United States Environmental Protection Agency

Transforming Water Systems Towards A More Sustainable Future

– Implications of Water-Energy Nexus

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A system is more than the sum of its parts.

– Aristotle

- Tools and metrics: emergy and LCA (life cycle assessment)
- System analyses examples
  - Nutrient recovery and removal
  - Energy recovery
  - Water reuse
  - City of Tomorrow

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Emergy is the available energy of any kind previously used both directly and indirectly to make another form of energy, product or service. (Odum, 1996)

Emergy might be thought of as energy memory.

Emergy analysis is an environmental accounting method.

What is EMERGY?

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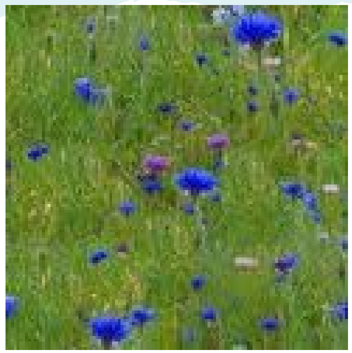
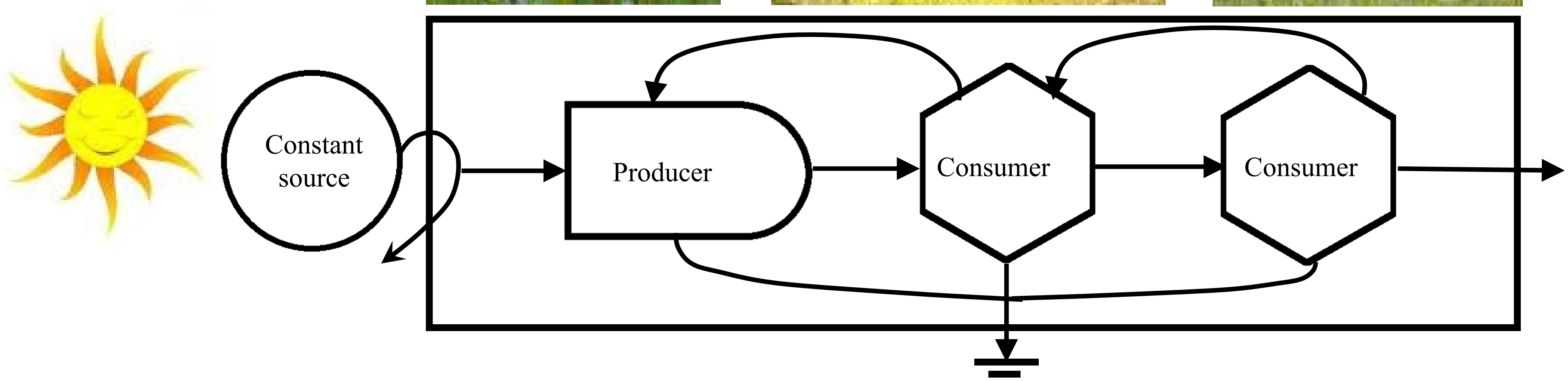
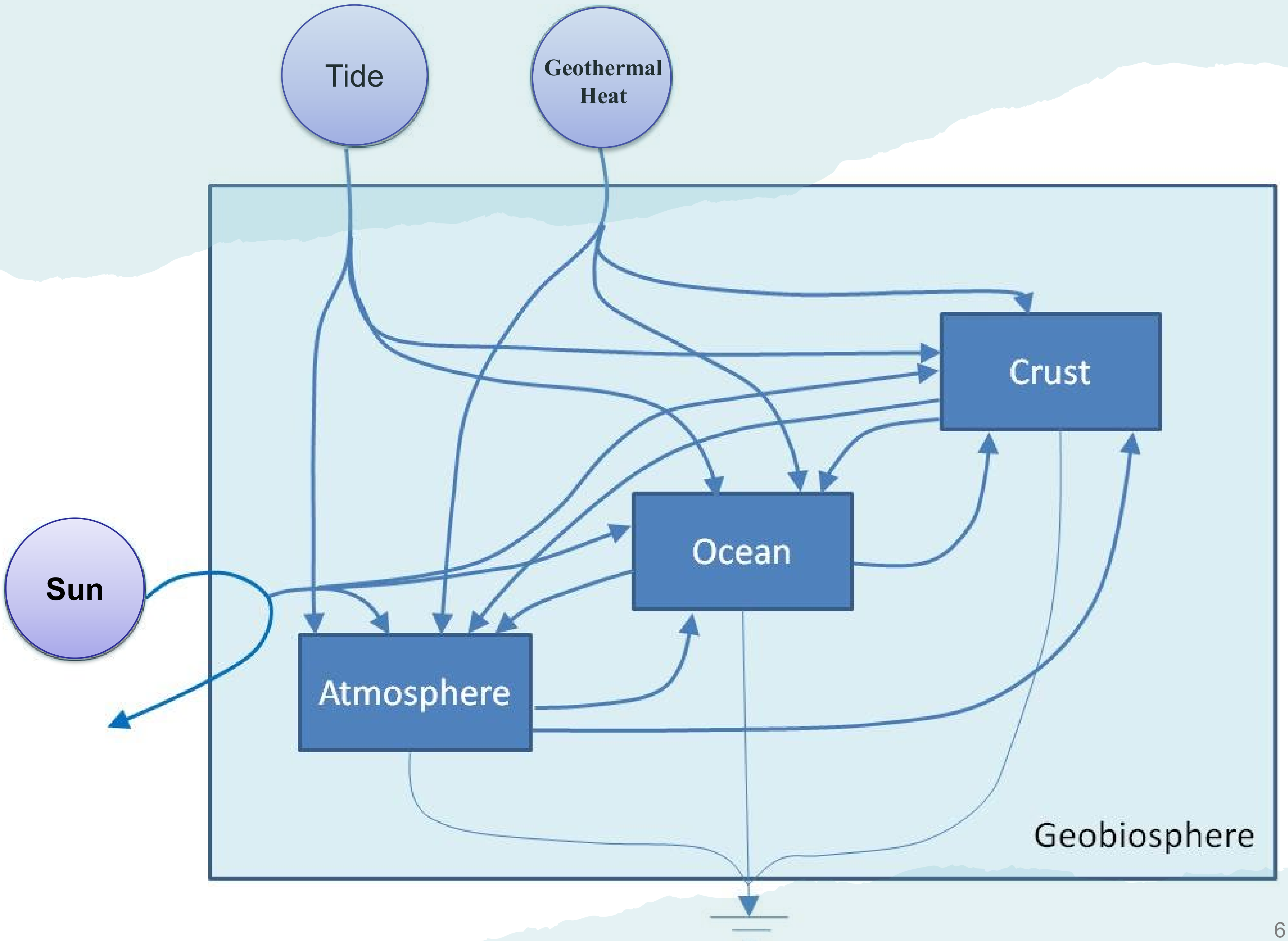
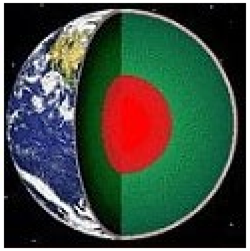





