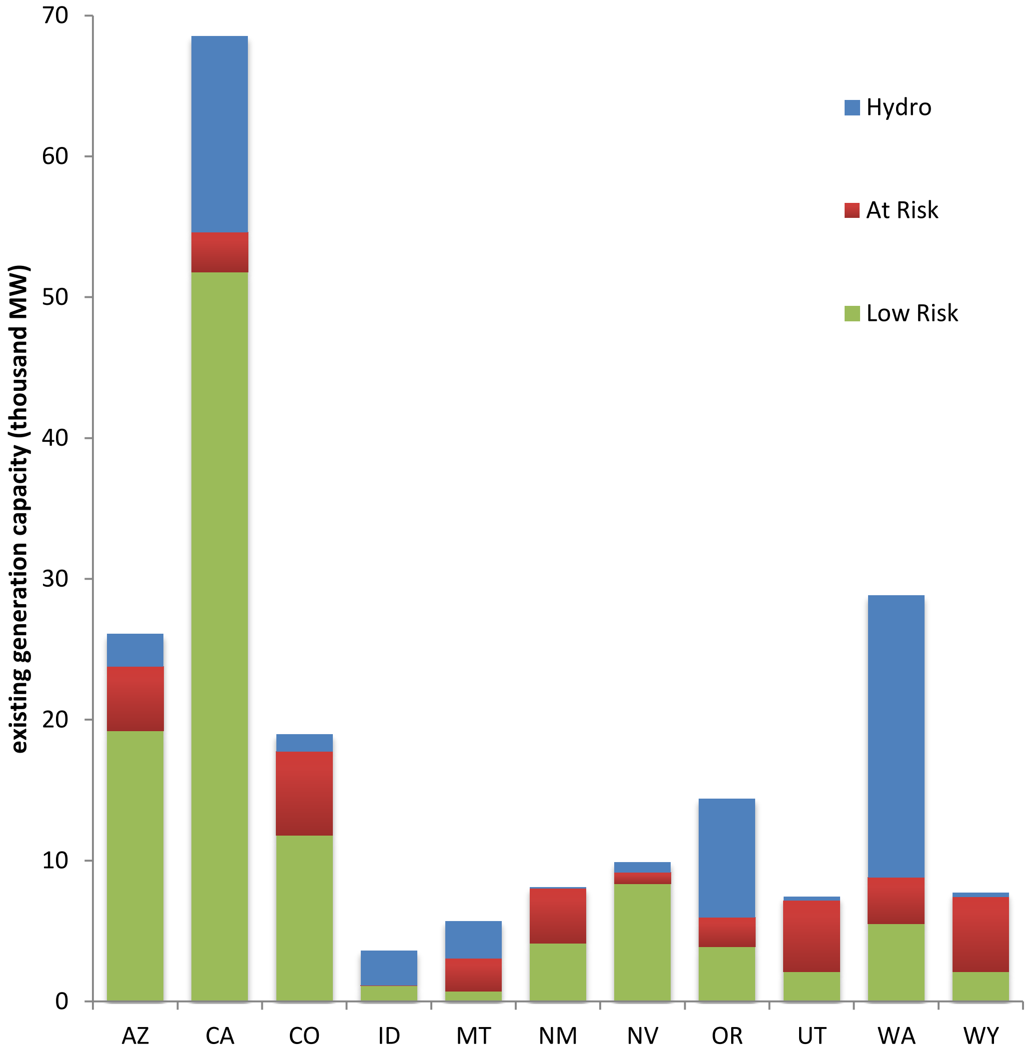
***Kumar and Singh*, 2005 found that arable land availability, not water availability drove production patterns for water embedded in international agricultural trade.**

Modeling Virtual Water Trade: Future Demands and Droughts

Plants grouped into three categories for response to drought

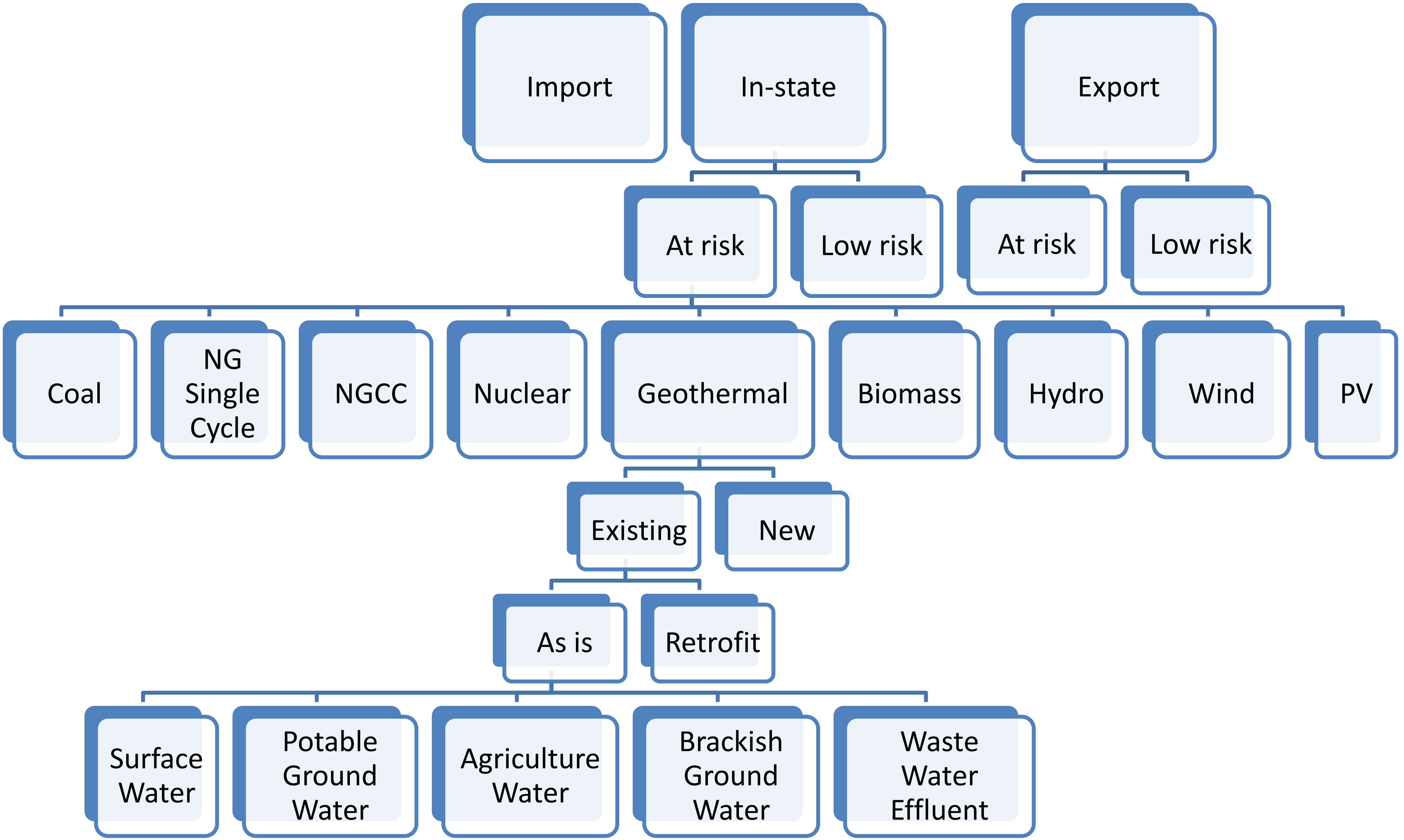
(Harto & Yan, 2011)

