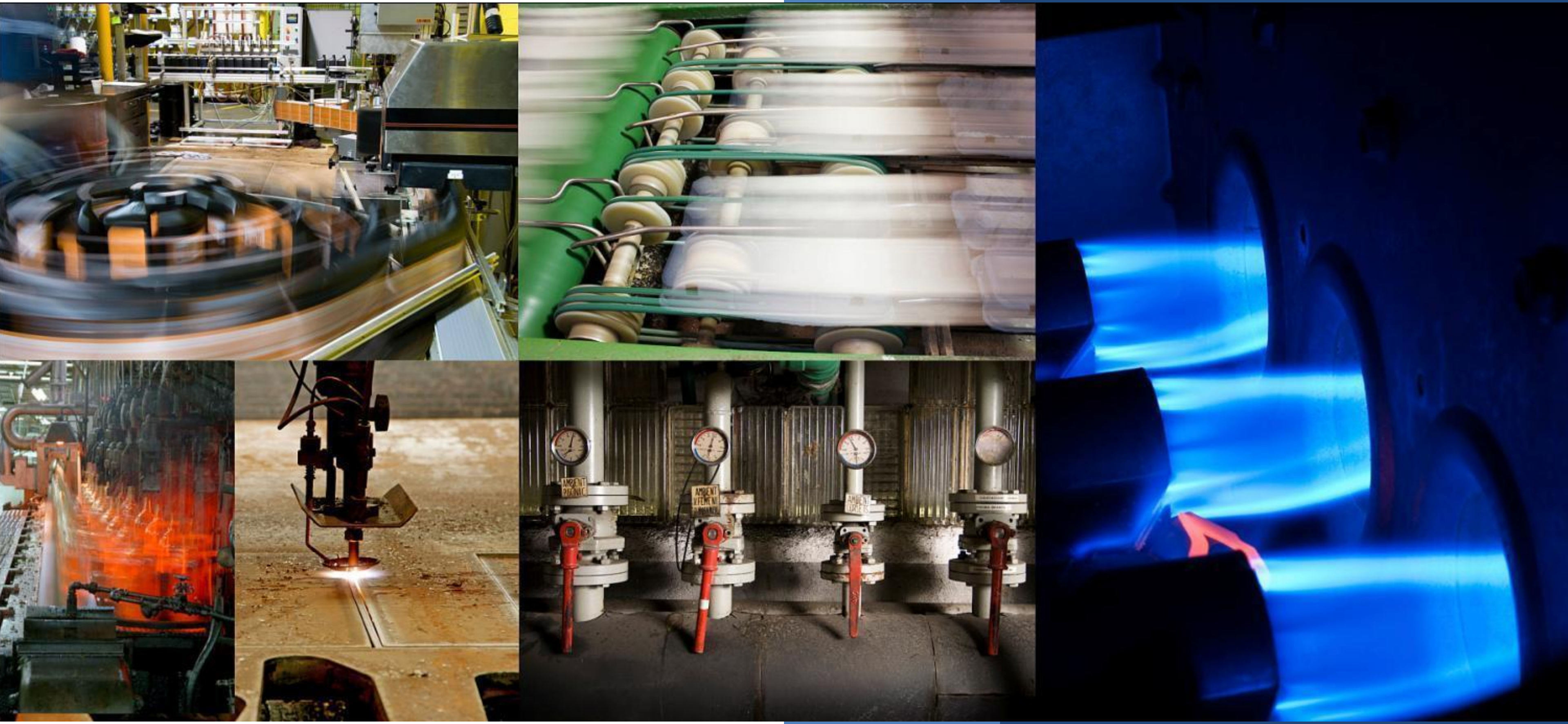
Office of Energy Efficiency & Renewable Energy
Advanced Manufacturing Office

U.S. DEPARTMENT OF ENERGY



An Overview of AMO Clean Water Analysis

Joe Cresko - Advanced Manufacturing Office, DOE

AMO Clean Water Workshop
Dallas, TX
July 11, 2017

AMO Strategic Goals

- Improve the productivity and energy efficiency of U.S. manufacturing.

- Reduce lifecycle energy and resource impacts of manufactured goods.

- Leverage diverse domestic energy resources in U.S. manufacturing, while strengthening environmental stewardship.

- Transition DOE supported innovative technologies and practices into U.S. manufacturing capabilities.

- Strengthen and advance the U.S. manufacturing workforce.

Multi-Year Program Plan

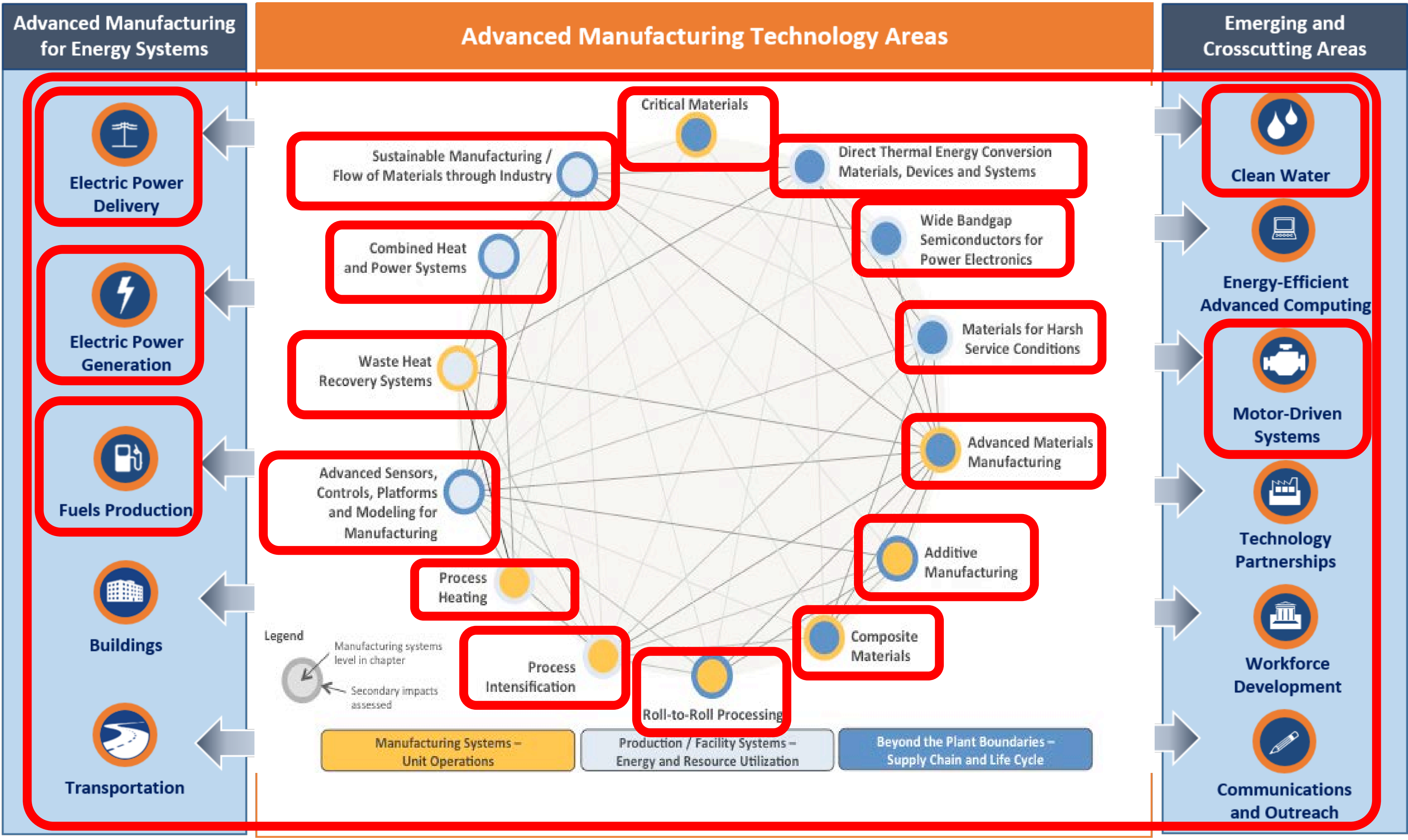
- Describes the Office mission, vision, and goals
- Identifies the technology, outreach, and crosscutting activities the Office plans to focus on over the next five years.

https://energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017

Public feedback and comments can be sent to AMO_MYPPInfo@ee.doe.gov

AMO Multi-Year Program Plan (MYPP) Framework and Clean Water

https://energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017



Manufacturing Technology Assessments can be found here:

https://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus#chap6ta

Clean Water Strategic Analysis Focus Areas

Manufacturing in a Connected Economy

e.g., What will be the impact of rapidly expanding information and smart products

Desalination Bandwidth Studies

e.g., What are the opportunities and impact of improved Desalination Technologies?

Clean Water

Analysis Methodology, Tools & Integrating Analysis

e.g., How can we improve integrated water and energy analyses

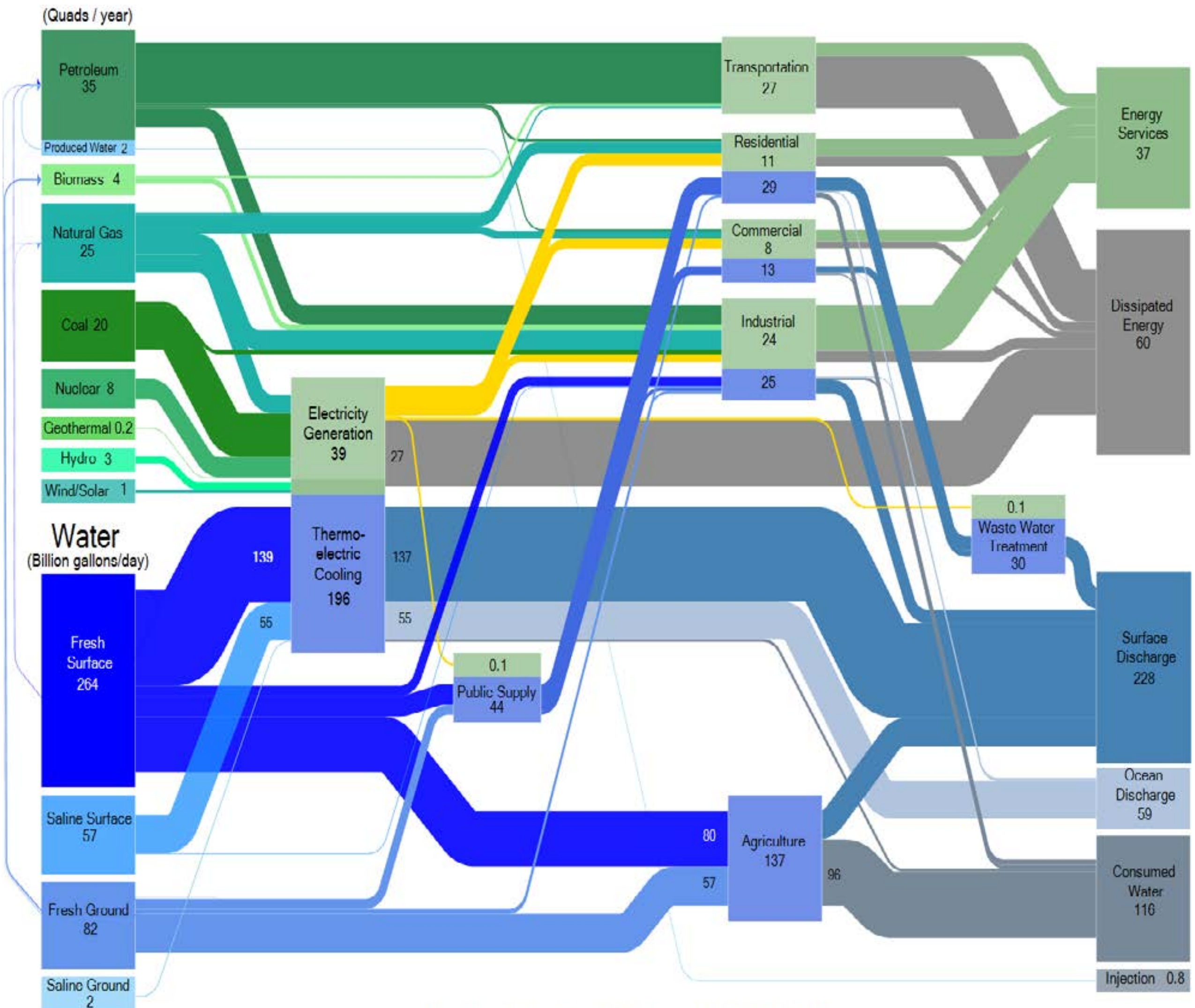
Sustainable Manufacturing

e.g., Industrial water use; Advanced manufacturing technologies at the intersection of water, energy and materials

Goal: Increase the effectiveness of research into materials, technologies, and processes to reduce the impacts of water processing and water use.

Analysis outputs: DOE reports, Bandwidth studies, conference presentations, white papers and refereed journal publications.

Energy-Water Nexus



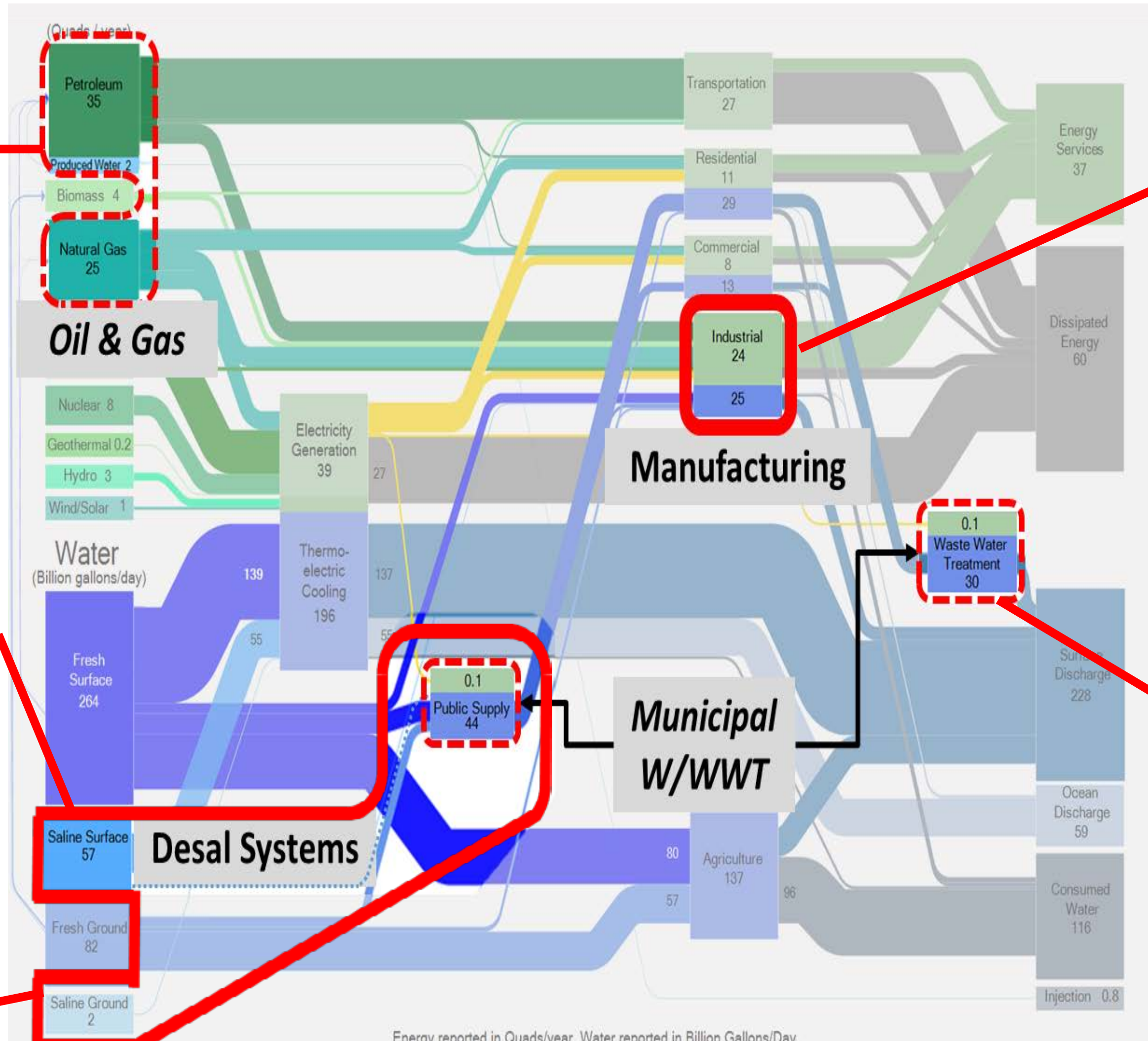
Energy reported in Quads/year. Water reported in Billion Gallons/Day.