Tide
Geothermal Heat
Sun
Crust
Ocean
Atmosphere
Geobiosphere

What is EMERGY?

- Its unit is the emjoule.
- In this global system, use the solar emjoule (sej).
- 3 primary energy sources: solar, crustal heat, tidal energy
- Annual energy and emergy input for geobiosphere



	solar	crustal heat	tidal
Energy (J/yr)	39300×10^{20}	13.21×10^{20}	0.52×10^{20}
Emergy (sej/yr)	3.93×10^{24}	8.06×10^{24}	3.83×10^{24}

Unit Emergy Value (UEV)

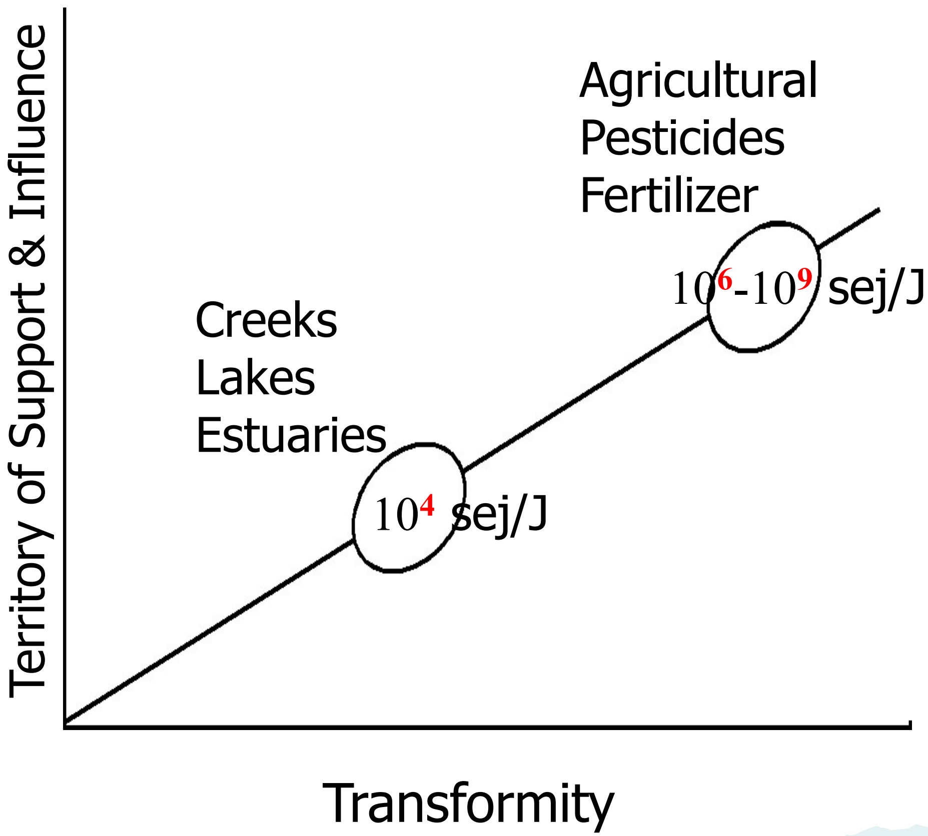
- Material (per mass) – specific emergy

$$\frac{\text{total emergy input}}{\text{mass output}} = \text{sej/g}$$

- Energy (per joule) –Transformity

$$\frac{\text{total emergy input}}{\text{energy output}} = \text{sej/J}$$

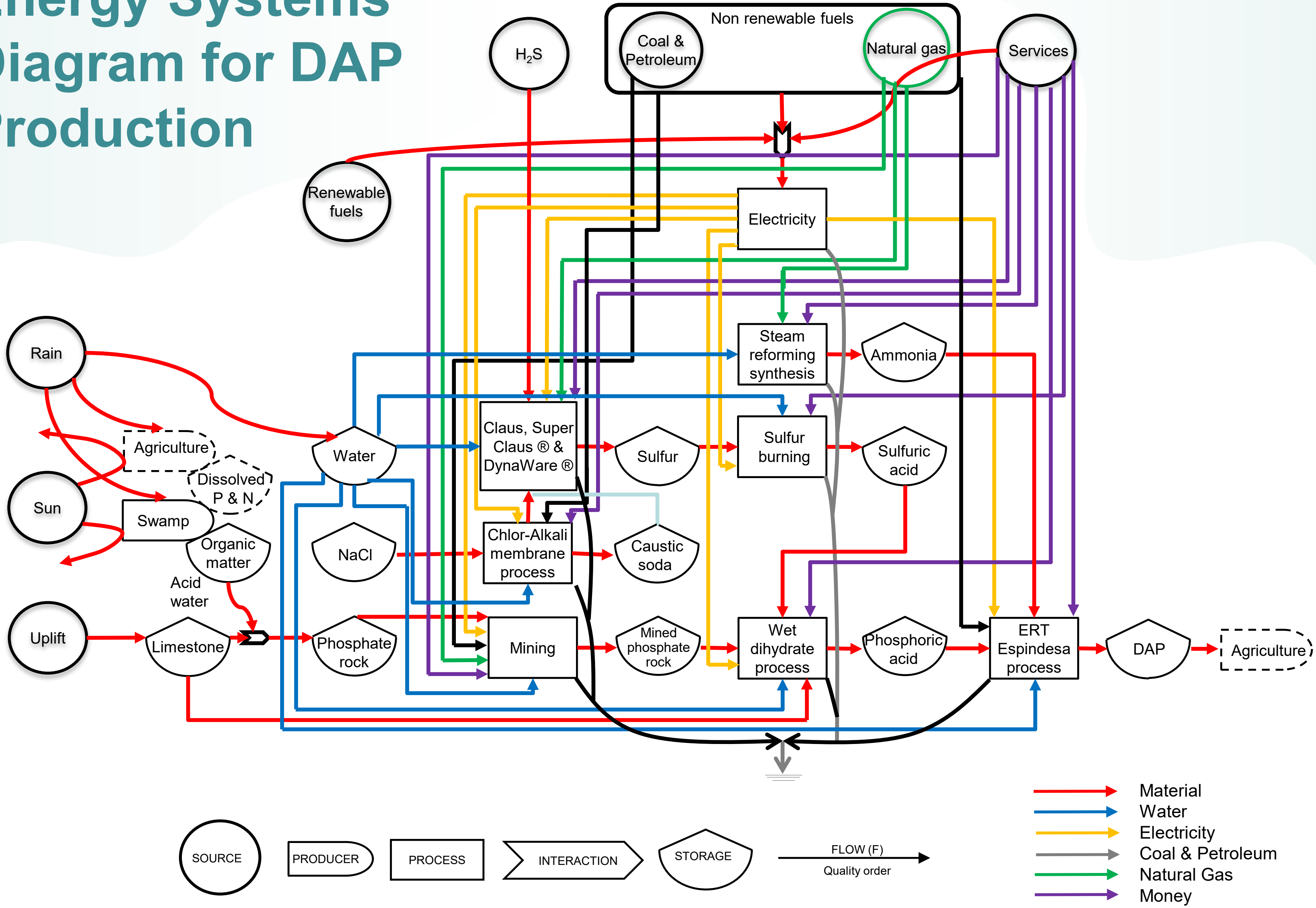
Transformity



- High transformity = high hierarchical order