- Low risk thermoelectric
- At risk thermoelectric
- Hydroelectric



Herron et al., in review

Methods and Assumptions: Generation Options

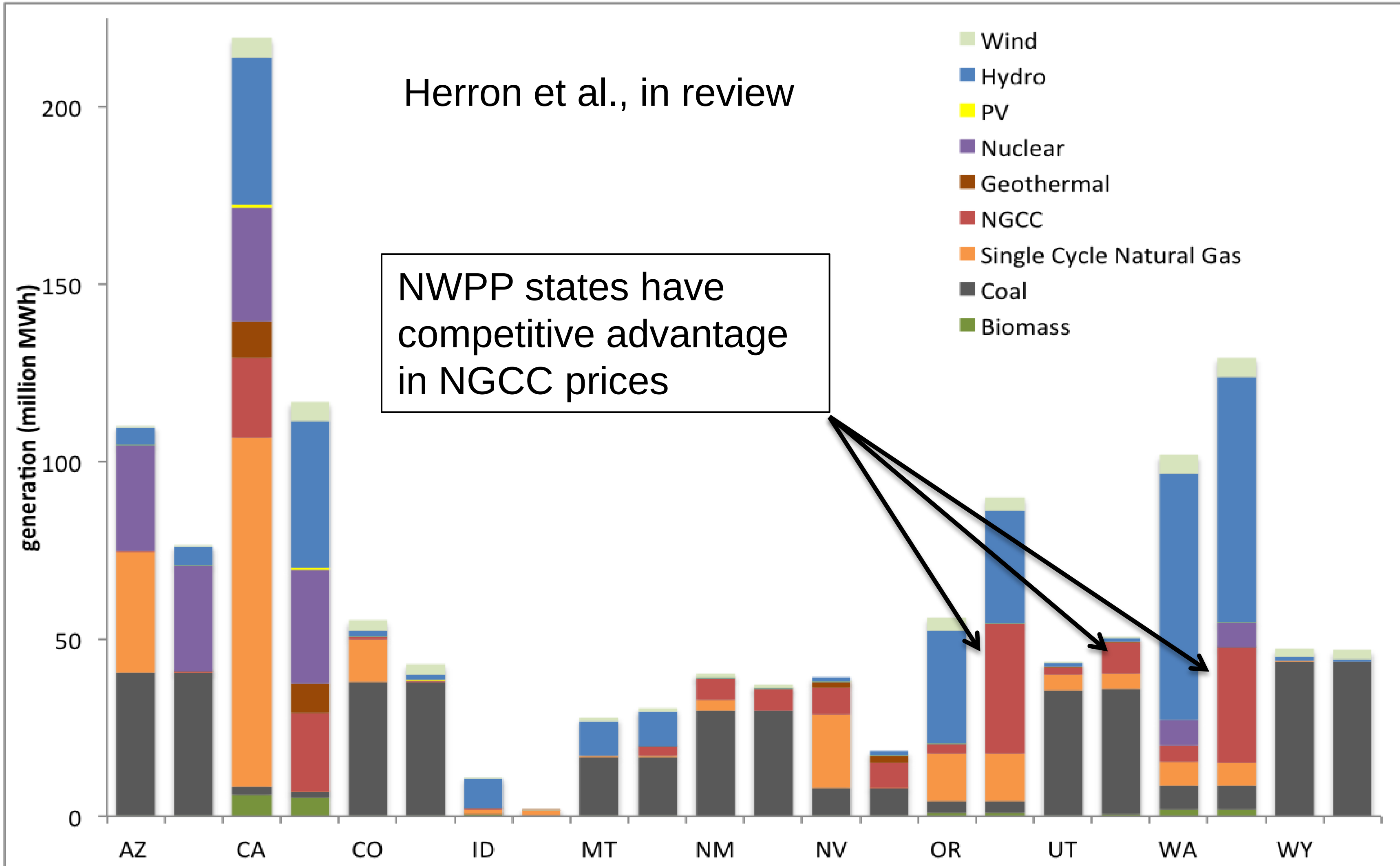


Methods and Assumptions: Scenarios

- Maximum Likely scenarios
  - Current demands vs 2040 projected demands (US EIA, 2013)
  - No drought vs full duration and intensity in all states
- Intermediate scenarios
  - Varying drought duration and intensity in all states
- Spatially varied scenarios
  - Drought in Pacific Northwest, California, Great Basin (NW) vs drought in Upper/Lower Colorado, Rio Grande, Missouri (SE) (Harto & Yan, 2011)
  - Varying drought duration and intensity in NW basins, with no drought in SE basins, and vice versa