Targeted Analyses → Example framing questions/issues

High Salinity feed water with variable contaminant mix to produce industrial/ag grade water w/ FO, RO viable candidates

Seawater for municipal potable water w/ RO, MSF, and MED candidates in focus

Brackish water for potable water w/CDI, EDR, MF/NF, RO as candidates



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

Reduce energy & water in specific sectors w/ sectors chosen based on watershed impact

Reduce energy consumption of the water and wastewater sectors, including advanced resource recovery and reuse possibilities

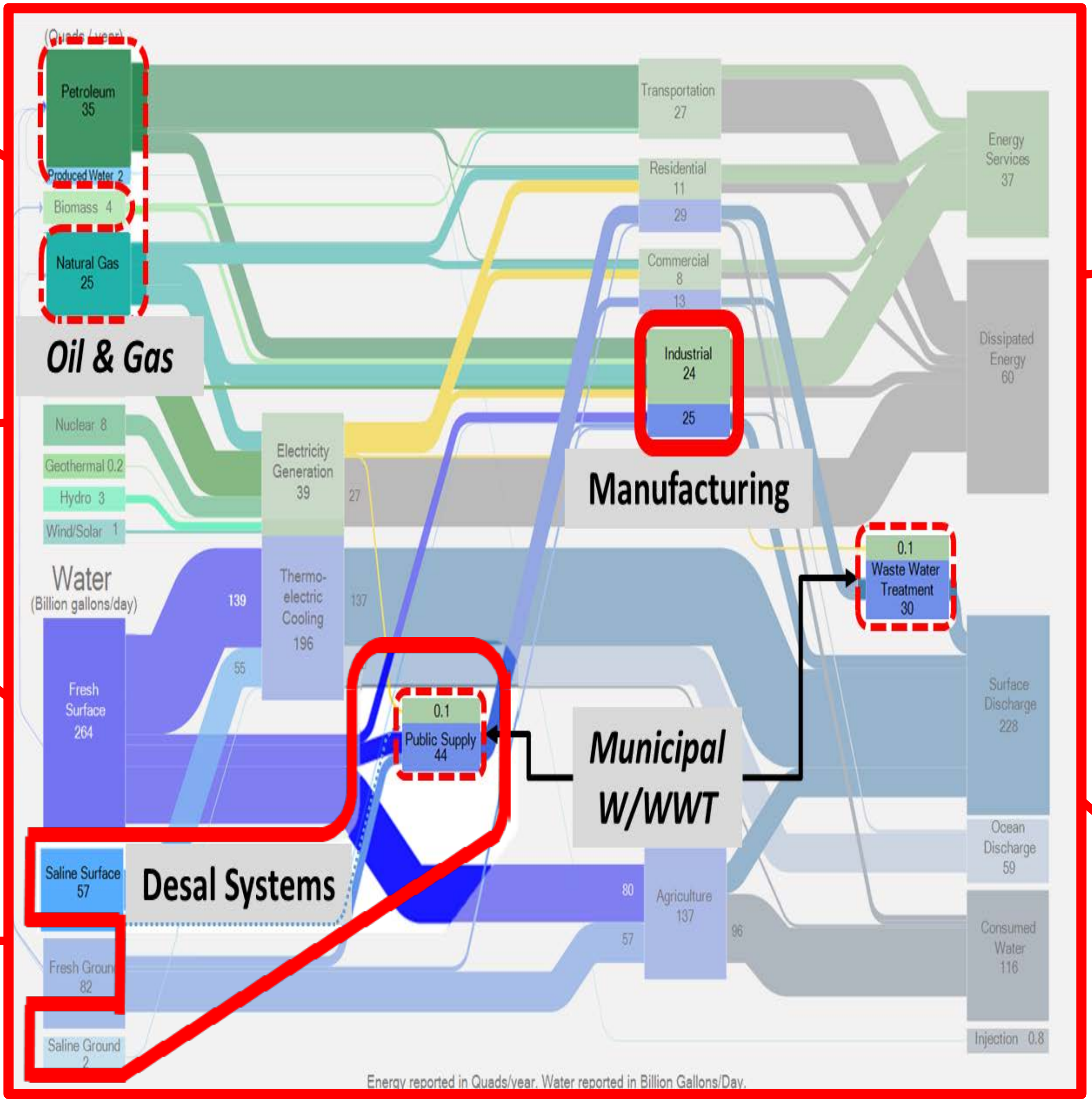
Crosscutting Technologies can have impact across the Energy-Water Nexus

Separations /treatment:
- Membranes
- Thermal

Fluids Pumping:
- Motor driven systems
- Materials

Heat transfer:
- Corrosion resistant materials
- Waste heat integration

Infrastructure:
- Piping
- Structural materials



System integration:
- Smart technologies
- Modular designs
- Processes
- Joint energy grid/water system management

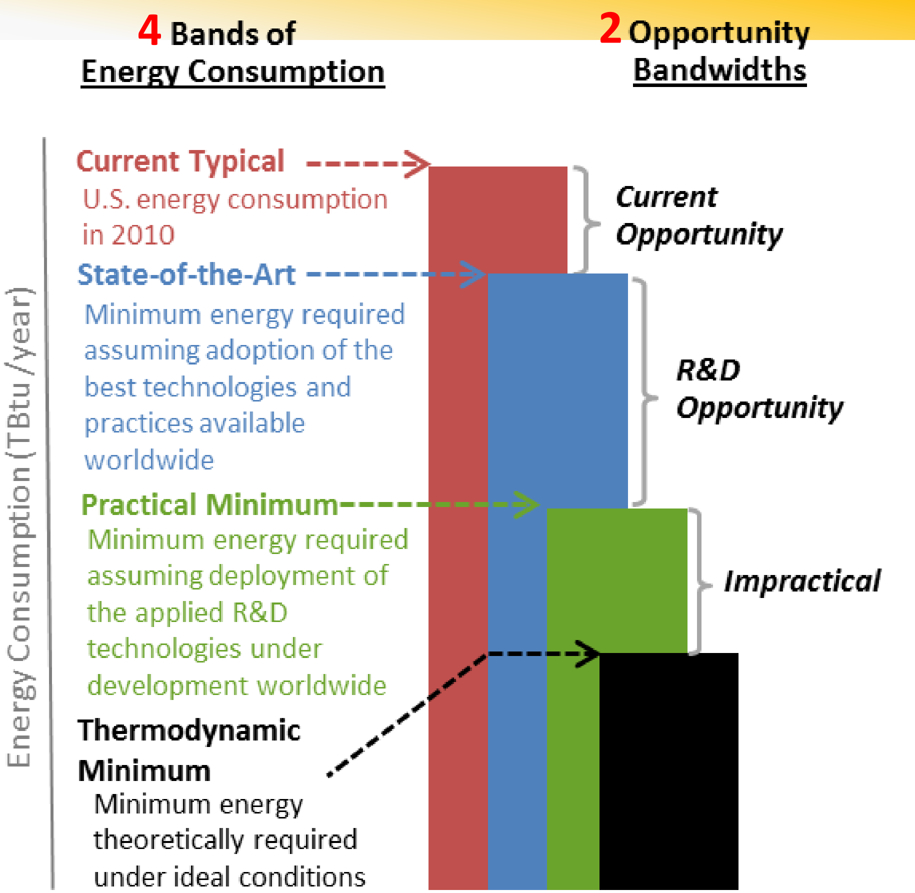
Sustainability:
- RE integration
- Consumptive water use
- Chemicals (alternatives)
- Life cycle water use
- Fit-for-use, reuse
- ZLD

Bandwidth Analyses

Energy Bandwidth Studies

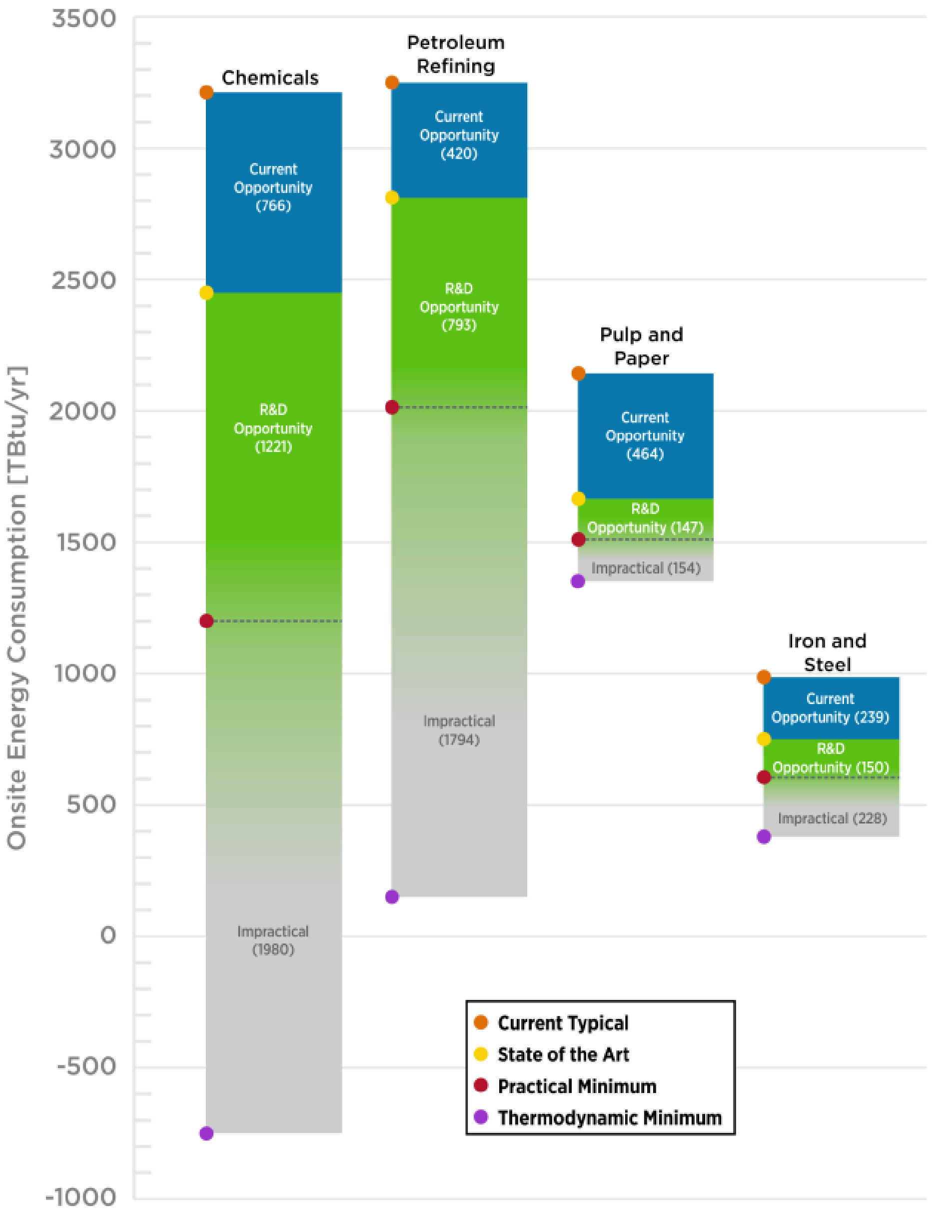
Comparison of energy consumption for defined industrial process areas to determine bandwidths of energy savings opportunity

These bands of energy consumption and bandwidths of opportunity are useful for identifying areas of R&D technology focus.



Current Typical (CT)	State of the Art (SOA)	Practical Minimum (PM)	Thermodynamic Minimum (TM)
Literature review and stakeholder outreach, based on current typical processes in the U.S.	Literature review and stakeholder outreach, based on the most energy-efficient technologies and practices available worldwide	Calculated based on plausible energy savings from identified R&D technologies under development worldwide	Calculated analytically using Gibbs free energy assuming ideal conditions

Recent Bandwidth Studies



https://energy.gov/eere/amo/energy-analysis-sector

Published 2015:

- Chemicals
- Petroleum Refining
- Pulp and Paper
- Iron and Steel

Published 2016:

Draft lightweight structural materials series:

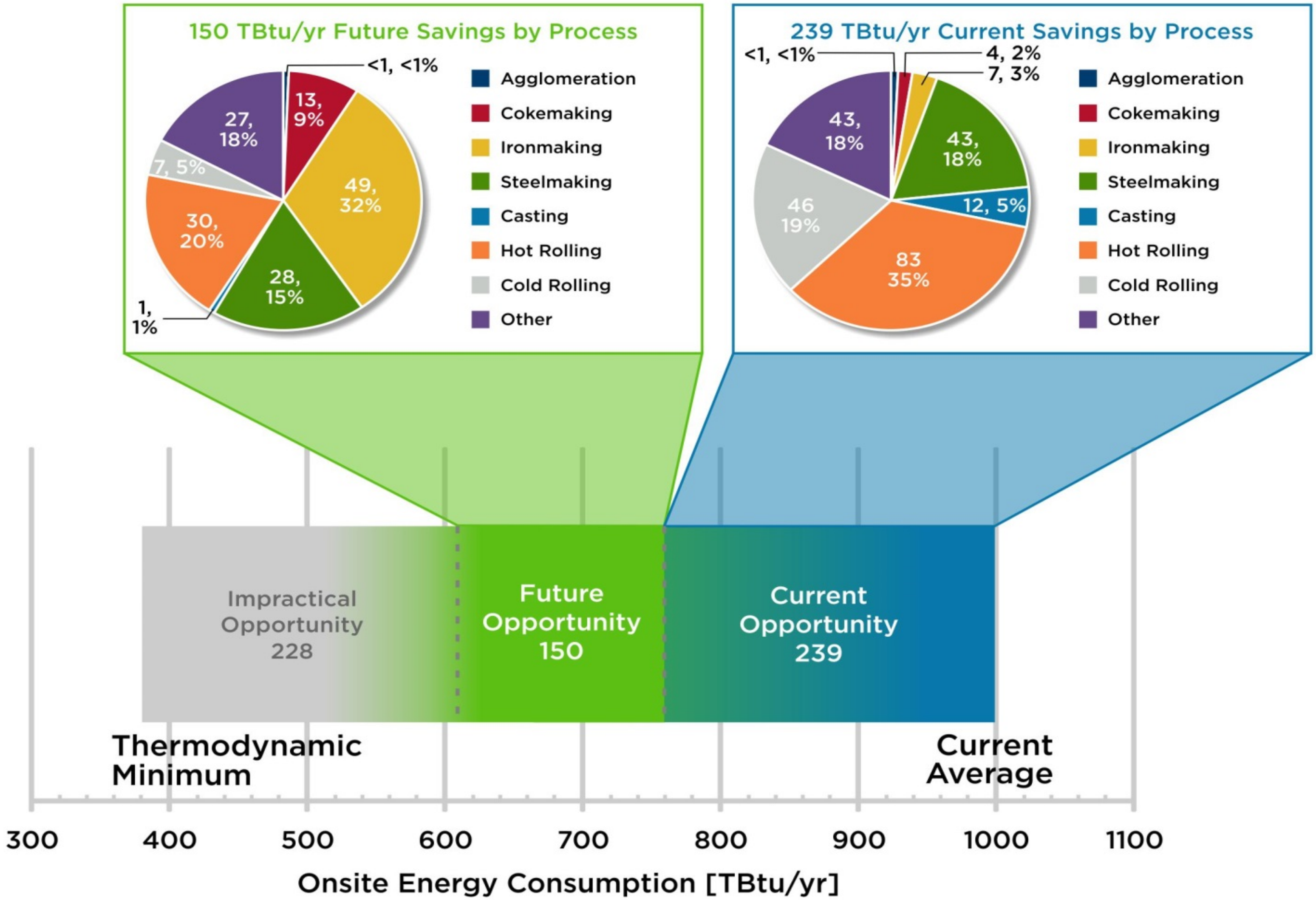
- Advanced High Strength Steel
- Aluminum
- Titanium
- Magnesium
- Carbon Fiber
- Glass Fiber

Underway:

- Cement
- Glass
- Plastics and Rubber Product
- Food and Beverage
- ***Seawater Desalination***

Bandwidth analyses are comprehensive, bottom-up studies starting at the manufacturing process/unit operation level ….