- High transformity = high territory of influence
- High transformity = more emergy required to make product flow
- High transformity = less efficient

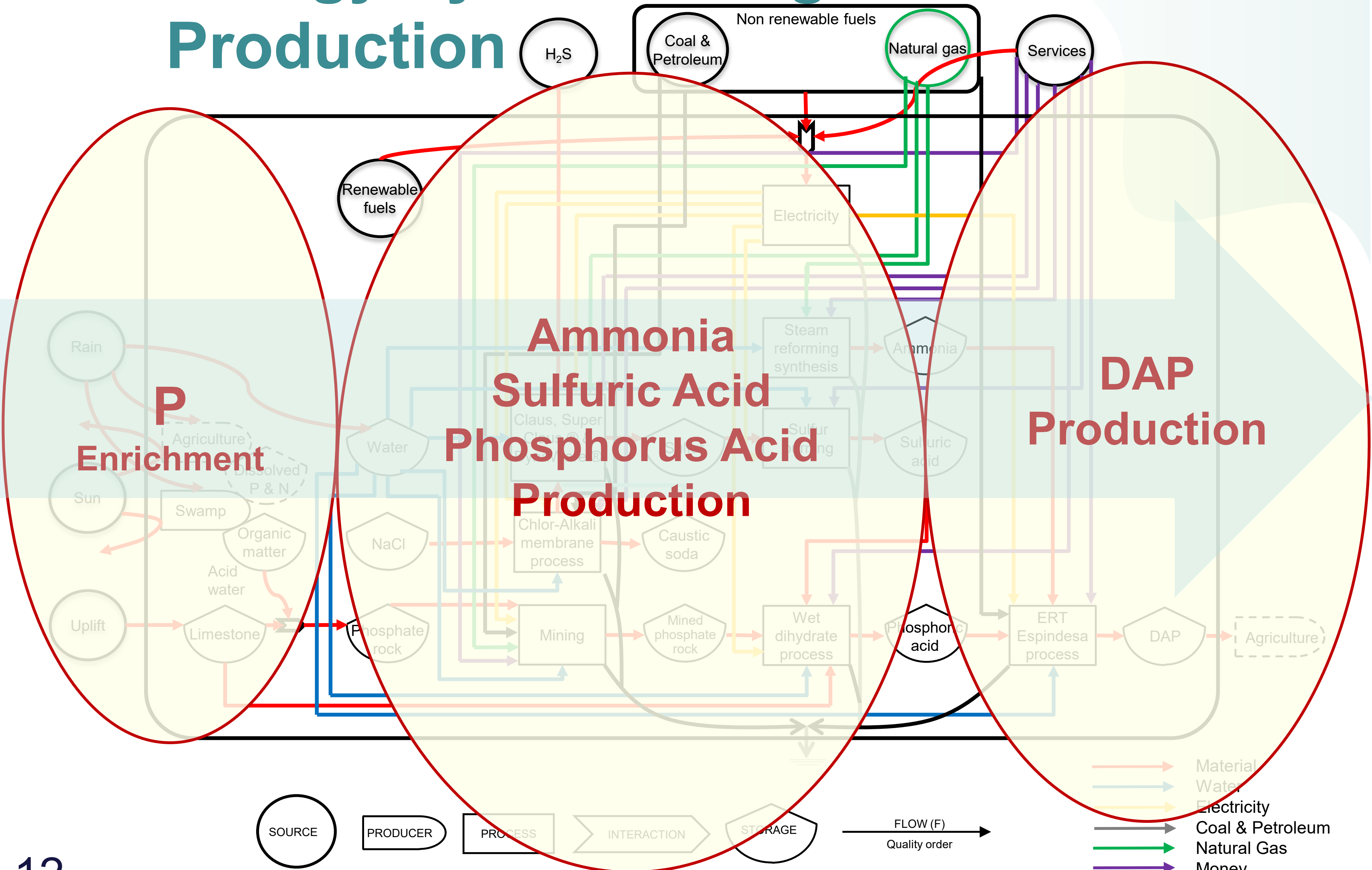
- Tools and metrics: emergy and LCA (life cycle assessment)
- System analyses examples
  - **Nutrient recovery and removal**
  - Energy recovery
  - Water reuse
  - City of Tomorrow