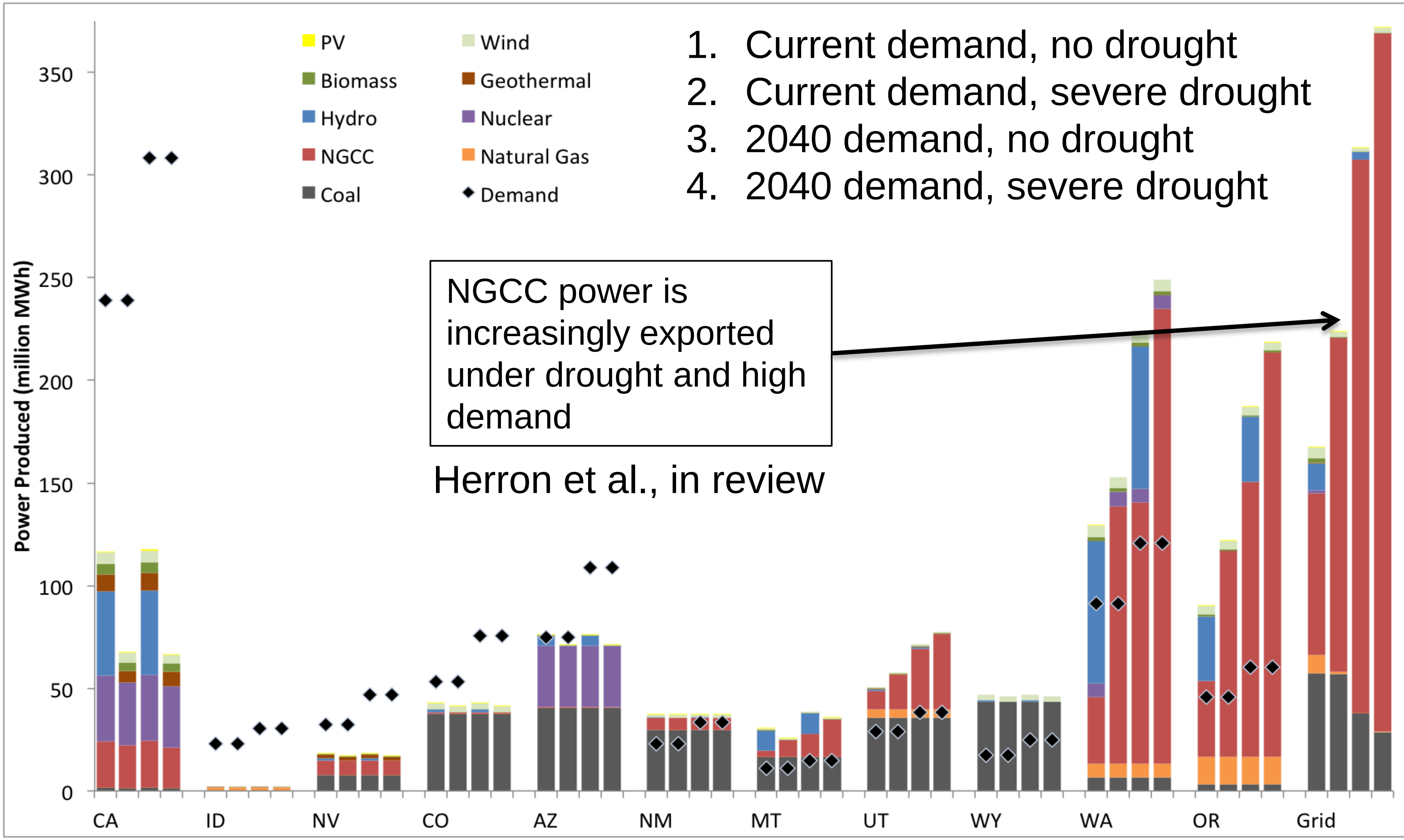
HUC-2 Basins (Harto & Yan, 2011)