Technical Energy Savings Opportunities: Iron & Steel Industry 2015 Bandwidth Study – potential by major process area



Source: DOE/AMO, Iron & Steel Industry Energy Bandwidth Study (2014)

Note: 1 quad = 1000 TBtu

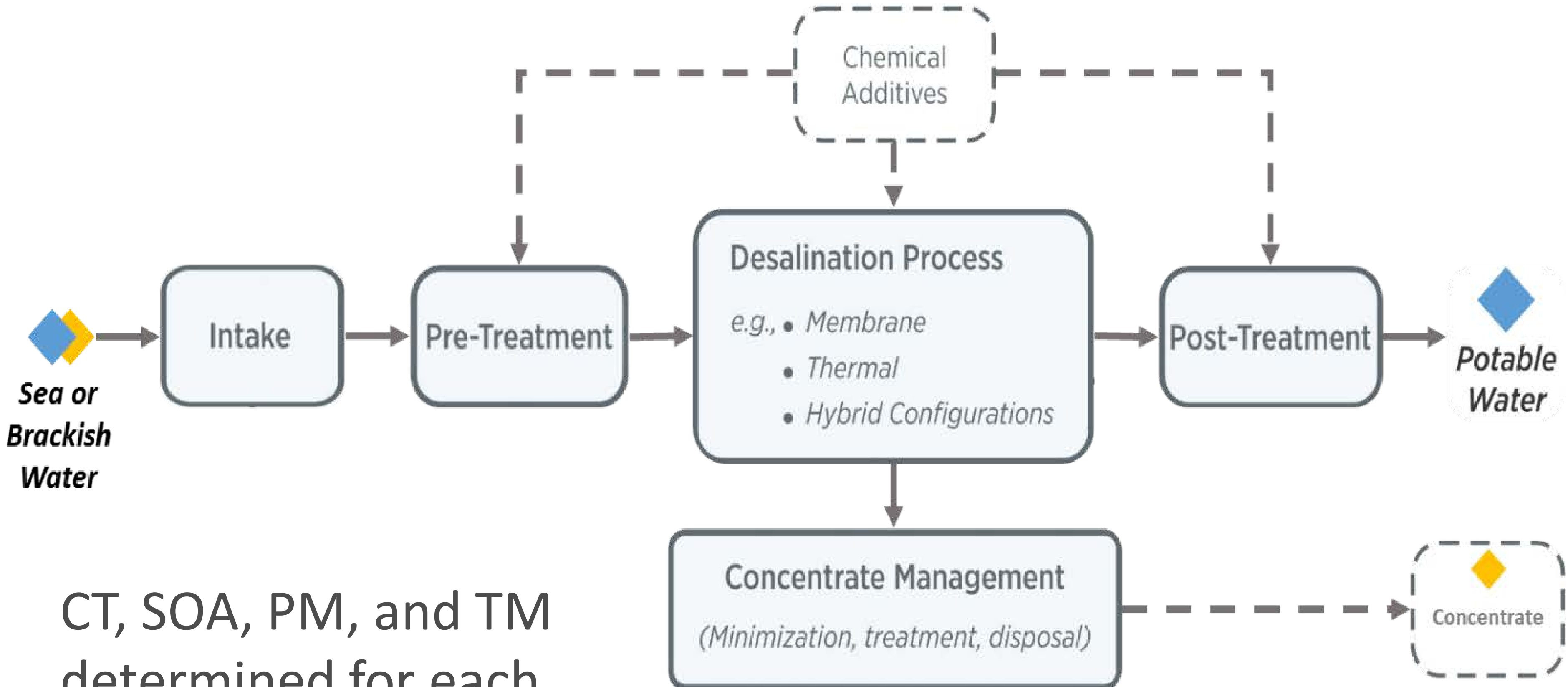
Seawater Desalination Analysis

Energy Water Bandwidth Study of Seawater Desalination: 2 Volumes

	Volume	Contents
Published	**Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems**	• **Boundary Analysis Framework** • **Energy Intensities for Five Unit Operations of Desalination** • **Framework for Desalination Uptake Scenarios**

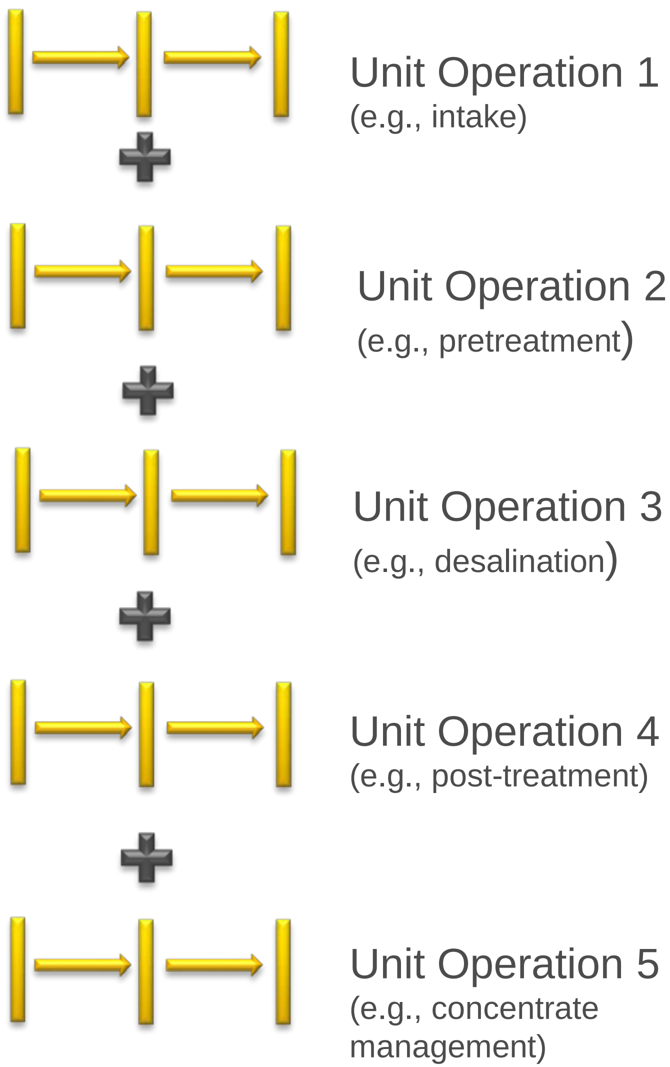
Under Review	**Volume 2: Energy-Water Bandwidth Study of Seawater Desalination Systems**	• **Energy Consumption and CO_2 Emissions for Several Sea-to-Potable Water Uptake Scenarios Evaluated at:**
		  ◦ *Current Typical (CT)*
		  ◦ *State-of-the-Art (SOA)*
		  ◦ *Practical Minimum (PM) Intensity*
		  ◦ *Thermodynamic Minimum (TM)*
		• **Energy Consumption and CO_2 Emissions for Brackish Water to Potable Water at CT Energy and CO_2 Intensity**
		• **Current and R&D Energy Savings Opportunity**

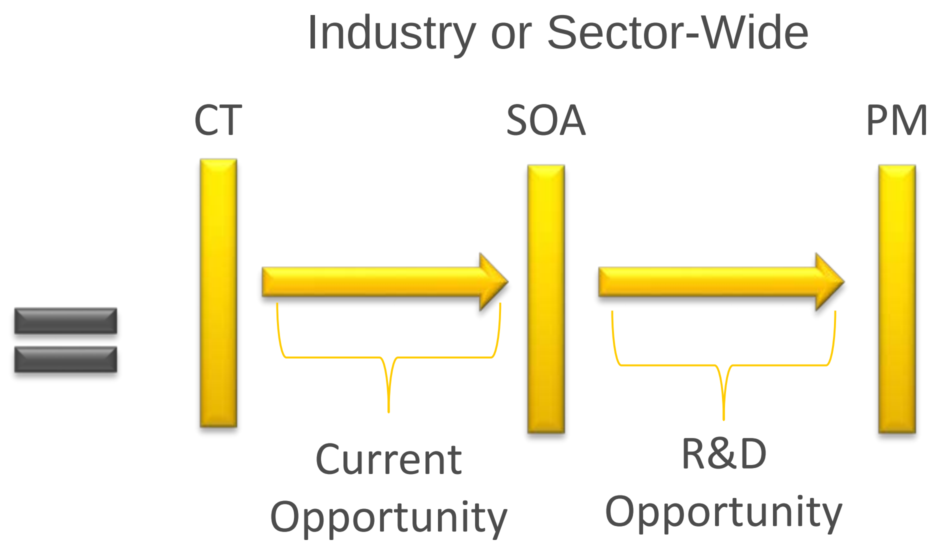
Desalination System Boundary



CT, SOA, PM, and TM determined for each unit operation

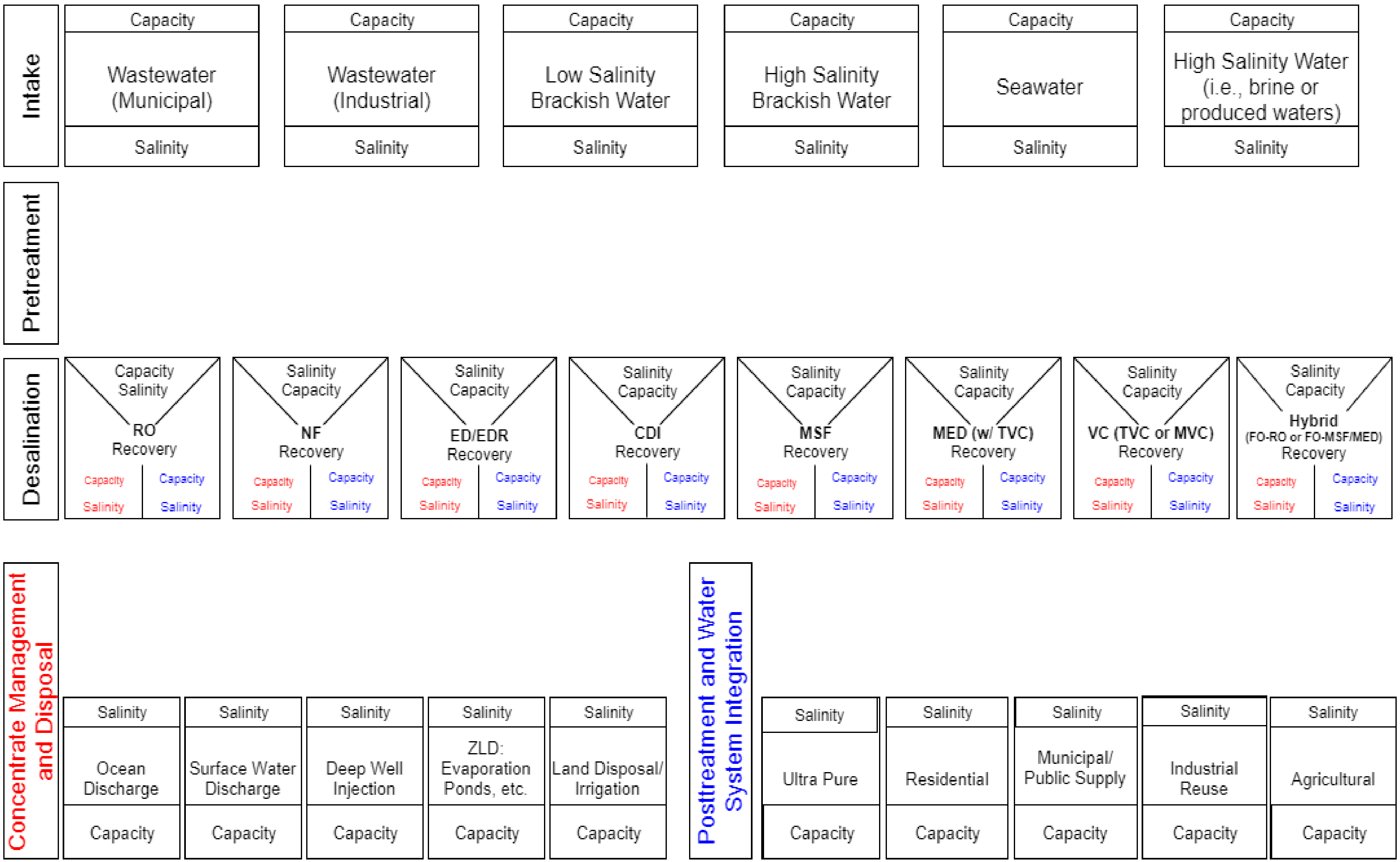
Energy Bandwidth Concept





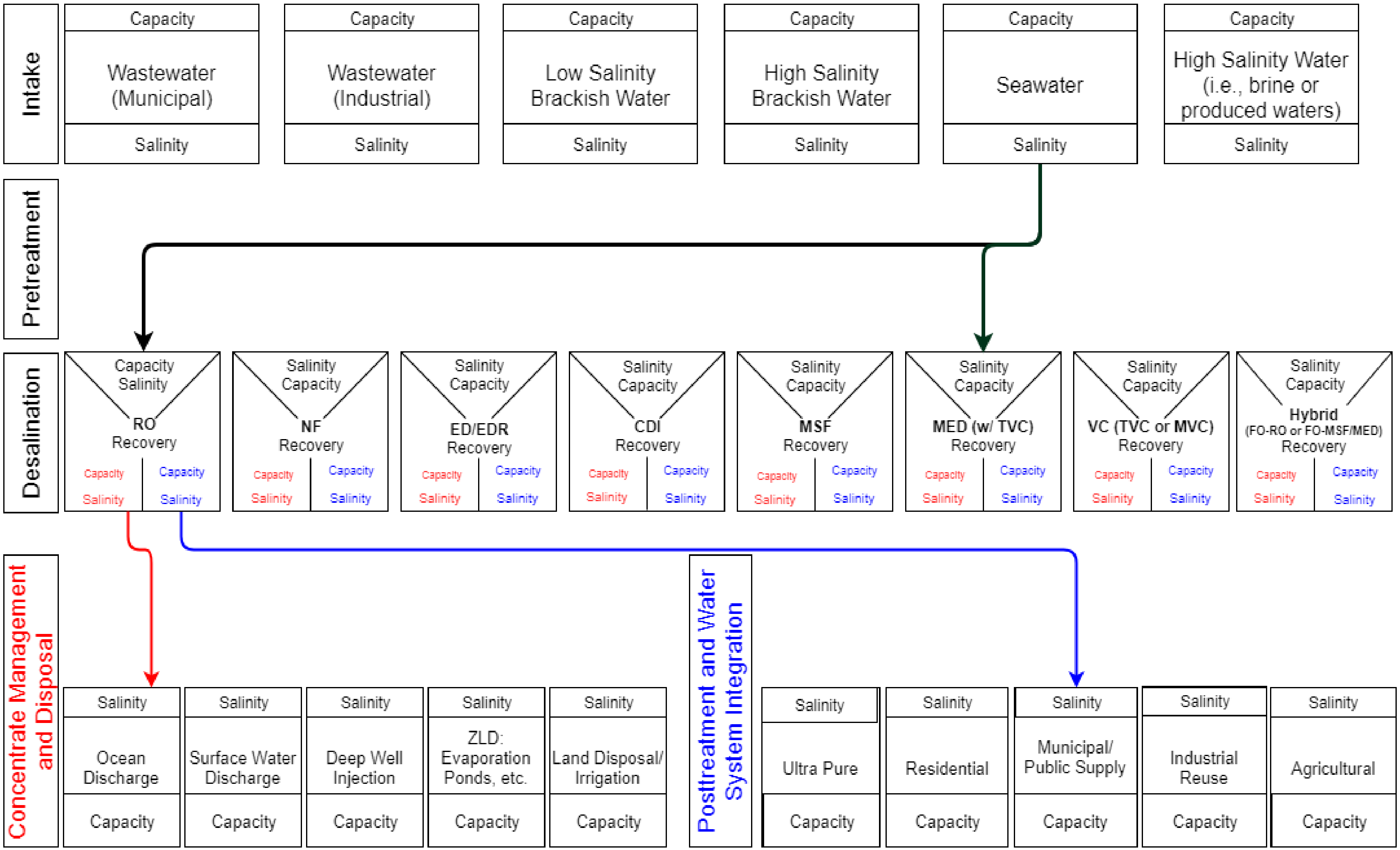
Energy bandwidth studies frame the range (or *bandwidth*) of potential energy savings, and the technology opportunities to realize those savings.