Energy Systems Diagram for DAP Production



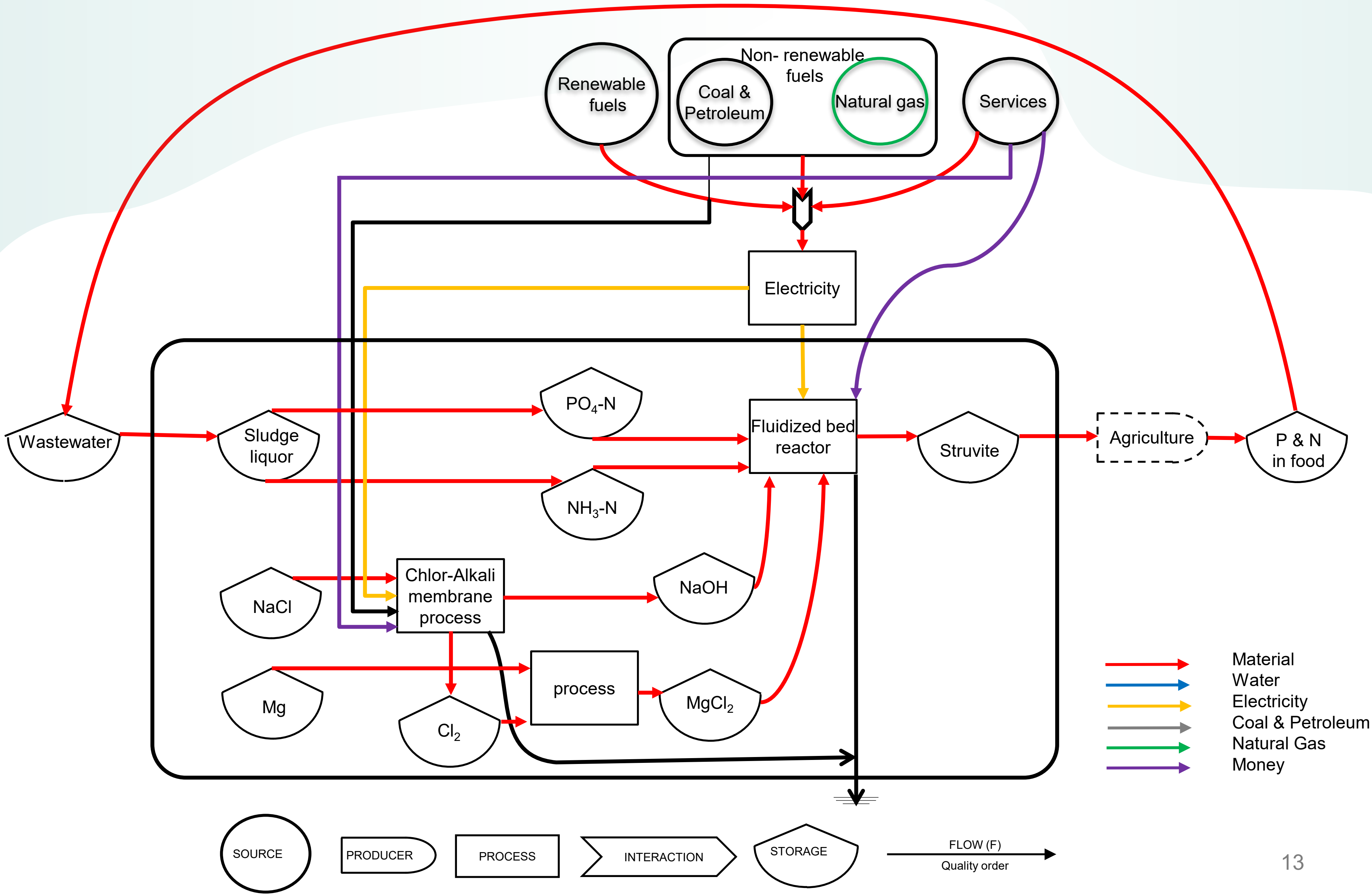
External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