Current Generation Mix



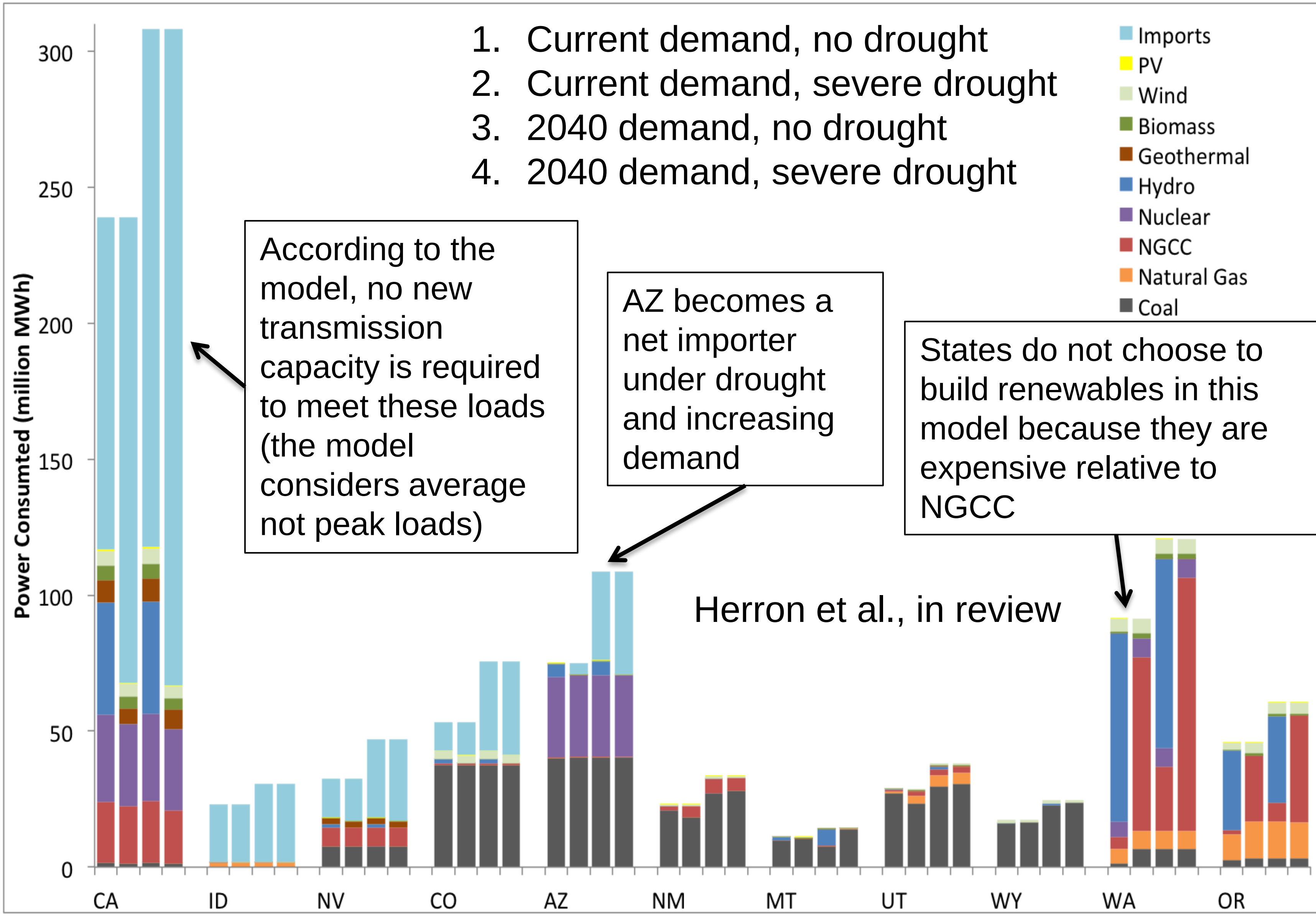
NGCC is most cost effective source. Model replaces expensive natural gas single-cycle plants with NGCC.

Results: Production MWh



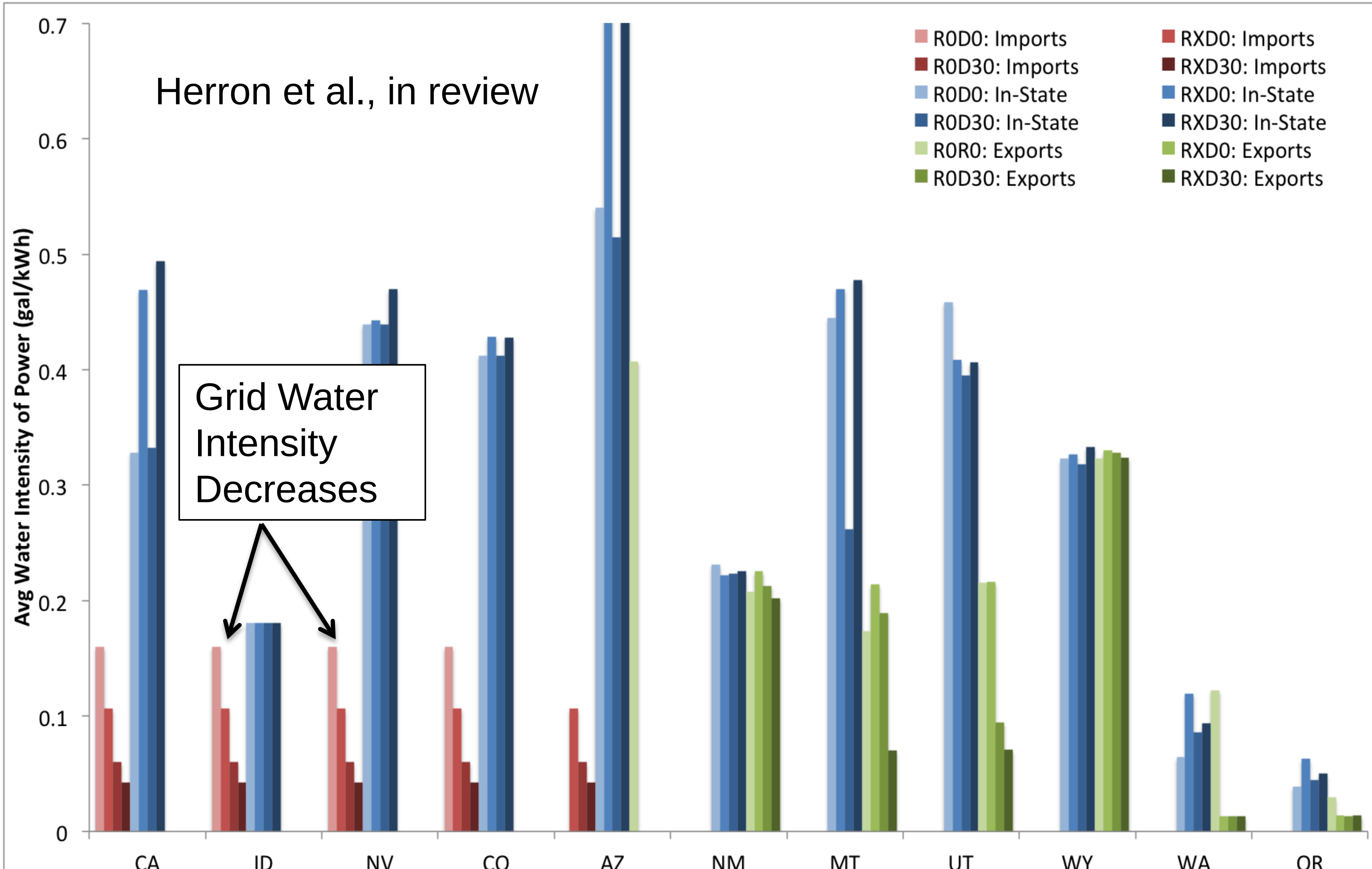
States with high in-state electricity prices and high costs to build new NGCC import (AZ, CA, CO, NV). States with low costs to build new NGCC export (MT, OR, UT, WA).