Many applications for water treatment through desalination



Seawater for Municipal Potable Water Pathways

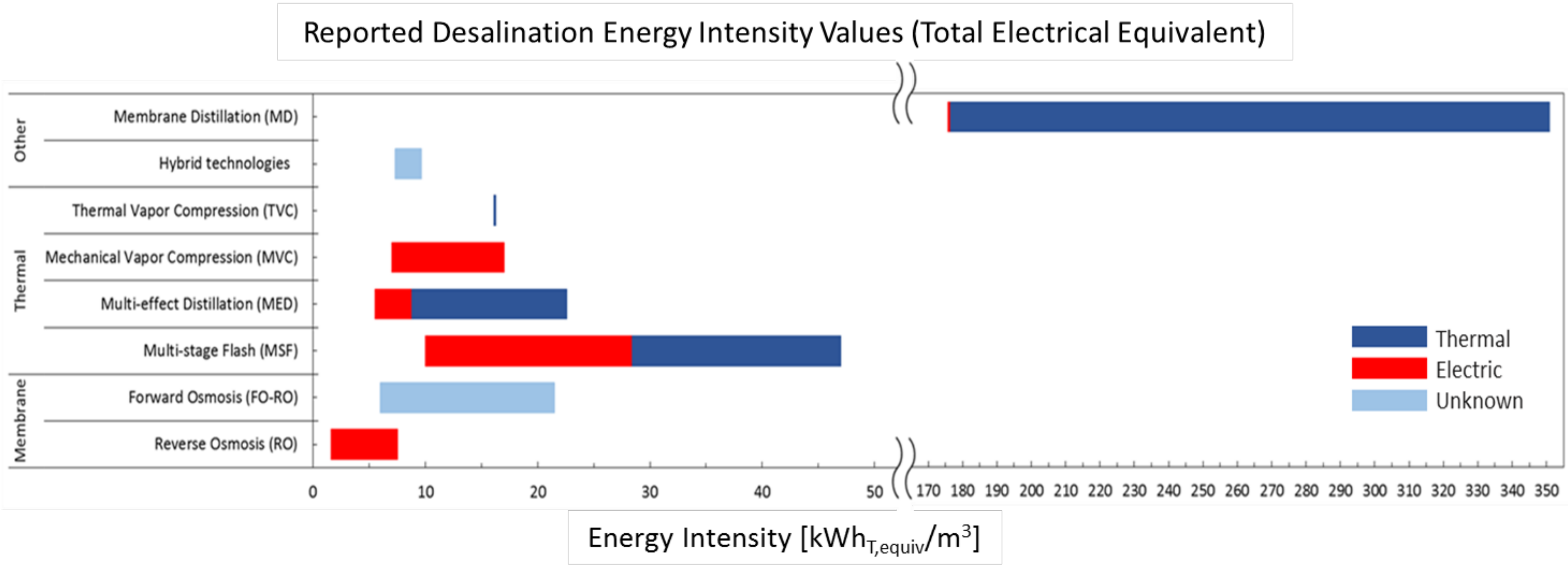
Analysis for seawater looks at two pathways for desalinating seawater into municipal potable water



Desalination Technologies Reviewed For Seawater Application

Intake	Pre-treatment	Desalination	Post-treatment	Concentrate
• Open-ocean intake - Screened • Subsurface intake - Beach wells - Offshore radial collector wells	• Membrane filtration - Microfiltration - Ultrafiltration • Media filtration • Sand filtration • Cartridge filtration • Disc filtration • Flocculation • Sedimentation • Chlorination • Dissolved air flotation	• Thermal vapor compression • Mechanical vapor compression • Multi-effect distillation • Multi-stage flash distillation • Reverse osmosis (RO) • Forward osmosis in combination with RO or a thermal technology	• Remineralization • Disinfection • Boron removal	• Surface water discharge • Zero liquid discharge - Brine concentration - Crystallization

Preliminary Energy Data (Seawater)



Finding: Reported energy data needs further refinement before being used:

- Values need to be reported with operational characteristics, *e.g. intake and product water flow rate, recovery and plant size, salinity, and temps (for thermal processes), desalination unit operation, use of energy recovery or waste heat*.

- Addition of electrical and thermal must account for generation losses associated with converting thermal energy to work.

Opportunities to reduce energy consumption for each unit operation

Unit Operation	Membrane Systems	Thermal Systems
Intake	Opportunities largely driven by improving pump and motor operating efficiency; site specific opportunities related to reducing total dynamic head may exist	
Pretreatment	Significantly impacted by intake design with subsurface lower than open ocean	On par with subsurface intake membrane systems
Desalination	Newer plants implementing SOA for membrane, and semi-batch RO identified as PM	MED-TVC identified as SOA, with designs that can reduce steam pressure requirements identified as PM
Post-treatment	Not a significant factor	Not a significant factor, though higher than membrane system
Concentrate Management	Opportunities largely driven by improving pump and motor operating efficiency	

Information on slides 20 – 28 are draft. Final results will be included in forthcoming Energy-Water Bandwidth Study of Seawater Desalination Systems available through DOE AMO.

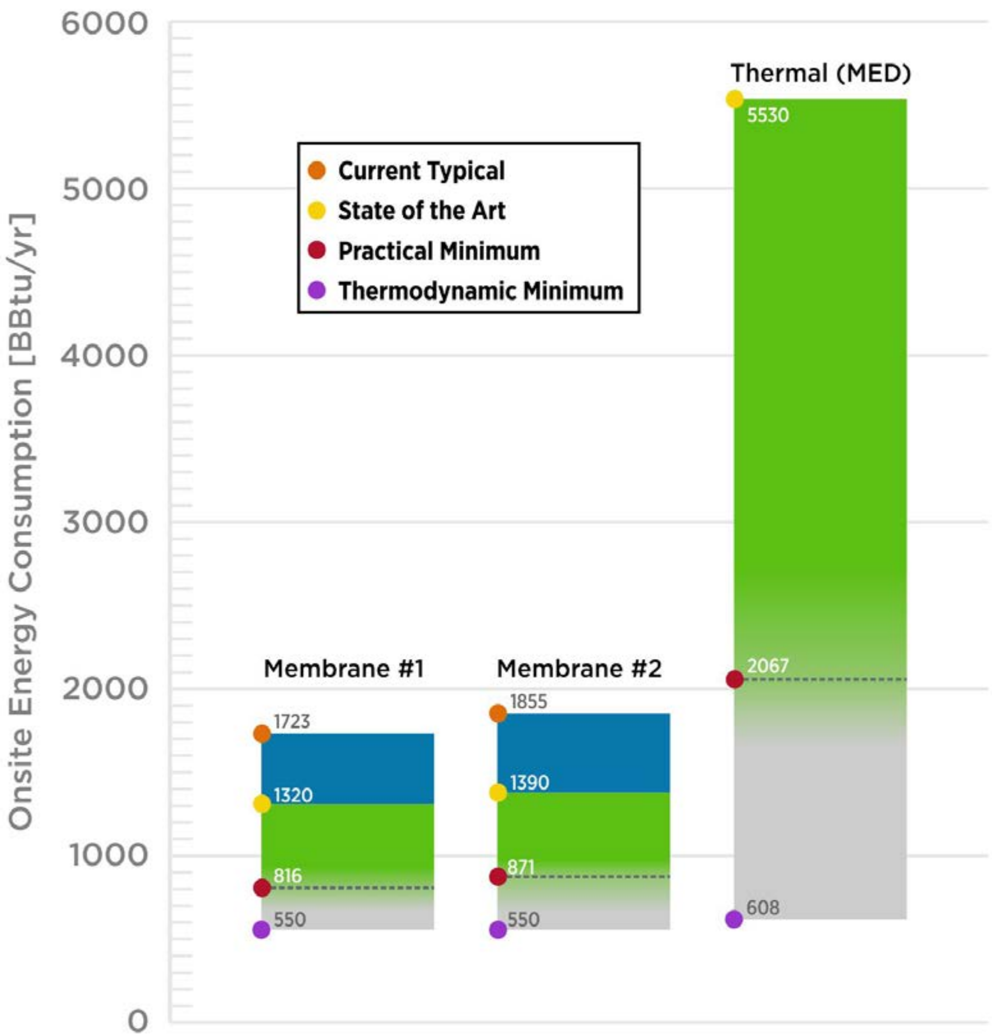
2016 Uptake for Seawater Desalination in the U.S.

Energy Consumption (Billion Btu/yr) =

Energy Intensity ($kWh_{total\ electrical\ equivalent}/m^3$) x **Current Uptake** ($m^3$/yr) x **C** (Billion Btu/kWh)

- In the U.S., annual municipal potable water production capacity from seawater desalination is 145,000,000 m^3 for 2016
- Since largely dominated by Carlsbad facility and other RO systems, broad assumption that this is at 50% recovery
  - *290,000,000 m^3 for intake annually*
- Assuming 16.5:1 concentrate dilution ratio for discharge, based on calculation
  - *2,531,000,000 m^3 pumped annually for discharge*
- For reference: energy consumption to source all currently desalinated seawater in the U.S. from fresh and ground water sources (excludes distribution) : *146 Billion Btu*
  - *Assumes national average energy intensity for providing municipal water from freshwater of 0.29 kWh/m^3*
  - *Higher in some regions: Southern California: 1,285 Billion Btu*

Energy Consumption and Savings Opportunity for 3 Systems

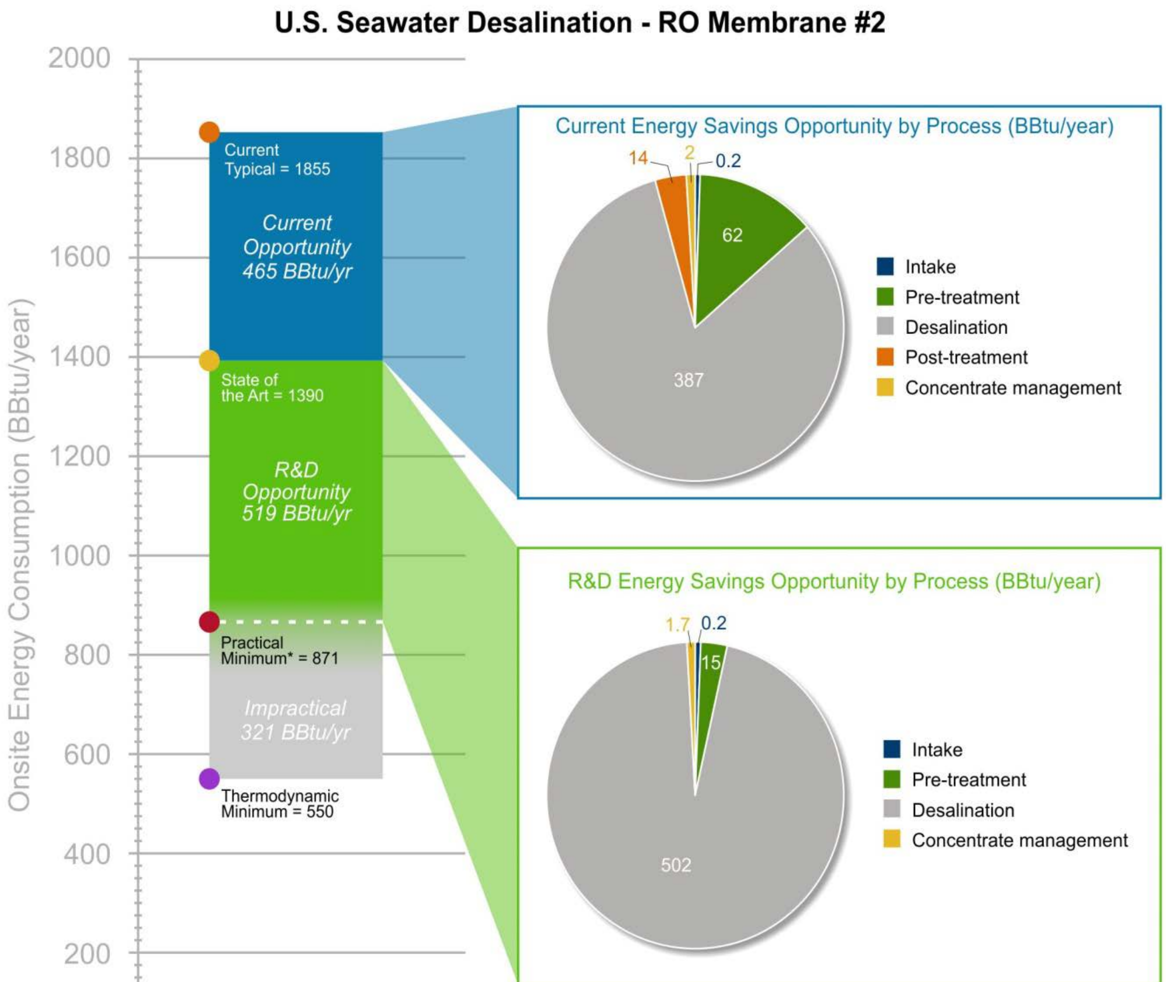


Membrane # 1: RO-based w/ subsurface intake operating at 50% recovery of 500 ppm (0 ppm for TM) product water from 35,000 ppm feedwater

Membrane #2: RO-based Open ocean intake at 50% recovery of 500 ppm (0 ppm for TM) product water from 35,000 ppm feedwater

Thermal: MED-based system at 35% recovery of <25 ppm (0 ppm for TM) product water from 45,000 ppm feedwater

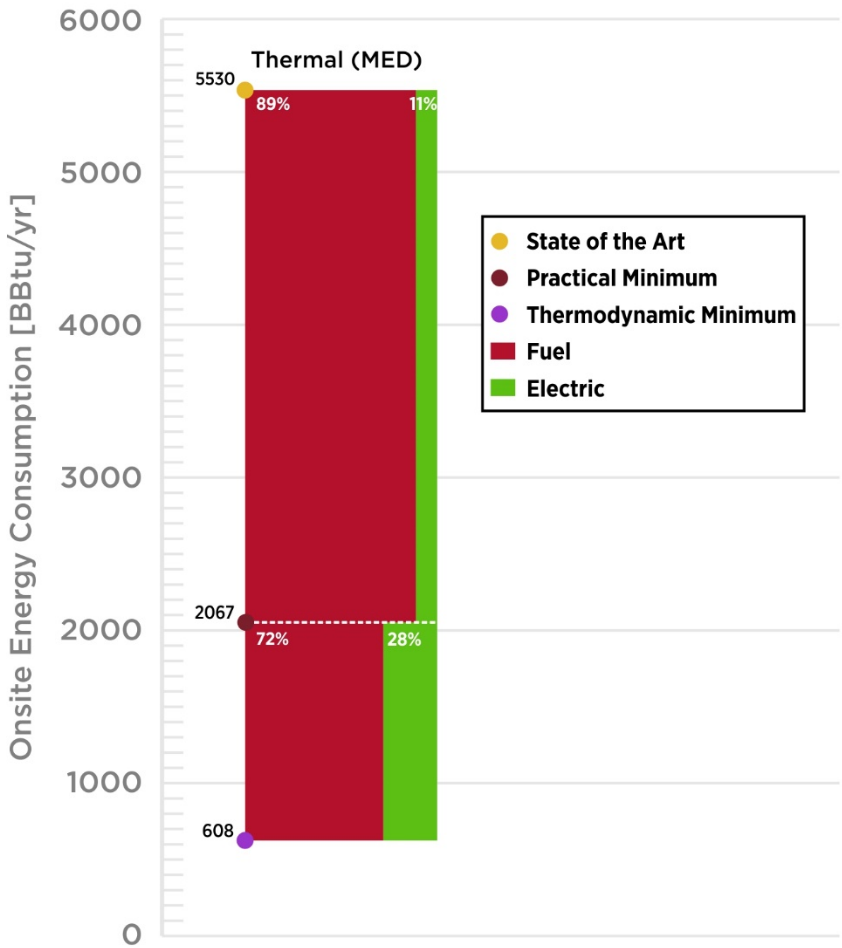
Energy Savings Opportunity for RO system w/Open Ocean Intake



CT, SOA, TM operating conditions: RO-based system at 50% recovery of 500 ppm (0 ppm for TM) product water from 35,000 ppm feedwater. PM operating conditions: semi-batch RO-based system at 42% recovery of 379 ppm product water from 36,357 ppm feedwater.

- **90% of the energy saving opportunity is in the desalination operation**
- **Pretreatment offers the next largest opportunity (8%)**
- **Much of U.S. production already operating at SOA conditions**

R&D Opportunity for Thermal (MED) System w/Open Ocean Intake



Thermal SOA, PM, TM operating conditions: MED-based system at 33.0-37.5% (35% average) recovery of <25 ppm (0 ppm for TM) product water from 45,000 ppm feedwater.