Energy Systems Diagram for DAP Production



External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

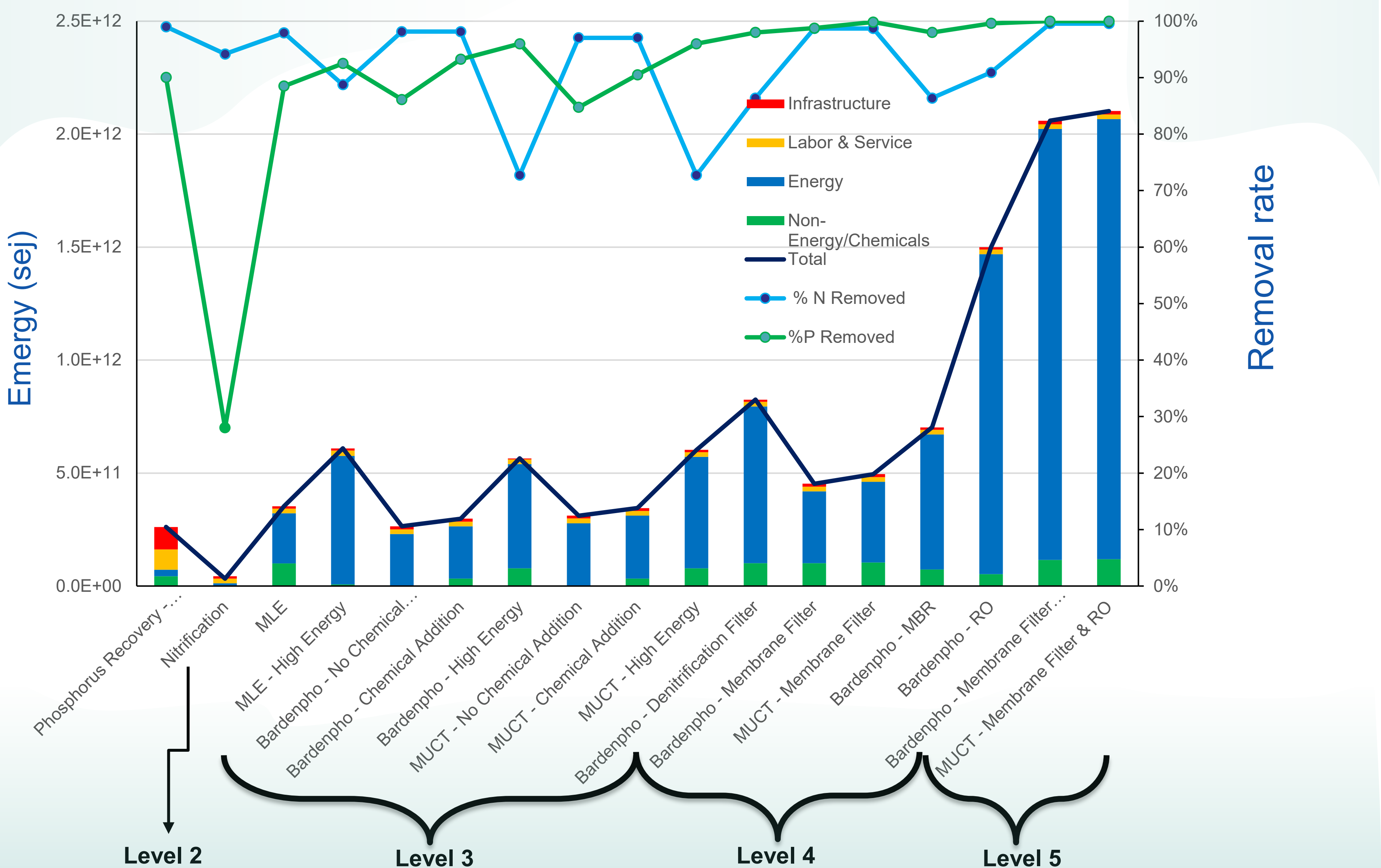
Emergy Systems Diagram for Nutrient Recovery