Results: Consumption MWh



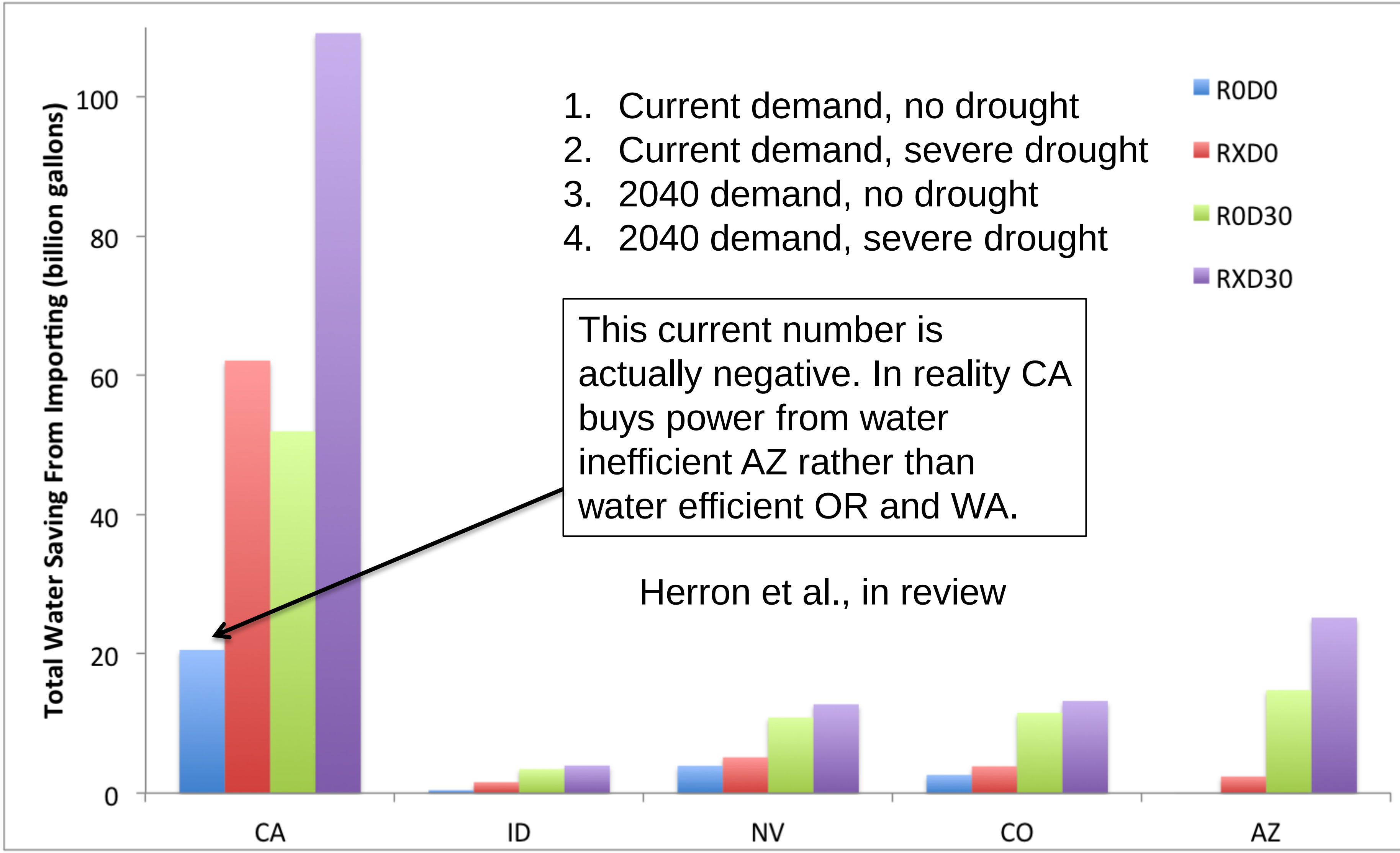
NGCC or importing always most cost-effective options, regardless of scenario