- Fuel sources in thermal desalination accounted for nearly all of the total energy savings for the R&D opportunity
- Opportunity for Waste Heat or Renewable Thermal Energy to Offset Direct Fuel Use in Thermal MED

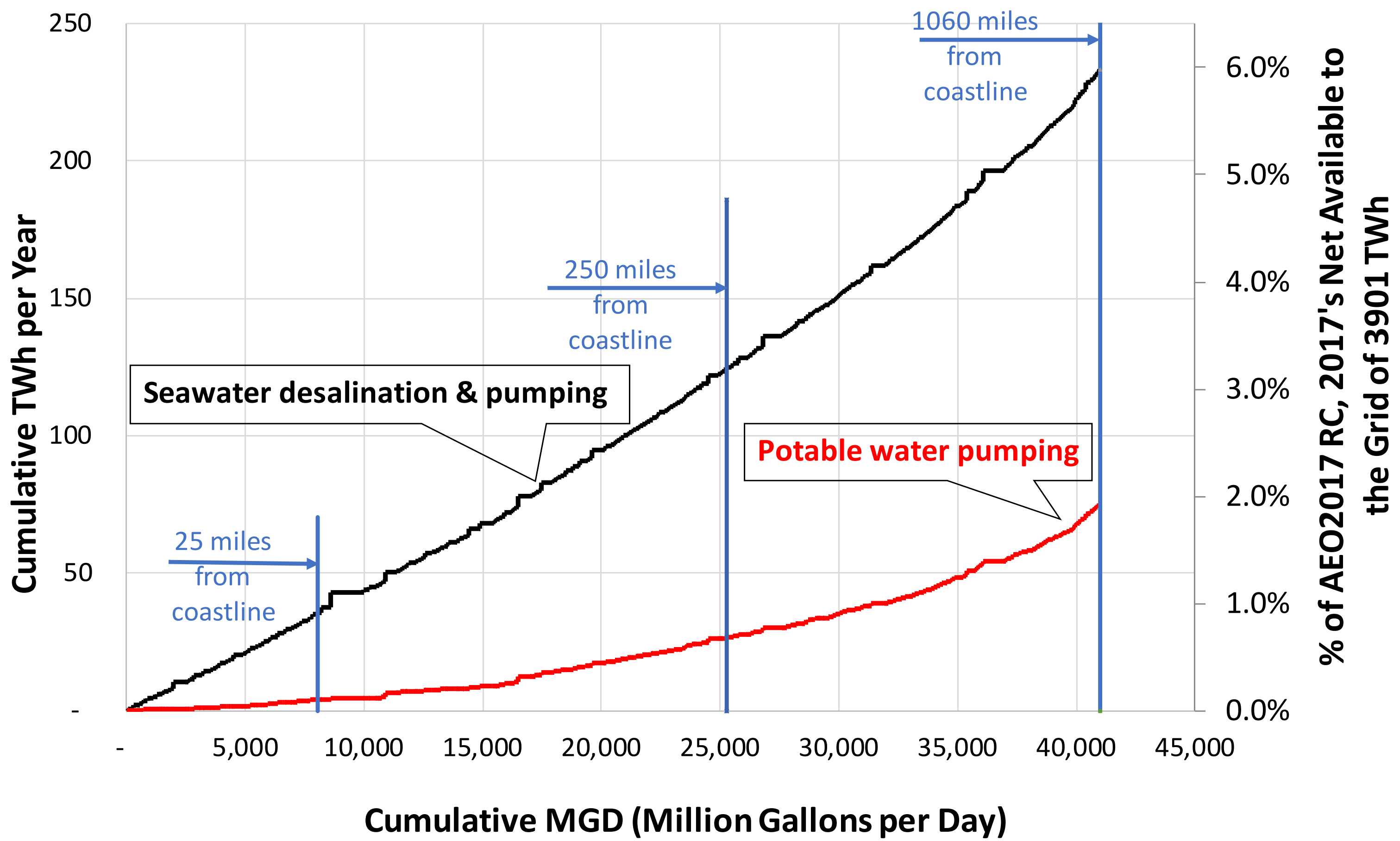
Scenarios: Potential Impact Under Greater Adoption

- Saline water (sea and brackish water) is a very small source of municipal water in the U.S. on the order of 0.1% → Hence, the impact on U.S. energy consumption is small at current uptake levels

- Potential impact of greater uptake:
  1) Scenario 1: supply all continental U.S. county's public water demand with desalinated water from U.S. coastal areas, and
  2) Scenario 2: supply all water stressed regions of the continental US with desalinated water from U.S. coastal areas

- Evaluated using open ocean intake RO system operating at SOA conditions with water demand equivalent to 2010 public water demand (from USGS)

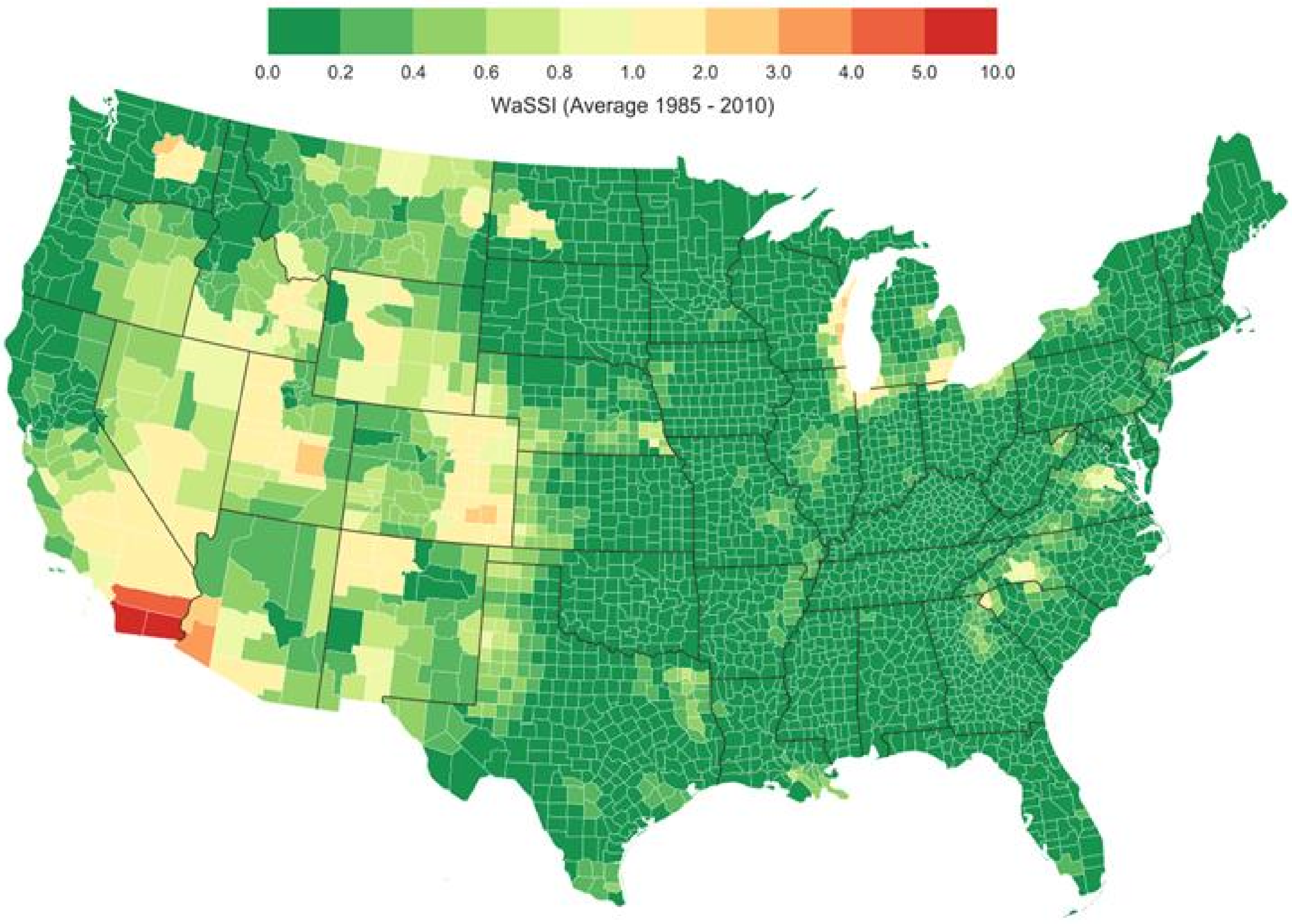
Scenario 1: Supplying All Municipal Water



Though impractical, sourcing all U.S. municipal water from seawater would represent **6% of projected 2017 electricity production**.

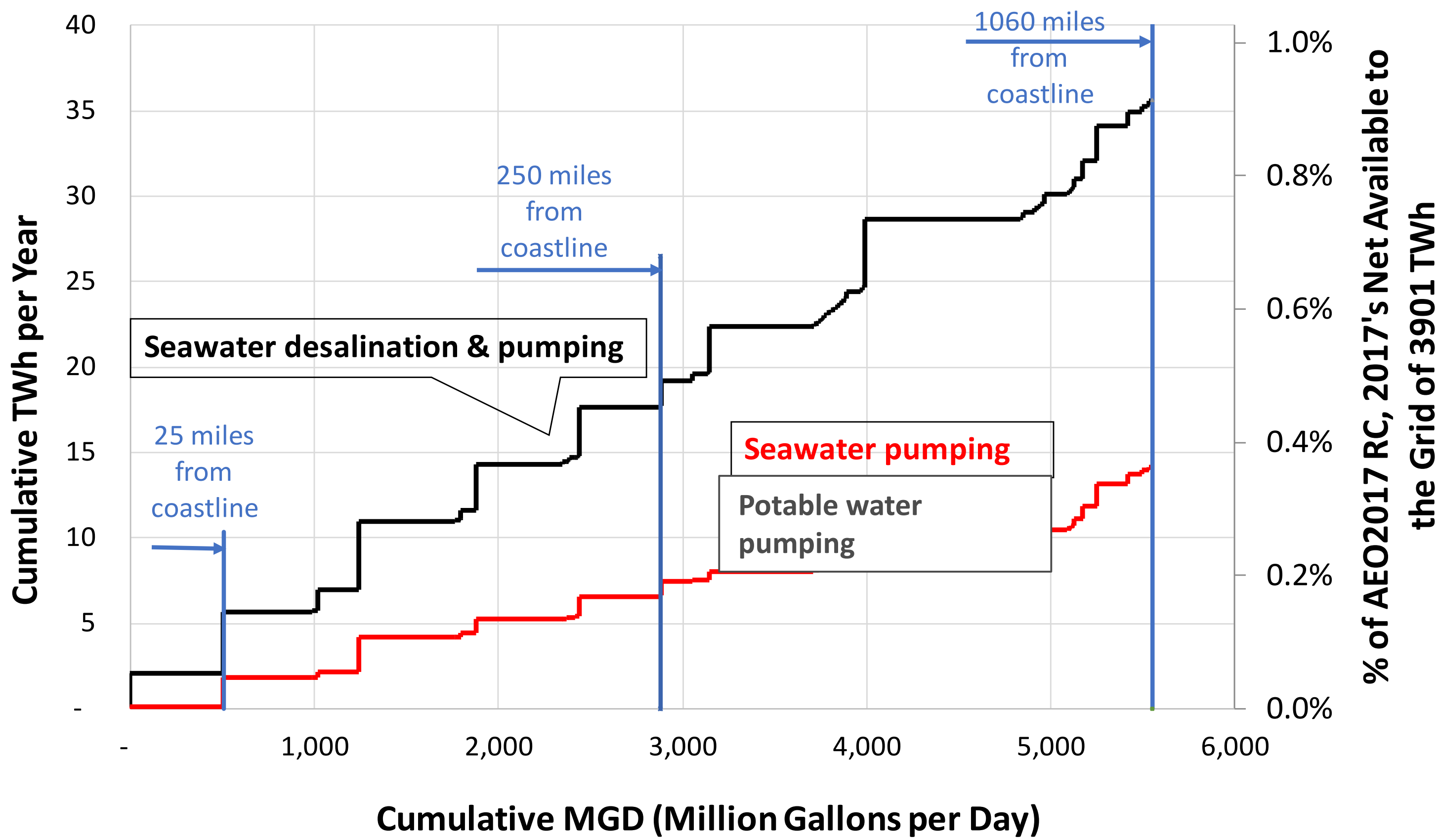
Provides an upper bound for seawater desalination impact on electric grid

Water Supply Stress Index



WaSSI estimated using *WaSSI Ecosystems Services Model* by NC State, USDA, and US Forest Service

Scenario 2: Supplying Water Stressed Counties



Supplying public water for counties with WaSSI > 1 and 250 miles from a coastline would require **0.5% of projected 2017 electricity production**

More likely that these counties would diversify water sources and some could meet a portion of their public water demand from seawater.

Manufacturing Water Use Analysis

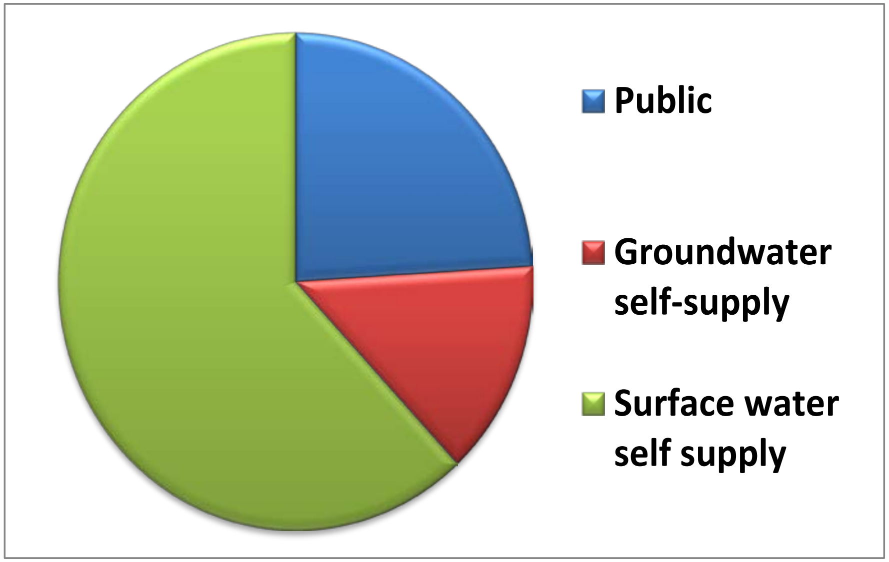
Industrial water use in 2010

75% (~16,000 MGD) is estimated to be self supplied (e.g. onsite surface or ground)

- Mostly freshwater; only 6% saline
- Down 12% from 2005
- Down 38% from 1985

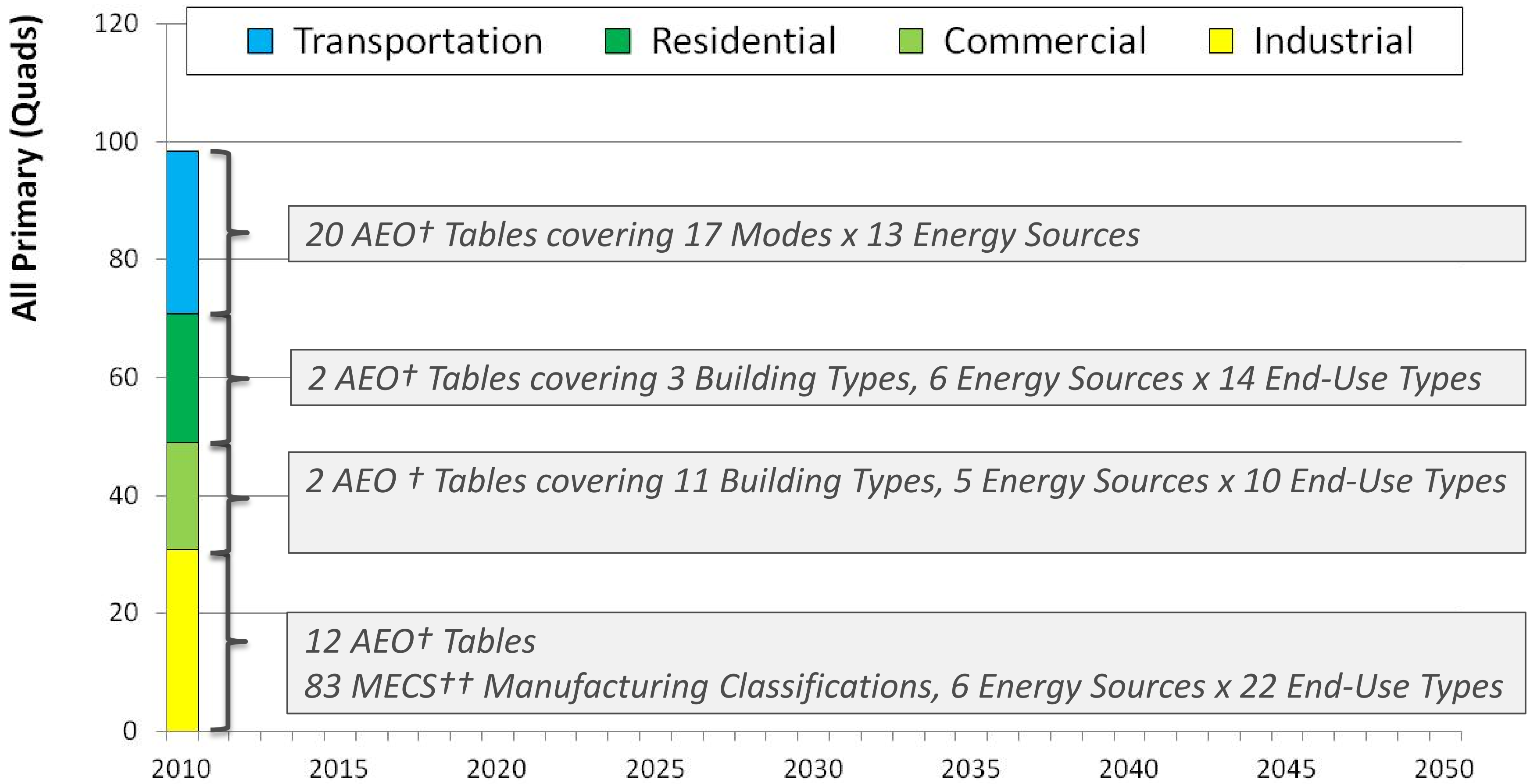
25% (~5,000 MGD) is estimated to be supplied from public supply