Results: Water Intensity of Power



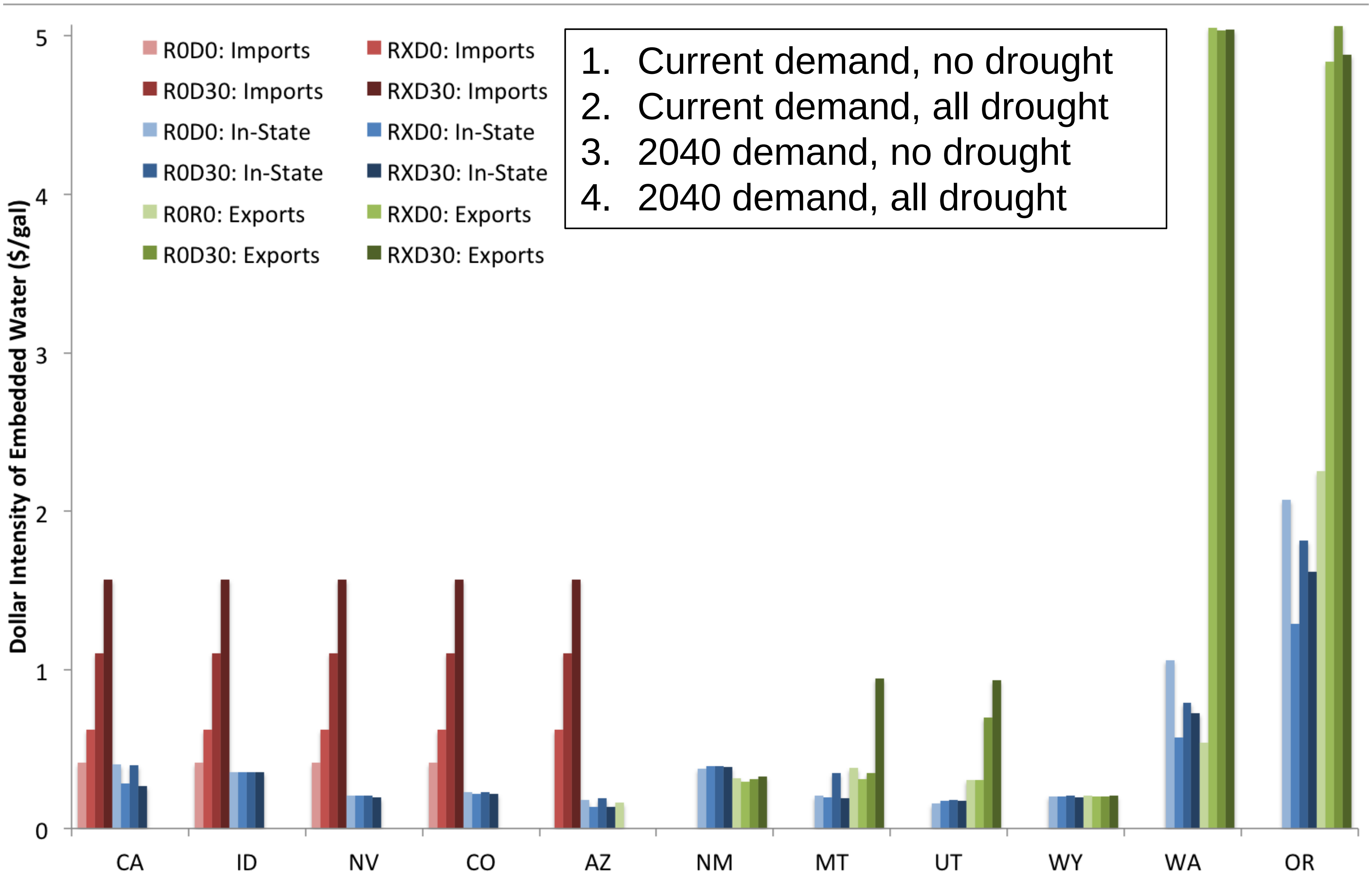
Drought increases water intensity of in-state power due to hydropower loss. Exported power becomes less water-intense because of expansion of NGCC.

Results: Water Savings from Trade in Power

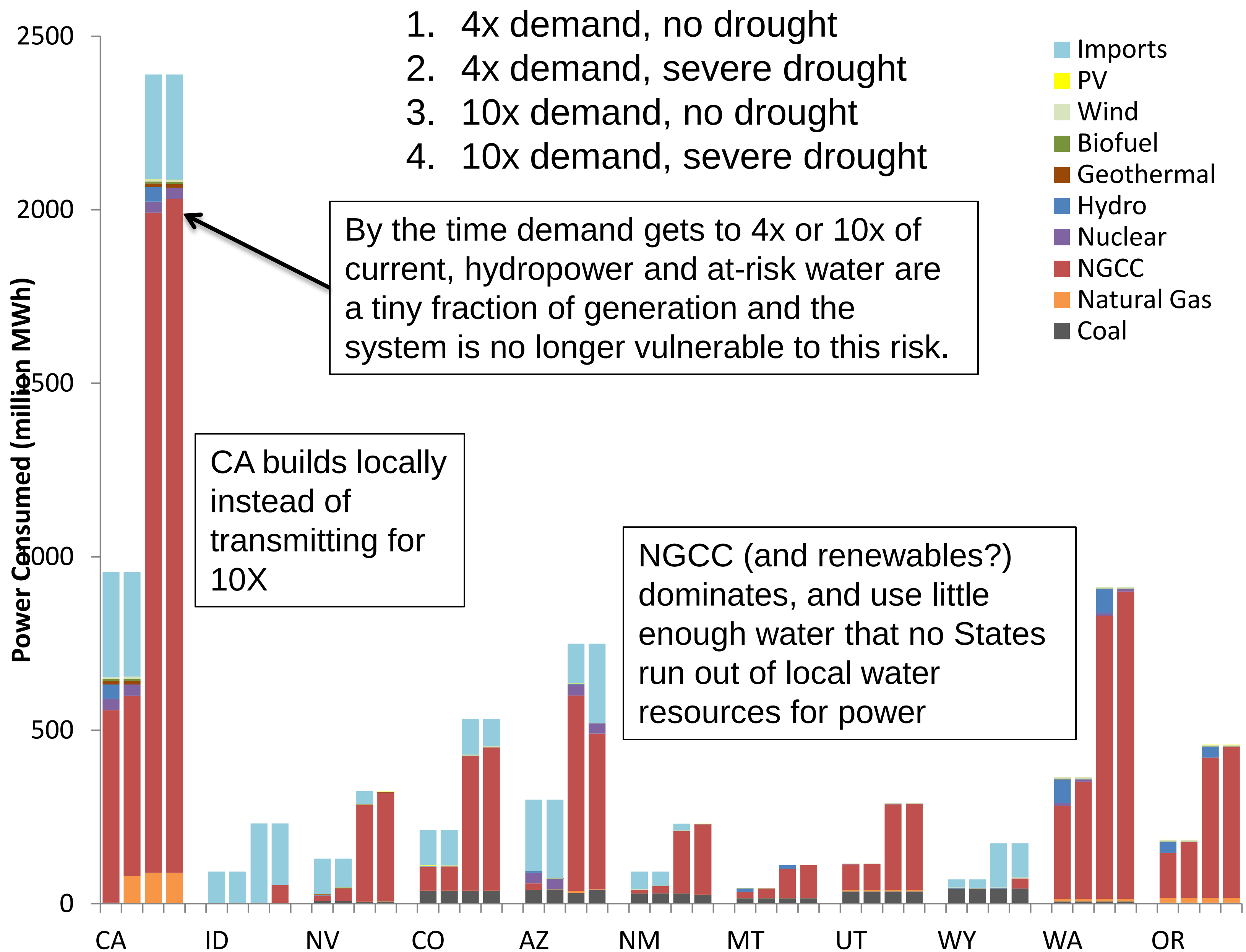


Importers save water via states with water efficient production. Savings increase under drought and demand pressure.