- USGS stopped estimating public supply by end use sector after 1995
- Assumed, based on 1995 estimates, that 12% of public supply is for industry



Estimates based on USGS data

Publically Available U.S. Energy Consumption Data



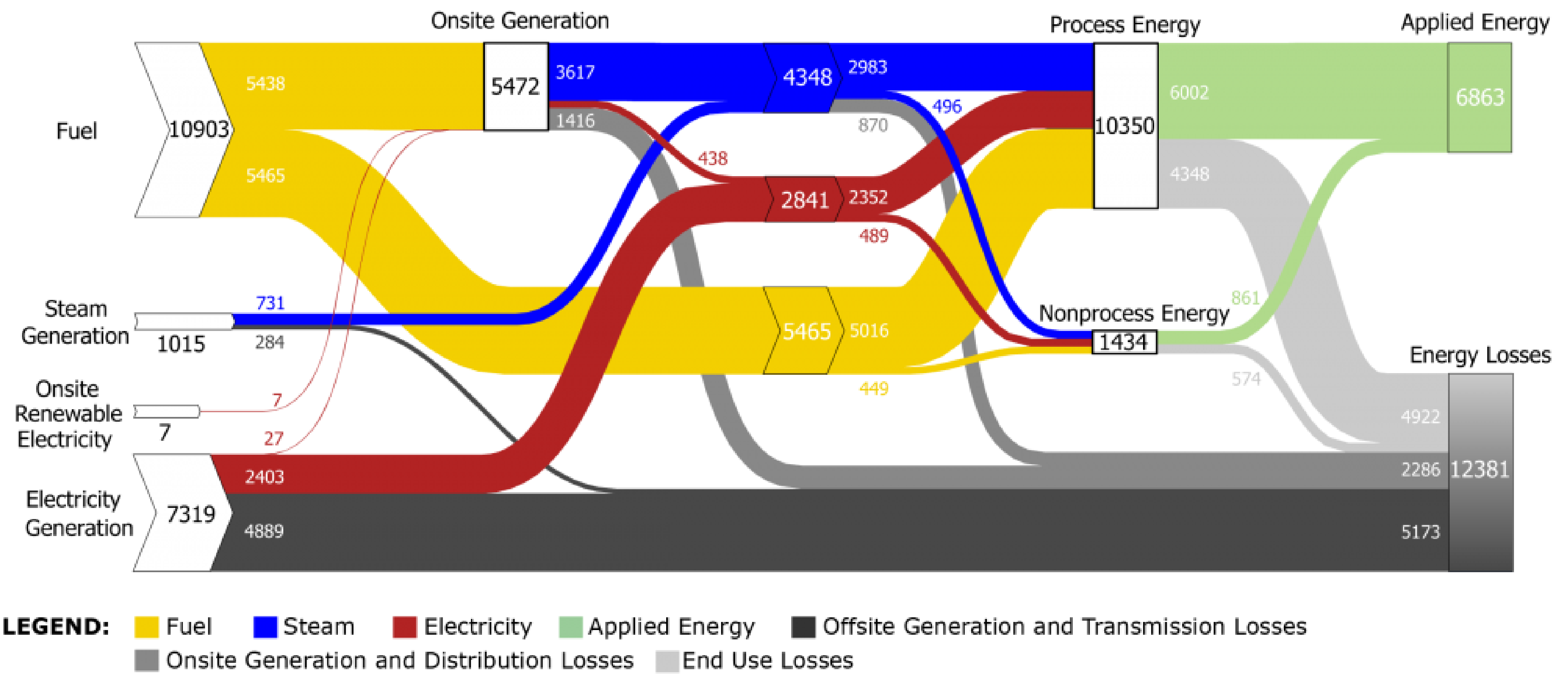
About the Data

† *Annual Energy Outlook (AEO) Tables* – U.S. economy-wide energy consumption forecast to 2040

†† *Manufacturing Energy Consumption Survey* (MECS) 2010 – Detailed energy consumption by end-uses

How to quantify the opportunity space? Start with current energy use within the manufacturing sector….

U.S. Manufacturing Sector (TBtu), 2010

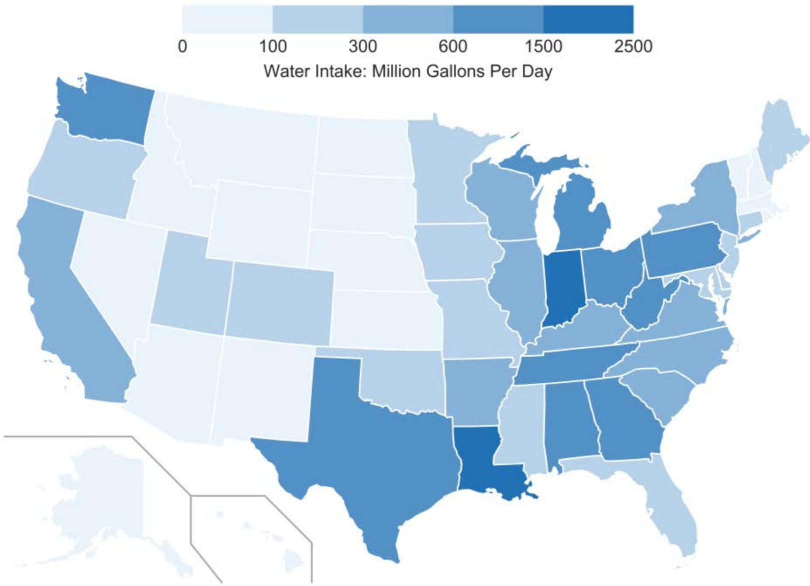


Note: 1 quad = 1,000 TBtu

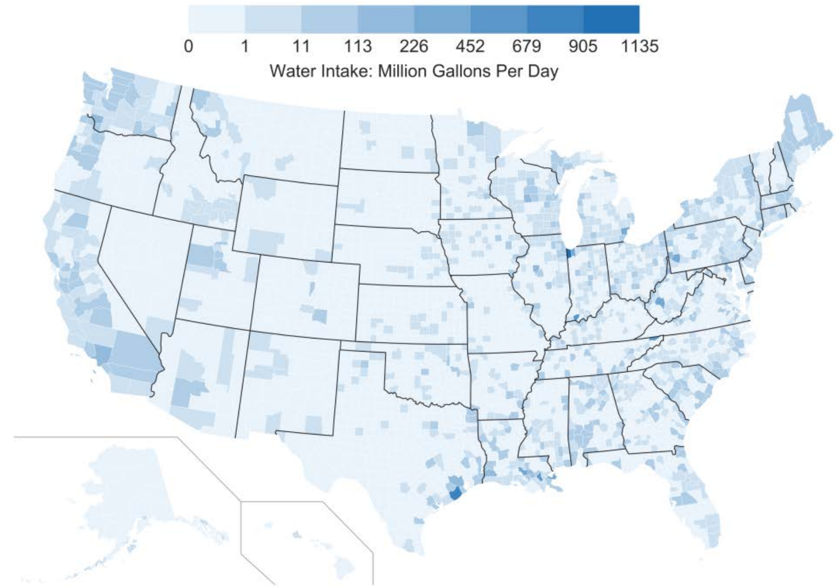
https://www.energy.gov/eere/amo/static-sankey-diagram-full-sector-manufacturing

Geographic Spread of U.S. Manufacturing Water Withdrawal (Estimated)

State



County



Estimates based on USGS data

Issues with U.S. Manufacturing Water Data Availability

- Water use conservation driven by risk mitigation within the manufacturing sector
- Little to no data on U.S. manufacturing water use and related characteristics
  - Limited to USGS 5-year estimates
  - Some data at individual state level or by sector
- Water use issues and risk are a local phenomena requiring data at the watershed level
  - Research based on broad national data may not target at-risk industries

Need for better data

Analysis Approach

Leverage existing data sets to:

Quantify manufacturing water withdrawals and consumption at the national, state, and county-levels broken down by sector using Canadian water and economic, USGS, and U.S. Economic Census data

↓

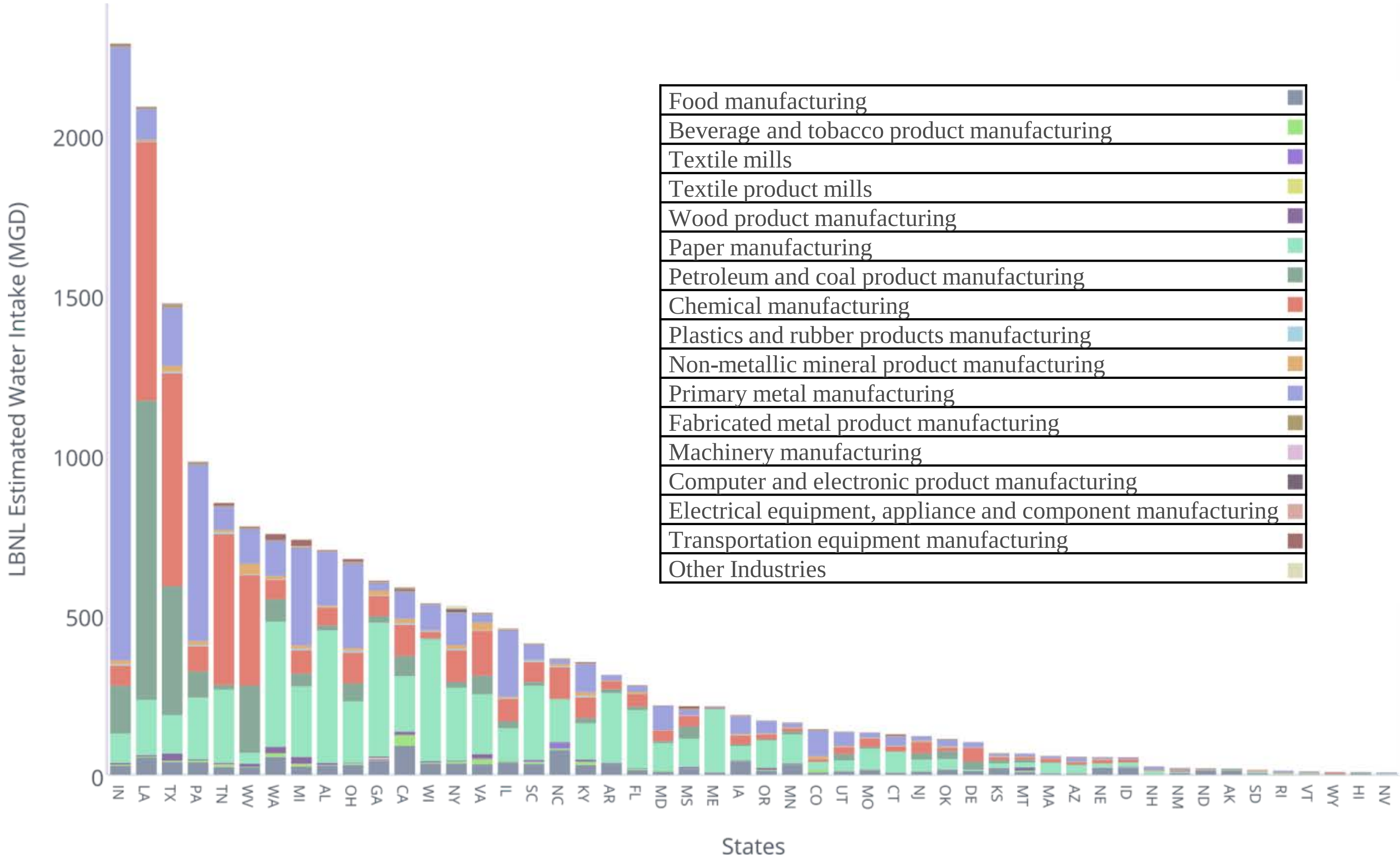
Identify sectors at-risk, defined as those sectors with large footprints in areas with long-term over-usage of locally available water supplies

↓

Use the results from 1 and 2 to identify sectors for subsequent Energy-Water Bandwidth Studies and other manufacturing water use-related research

For further details on methods and results for estimates presented on slides 36-38, see: Rao, P., Sholes, D., Morrow, W.R., and J. Cresko. 2017. "Estimating U.S. Manufacturing Water Use". American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Industry. Denver, CO. August 16 – 18.

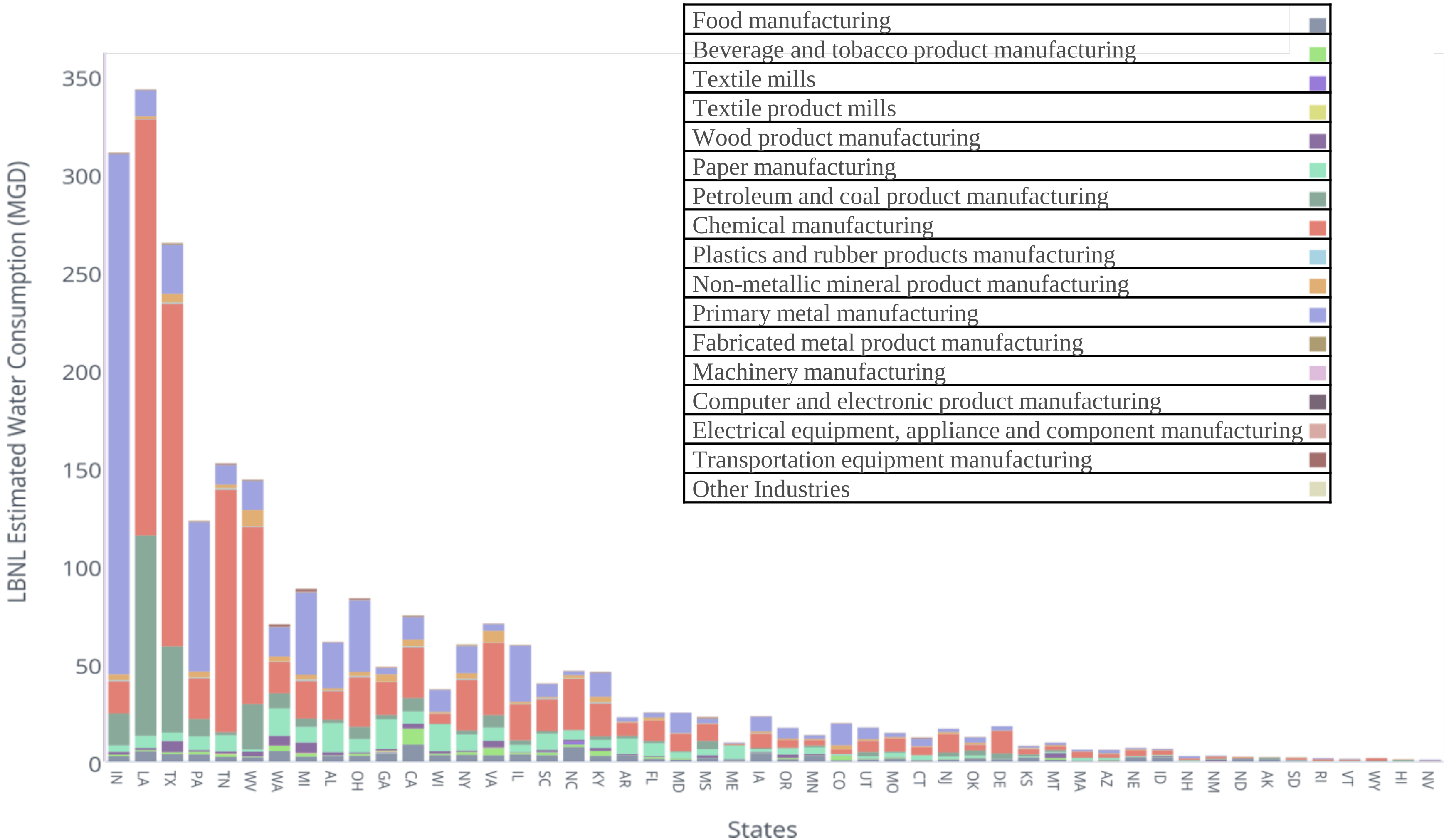
U.S. Manufacturing Water Withdrawals by Sector and State



Allows for better understanding of water use distribution:

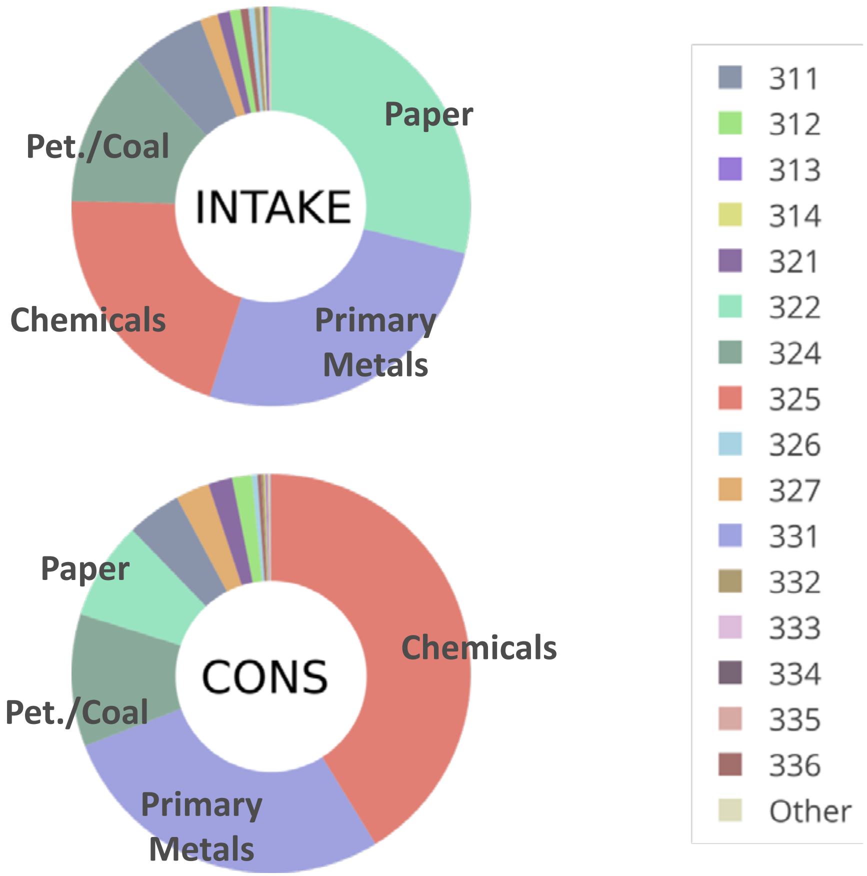
- IN and LA estimated to have the largest annual withdrawals
- Withdrawals in some states dominated by single industry (i.e., primary metals in IN, paper & pulp in ME)
- Other states have more diversity in their water withdrawals (e.g., MI, TX, NC)

U.S. Manufacturing Water Consumption by Sector and State



- Consumptive use will have greater impact on operational risk than withdrawals
- LA has highest amount of consumptive use
- Two of the top ten states in terms of consumption are drought prone (CA and TX)

U.S. Manufacturing Water Withdrawals and Consumption



311	Food manufacturing
312	Beverage and tobacco product manufacturing
313	Textile mills
314	Textile product mills
321	Wood product manufacturing
322	Paper manufacturing
324	Petroleum and coal product manufacturing
325	Chemical manufacturing
326	Plastics and rubber products manufacturing
327	Non-metallic mineral product manufacturing
331	Primary metal manufacturing
332	Fabricated metal product manufacturing
333	Machinery manufacturing
334	Computer and electronic product manufacturing
335	Electrical equipment, appliance and component manufacturing
336	Transportation equipment manufacturing
Other	Other Industries

- Largest sectors by withdrawals: 1) Pulp & Paper 2) Primary Metals 3) Chemicals
- Largest sectors by consumptive use: 1) Chemicals 2) Primary Metals 3) Petroleum and Coal Products

Evaluation of Sector Water Use "At-Risk"

Sectors in red are those that have the highest share of their water use in locations with WaSSI > 1 (i.e., locations where total water use exceeds local supplies)

NAICS ID	Manufacturing Sector	Estimated % Water Intake within each WaSSI Bin				
		[0.0,0.2)	[0.2,0.4)	[0.4,0.8)	[0.8,1.0)	[1.0,inf)
311	Food	71.79	11.27	6.67	3.29	6.97
312	Beverage and Tobacco Product	71.27	9.13	11.04	2.44	6.12
313	Textile Mills	80.05	8.57	4.05	5.71	1.61
314	Textile Product Mills	87.57	5.28	2.14	2.14	2.86
321	Wood Product	83.76	6.19	2.90	5.51	1.65
322	Paper	78.93	7.92	5.38	1.47	6.30
324	Petroleum and Coal Product	51.90	28.88	8.97	1.23	**9.02**
325	Chemical	65.63	25.28	4.88	1.15	3.06
326	Plastics and Rubber Products	70.70	12.61	5.48	2.65	**8.57**
327	Non-metallic Mineral Product	67.68	11.11	6.04	6.69	**8.49**
331	Primary Metal	51.57	8.17	4.57	1.05	**34.64**
332	Fabricated Metal Product	67.55	13.56	6.09	2.86	**9.95**
333	Machinery	69.55	14.53	6.06	1.67	**8.19**
334	Computer and Electronic Product	67.96	12.64	7.95	4.54	6.92
335	Electrical Equipment, Appliance and Component	75.53	11.79	4.78	2.69	5.20
336	Transportation Equipment	72.18	9.21	6.07	2.20	**10.35**
Other	Other Industries [315,316,323,337,339]	73.81	10.33	3.37	4.11	8.38

Extending the Analysis of Water in Manufacturing

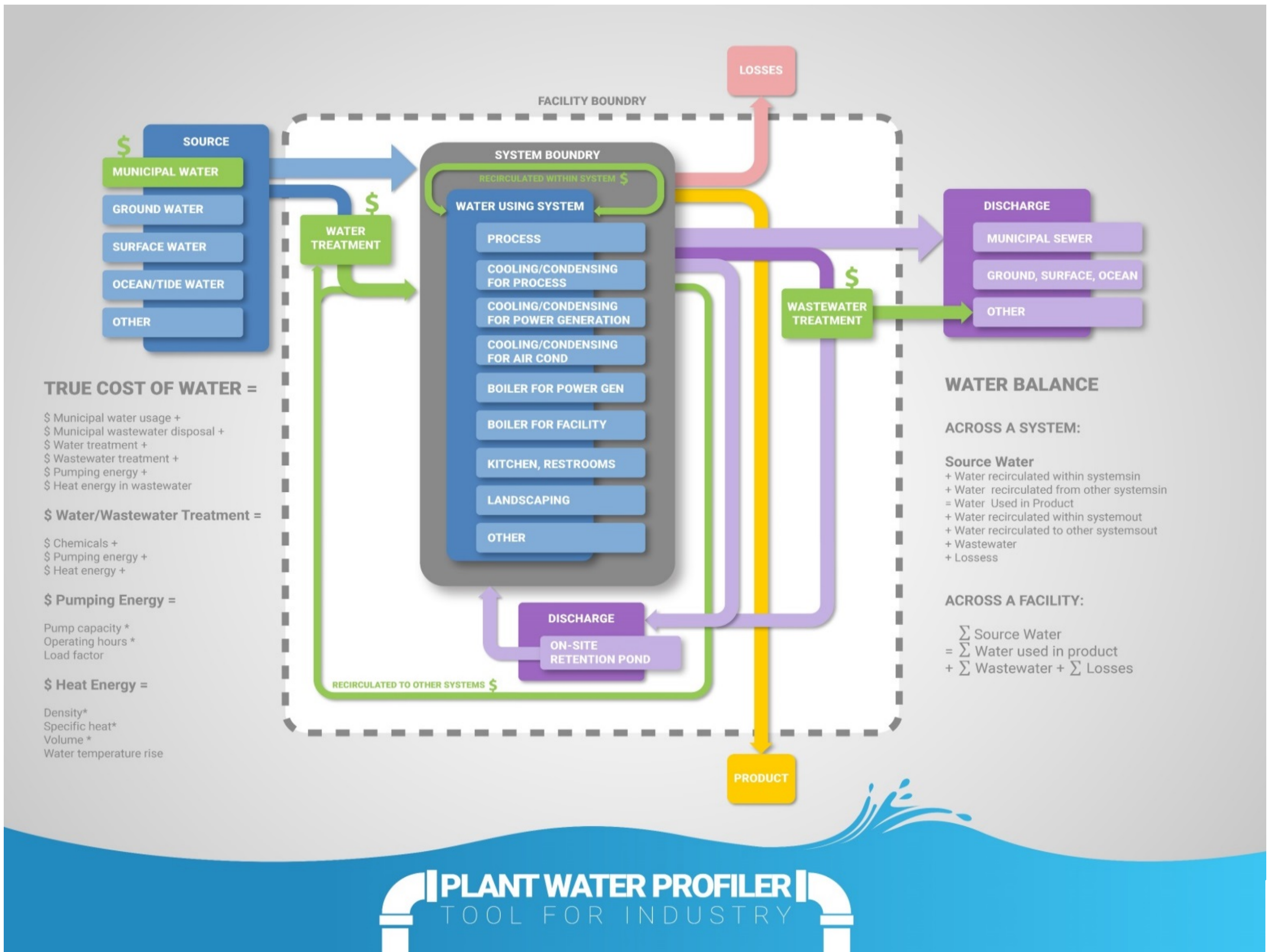
- Bandwidth Studies to understand technologies that could realize joint water-energy savings

- Software tools to empower end users' water conservation efforts

- Analysis to identify water substitutes

Plant Water Profiler (PWP) Tool for Industry

- Identify how water is being procured and consumed at facilities,
- Quantify true cost of water used in different systems,
- Quantify potential water and cost savings,
- Identify steps to save water.

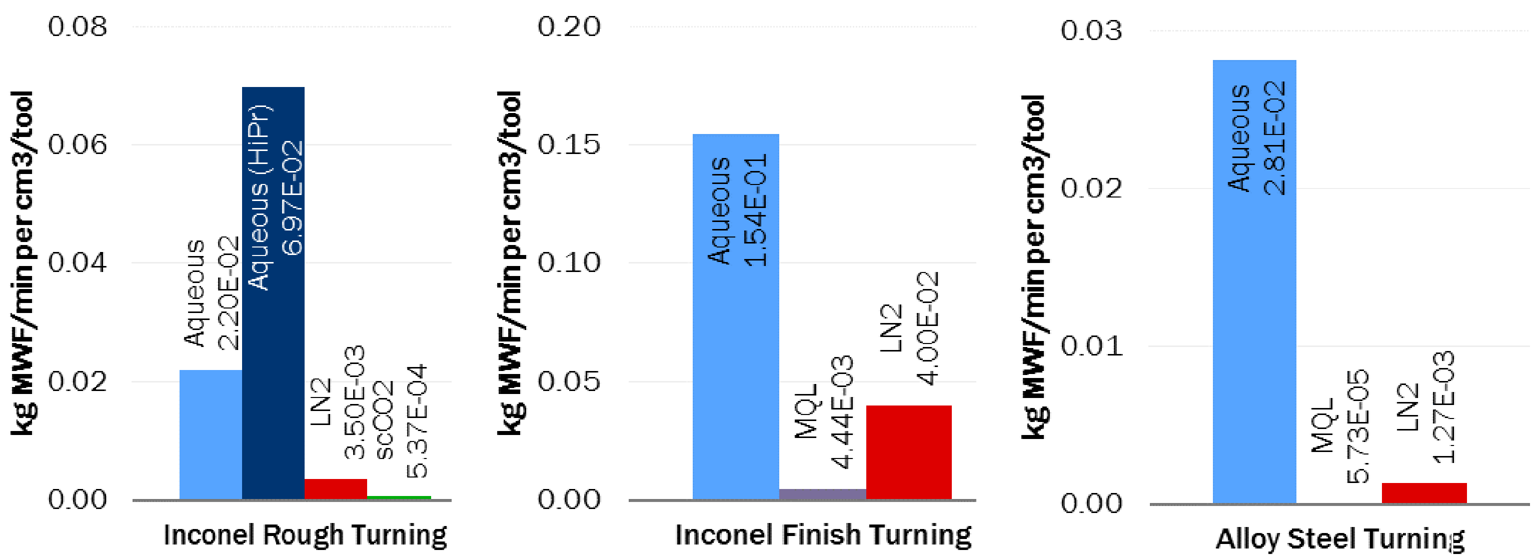


Water Consumption in the Fabricated Metals Industry

Motivation: Reduce the environmental and health burden of water use in the metals fabrication industry – substitution with industrial gases as process fluids.

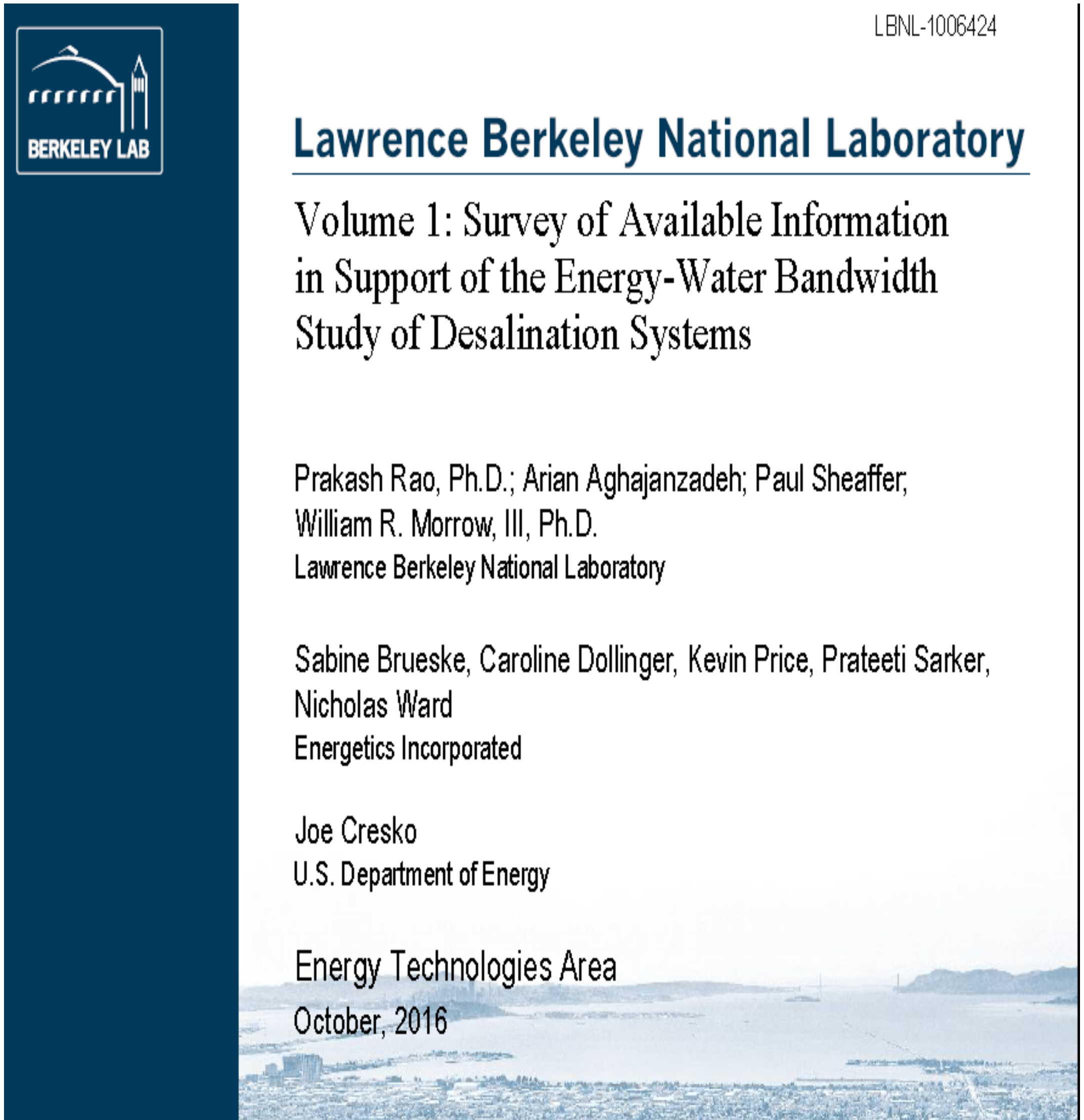
Method: Deploy a metric to quantify, harmonize, and compare flow rates of different metalworking fluids (MWF) and their efficacy in heat removal and lubrication in a wide range of processes and materials

Early Results for Performance-Normalized MWF Usage



Take a look:

Volume 1 report published


LBNL-1006424

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Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems

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Energy Technologies Area
October, 2016

Next steps:

- Energy-Water Bandwidth Study for Seawater Desalination Systems report to be published Summer of 2017.
- Manufacturing analyses under development.