Modeled Dollar Intensity

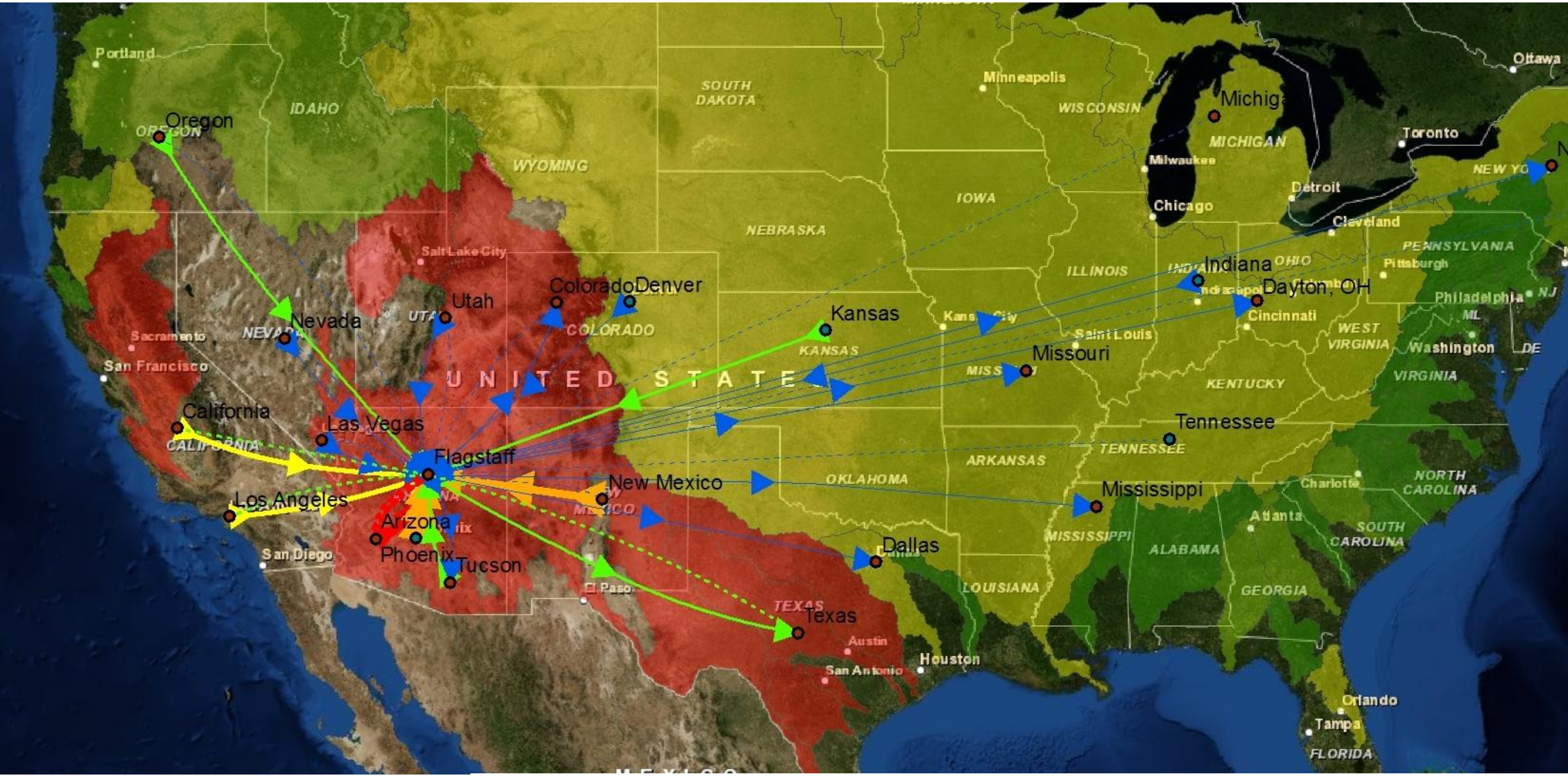


Results: Extreme Demand Scenarios



Virtual Water Trade Network for Flagstaff, AZ

Cities are the hubs of the water network and they use/outsource water to obtain what they value (next slide)