Thank you.

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ANL – Diane Graziano, Matt Riddle, Sarang Supekar

LBNL – Arman Shehabi, William Morrow, Sarah Smith, Prakash Rao

NREL – Alberta Carpenter, Maggie Mann, Rebecca Hanes, Samantha Reese, Kelsey Horowitz, Timothy Remo

ORNL – Sujit Das, Sachin Nimbalkar, Pablo Cassorla, Kristina Johnson

Energetics – Sabine Brueske, Heather Liddell, Caroline Dollinger, Hani Hawa

Back-up Slides

Energy Intensity for Membrane System 1: RO System w/ Subsurface Intake

Unit Operation	CT	SOA	PM	TM
Intake @ 1 m TDH	0.0040 kWh_e/m^3 (Subsurface)	0.0036 kWh_e/m^3 (Subsurface)	0.0034 kWh_e/m^3 (Subsurface)	0.0028 kWh_e/m^3 (Subsurface)
Pretreatment	0.02 kWh_e/m^3 (Cartridge filtration + bag filter)	Same as CT	Same as CT	0 kWh_e/m^3 (None)
Desalination (all at ~50% recovery and ~3.5% salinity)	3.3 kWh_e/m^3 (RO)	2.5 kWh_e/m^3 (RO at Carlsbad)	1.48 kWh_e/m^3 (Semi-batch RO)	1.06 kWh_e/m^3 (Salt from water)
Post-treatment	0.08 kWh_e/m^3 (Remineralization + disinfection)	0.06 kWh_e/m^3 (Remineralization + disinfection)	Same as SOA	0 kWh_e/m^3 (None)
Concentrate Management @ 1 m TDH	0.0040 kWh_e/m^3 (To surface water)	0.0036 kWh_e/m^3 (To surface water)	0.0034 kWh_e/m^3 (To surface water)	0.0028 kWh_e/m^3 (To surface water)

Energy Intensity for Membrane System 2: RO System w/ Open Ocean Intake

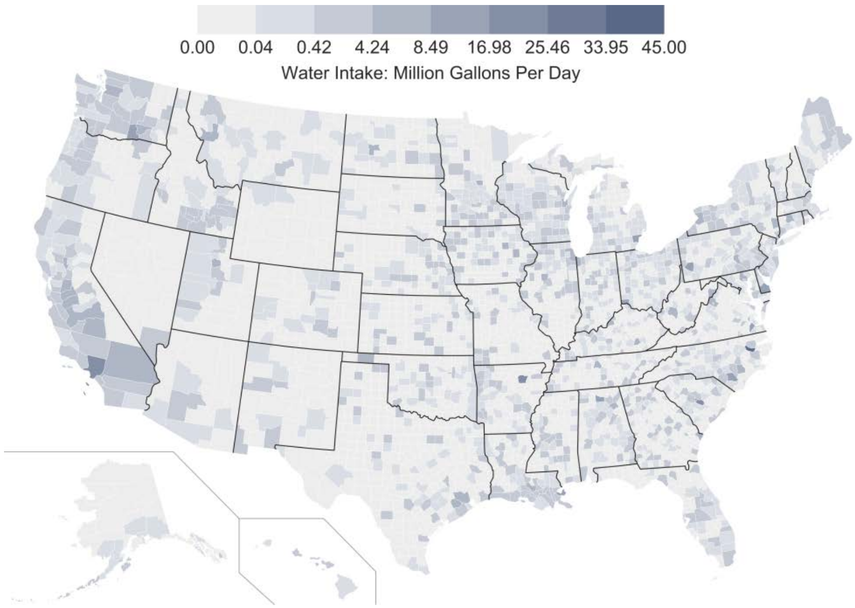
Unit Operation	CT	SOA	PM	TM
Intake @ 1 m TDH	0.0040 kWh_e/m^3 (Open ocean intake)	0.0036 kWh_e/m^3 (Open ocean intake)	0.0034 kWh_e/m^3 (Open ocean intake)	0.0028 kWh_e/m^3 (Open ocean intake)
Pretreatment	0.29 kWh_e/m^3 (Flocculation/ coagulation/ sand and cartridge filtration)	0.16 kWh_e/m^3 (Flocculation/ coagulation/ sand and cartridge filtration)	0.13 kWh_e/m^3 (Vacuum-driven MF)	0 kWh_e/m^3 (none)
Desalination (all at ~50% recovery and ~3.5% salinity)	3.3 kWh_e/m^3 (RO)	2.5 kWh_e/m^3 (RO at Carlsbad)	1.48 kWh_e/m^3 (Semi-batch RO)	1.06 kWh_e/m^3 (Salt from water)
Post-treatment	0.06 kWh_e/m^3 (Remineralization + disinfection)	0.08 kWh_e/m^3 (Remineralization + disinfection)	Same as SOA	0 kWh_e/m^3 (None)
Concentrate Management @ 1 m TDH	0.0040 kWh_e/m^3 (To surface water)	0.0036 kWh_e/m^3 (To surface water)	0.0034 kWh_e/m^3 (To surface water)	0.0028 kWh_e/m^3 (To surface water)

Energy Intensity for Thermal System

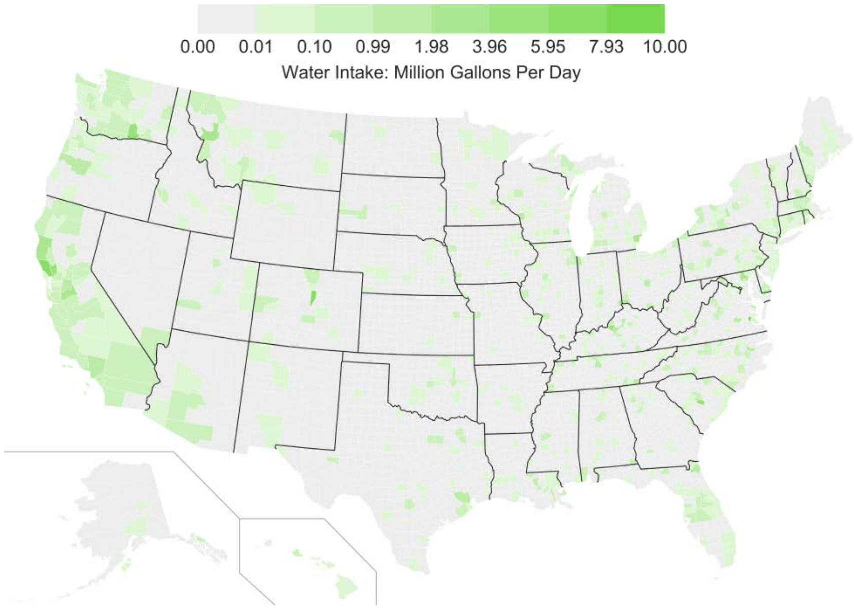
Unit Operation	CT	SOA	PM	TM
Intake @ 1 m TDH	N/A in U.S.	0.0036 kWh_e/m^3 (Open ocean intake)	0.0034 kWh_e/m^3 (Open ocean intake)	0.0028 kWh_e/m^3 (Open ocean intake)
Pretreatment	N/A in U.S.	0.05 kWh_e/m^3 (Gravity-fed media filtration + chlorination)	0.035 kWh_e/m^3 (NF)	0 kWh_e/m^3 (None)
Desalination (all at 35% recovery and 4.5% salinity)	N/A in U.S.	11 $kWh_{T,equiv}/m^3$ (MED – TVC)	4 $kWh_{T,equiv}/m^3$ (Condensing MED)	1.20 $kWh_{T,equiv}/m^3$ (Salt from water)
Post-treatment	N/A in U.S.	0.11 kWh_e /m^3 (Remineralization+ Disinfection)	Same as SOA	0 kWh_e/m^3 (None)
Concentrate Management @ 1 m TDH	N/A in U.S.	0.0036 kWh_e/m^3 (To surface water)	0.0034 kWh_e/m^3 (To surface water)	0.0028 kWh_e/m^3 (To surface water)

Water Withdrawals by Sector and County

311 - Food

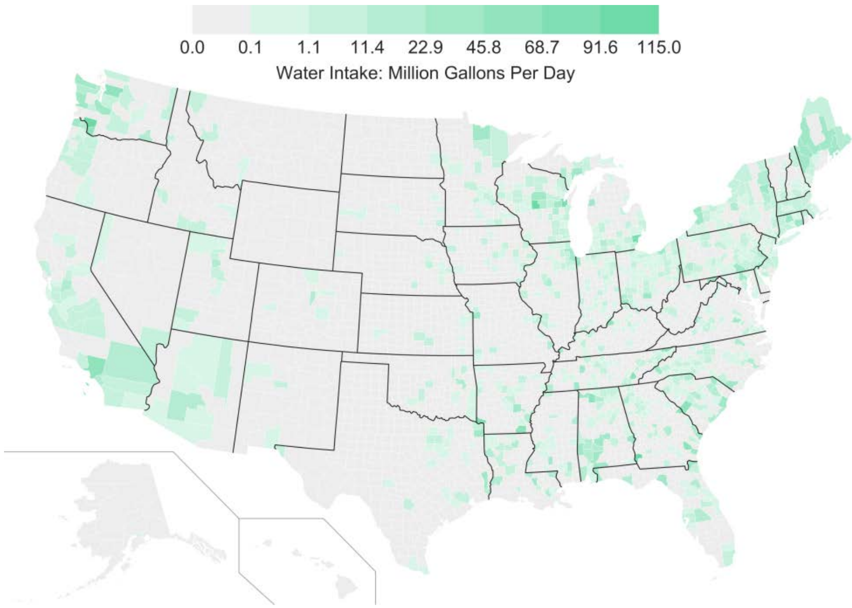


312 – Bev. And Tobacco

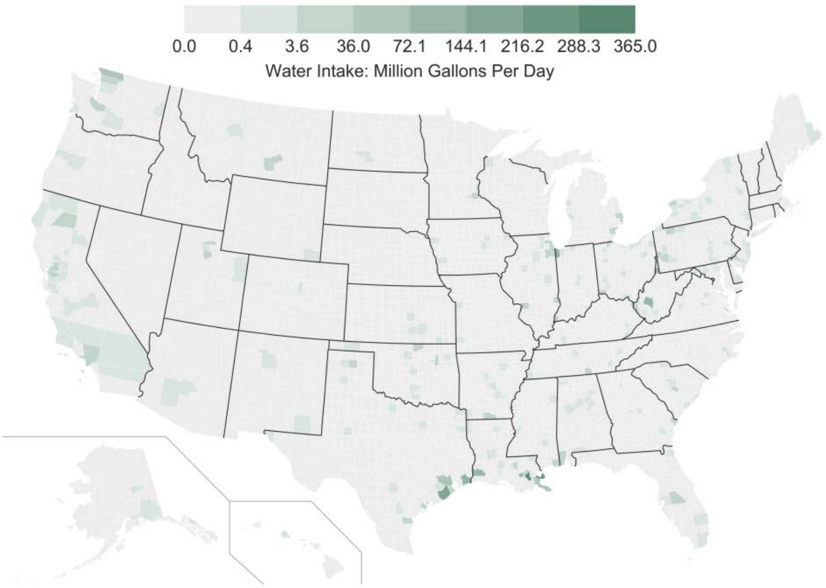


Water Withdrawals by Sector and County

322- Paper

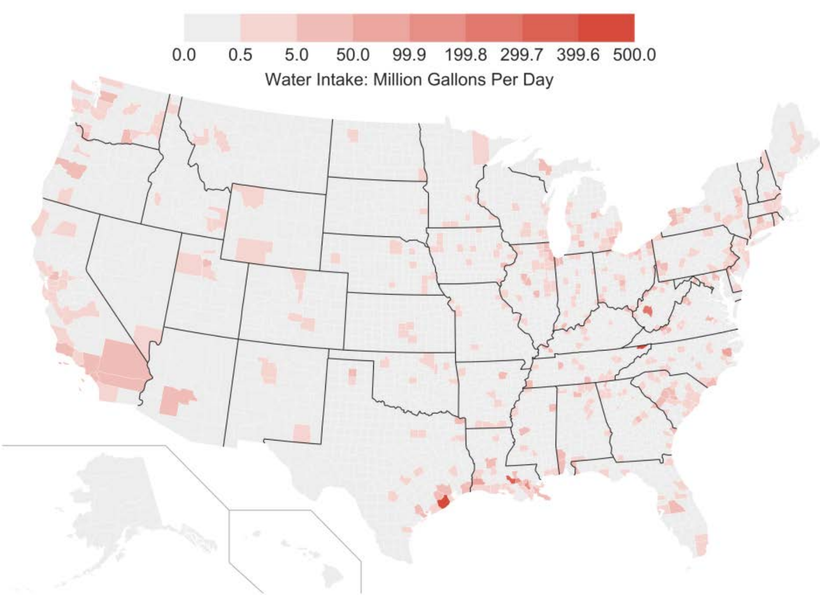


324 - Petroleum

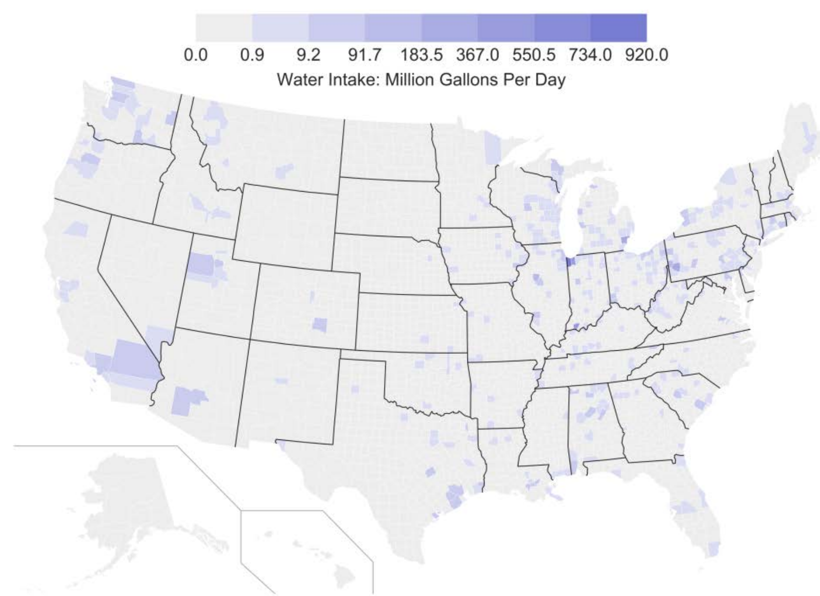


Water Withdrawals by Sector and County

325 - Chemicals



331 – Primary Metals



Links to Bandwidths Studies

- Chemicals Industry Energy Bandwidth Study, 2015. Available electronically at http://energy.gov/sites/prod/files/2015/08/f26/chemical_bandwidth_report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing, 2015. Available electronically at http://energy.gov/sites/prod/files/2015/08/f26/pulp_and_paper_bandwidth_report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining, 2015. Available electronically at http://energy.gov/sites/prod/files/2015/08/f26/petroleum_refining_bandwidth_report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing, 2015. Available electronically at http://energy.gov/sites/prod/files/2015/08/f26/iron_and_steel_bandwidth_report_0.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing of Lightweight Materials: Carbon Fiber Reinforced Polymer Composites, 2016 (DRAFT). Available electronically at http://energy.gov/sites/prod/files/2016/04/f30/Carbon%20Fiber%20Report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing of Lightweight Materials: Glass Fiber Reinforced Polymer Composites, 2016 (DRAFT). Available electronically at http://energy.gov/sites/prod/files/2016/04/f30/Glass%20Fiber%20Report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing of Lightweight Materials: Aluminum, 2016 (DRAFT). Available electronically at http://energy.gov/sites/prod/files/2016/04/f30/Aluminum%20Report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing of Lightweight Materials: Advanced High Strength Steel, 2016 (DRAFT). Available electronically at http://energy.gov/sites/prod/files/2016/04/f30/AHSS%20Report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing of Lightweight Materials: Magnesium, 2016 (DRAFT). Available electronically at http://energy.gov/sites/prod/files/2016/04/f30/Magnesium%20Report.pdf
- Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing of Lightweight Materials: Titanium, 2016 (DRAFT). Available electronically at http://energy.gov/sites/prod/files/2016/04/f30/Titanium%20Report.pdf