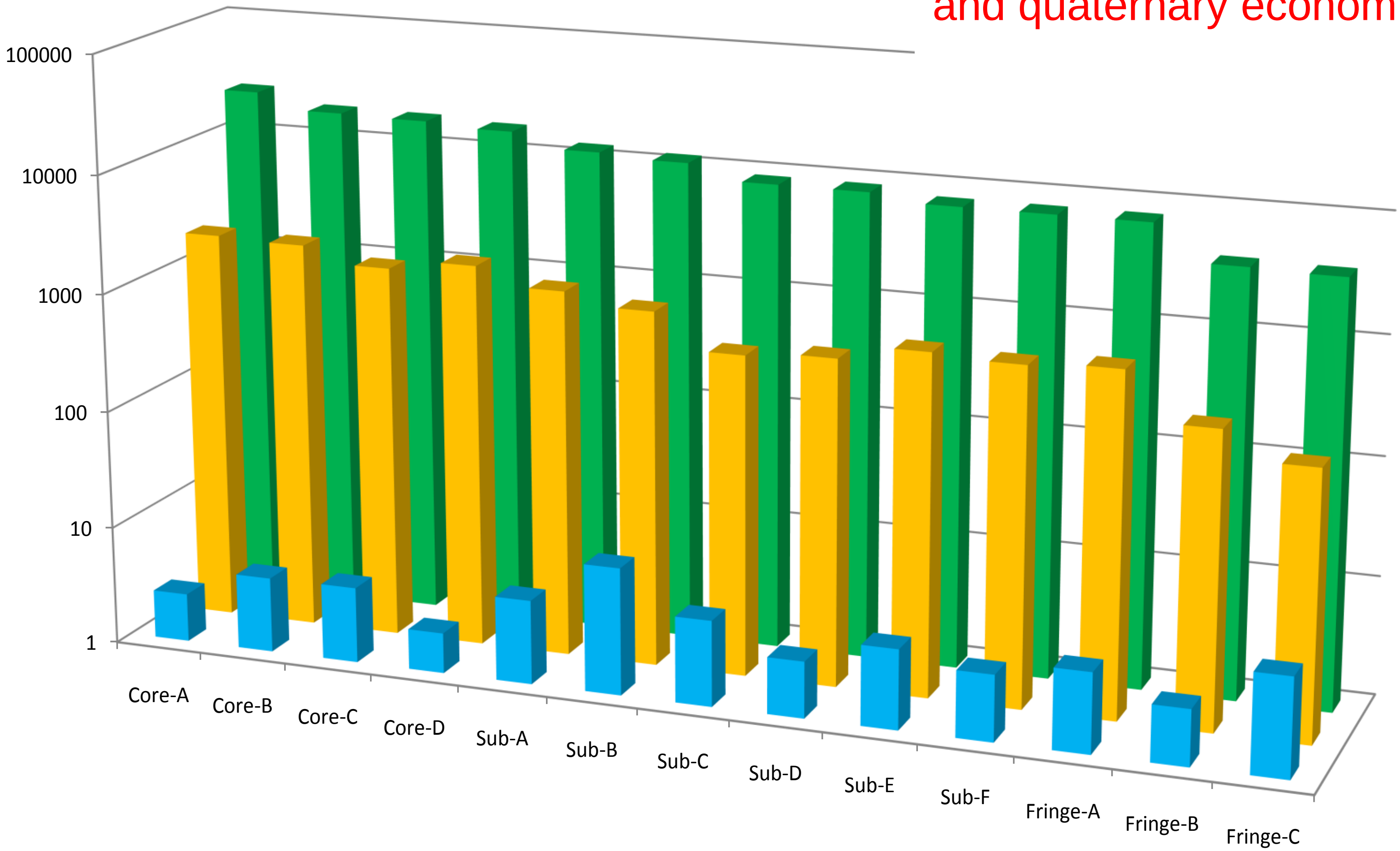
Network based on the 2007 US Commodity Flow Survey; watershed color indicates water stress (Hoekstra and Mekonnen, 2011)

- Interstate trade is primarily West to East, indicating a <u>flow of embedded water from drier to wetter areas</u> (except KS and OR)
- Local trade is primarily imports of raw materials and agricultural

Value Intensity of Combined Direct and Indirect Water Use of Phoenix Area Cities

'Core' cities are massive net importers of VW and use far more water than it appears, including via labor from bedroom communities. But they produce even more value because they specialize in high-value tertiary and quaternary economic sectors.

[#/ac-ft] Population Payroll Revenue



Conclusions

- This helps us understand SYSTEM LEVEL sustainability and resilience, and the interaction of economics with water resources.
- Every connection is both a vulnerability and an opportunity.
- Water use is currently increased and shifted to drier and junior water rights States by the electrical power system as a whole
- Large fractions of California's (and Idaho's) water use is outsourced
- Most of California's outsourcing is to CO basin, a built-in conflict
- Future drought and demand will drive a shift to NGCC in locations with relatively low costs; electrical trade and transmission totals increase
- It is possible to handle even large demand increases and severe droughts through system level trade
- Shift to NGCC will dramatically reduce systemic water consumption, with embedded water reductions concentrated in traded power
- We have enough water, and transmission capacity for VW trade, if we use low-cost and low-water generation technologies.

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Water resources are a key element in the global coupled natural-human (CNH) system, because they are tightly coupled with the world's social, environmental, and economic subsystems, and because water resources are under increasing pressure worldwide. A fundamental adaptive tool used especially by cities to overcome local water resource scarcity is the outsourcing of water resource impacts through substitutionary economic trade. This is generally understood as the indirect component of a water footprint, and as 'virtual water' trade.

The presented work employs generalized CNH methods, Embedded Resource Impact Accounting (ERA), to reveal the trade in water resource impacts embedded in electrical energy within the Western US power grid, and the relationship of these impacts to the human economy's structure. We then utilize a general equilibrium economic trade model combined with drought and demand growth constraints to estimate the future status of this trade. Trade in embedded water resource impacts currently increases total water used for electricity production in the Western US and shifts water use to more water-limited States. Extreme drought and large increases in electrical energy demand increase the need for embedded water resource impact trade, while motivating a shift to more water-efficient generation technologies and more water-abundant generating locations. Cities are the largest users of electrical energy, and in the 21st Century will outsource a larger fraction of their water resource impacts through trade. This trade exposes cities to risks associated with disruption of long-distance transmission and distant hydrological droughts.

Such as time allows, a more detailed introduction to the general concepts and methods of Embedded Resource Impact Accounting and its applications to urban and watershed systems in the US will be presented. Municipalities are connected to each other and to surrounding landscapes through trade and the attendant embedded water impacts form a rich network of interactions between the human and natural system. These interactions have important implications for economics and resilience, as well as for achieving system-level solutions to environmental problems in the 21st century.