Removal Processes Considered for the Study

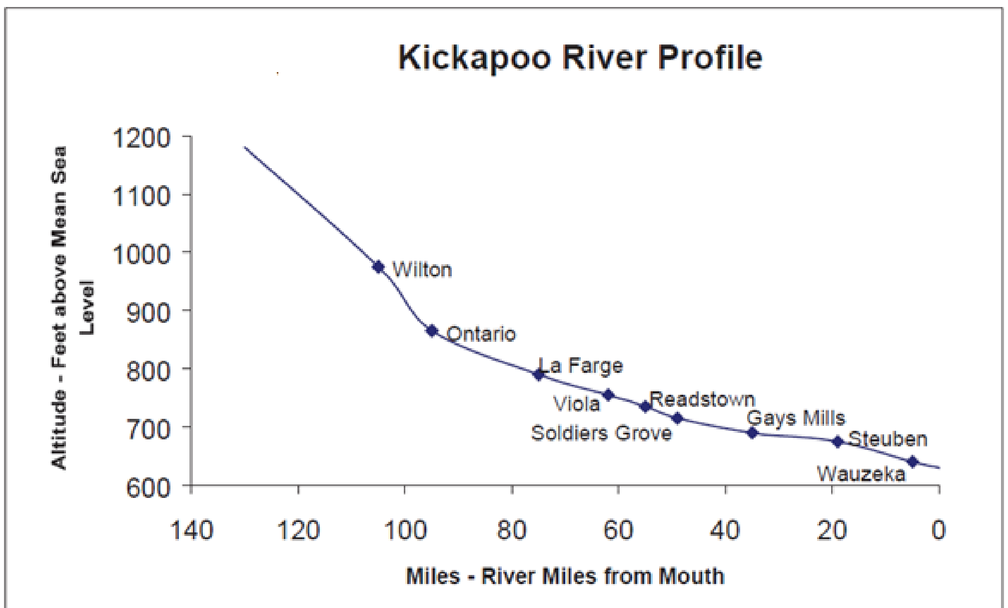
Treatment Level (Effluent Limits)	Nutrient Removal/Recovery Process	Energy (kWh/m^3)	Influent Ammonia (mg/L as NH_3-N)	Influent P (mg/L as P)
Recovery	Phosphorus Recovery - Anammox	0.14	20	7
Level 2 (TN – 8 mg/L, TP – 1 mg/L)	Nitrification	0.23	24	10
Level 3 (TN – 4-8 mg/L, TP – 0.1-0.3 mg/L)	MLE	0.28	23	8
	MLE - High Energy	0.59	32	8
	Bardenpho - No Chemical Addition	0.29	23	8
	Bardenpho - Chemical Addition	0.29	23	8
	Bardenpho - High Energy	0.58	22	5
	MUCT - No Chemical Addition	0.35	23	8
	MUCT - Chemical Addition	0.35	23	8
	MUCT - High Energy	0.56	22	5
Level 4 (TN – 3 mg/L, TP – 0.1 mg/L)	Bardenpho - Denitrification Filter	0.53	22	5
	Bardenpho - Membrane Filter	0.4	23	8
	MUCT - Membrane Filter	0.45	23	8
	Bardenpho - MBR	0.53	22	5
Level 5 (TN - <2 mg/L, TP<0.02 mg/L)	Bardenpho - RO	0.60	22	5
	Bardenpho - Membrane Filter & RO	2.4	23	8
	MUCT - Membrane Filter & RO	2.45	23	8

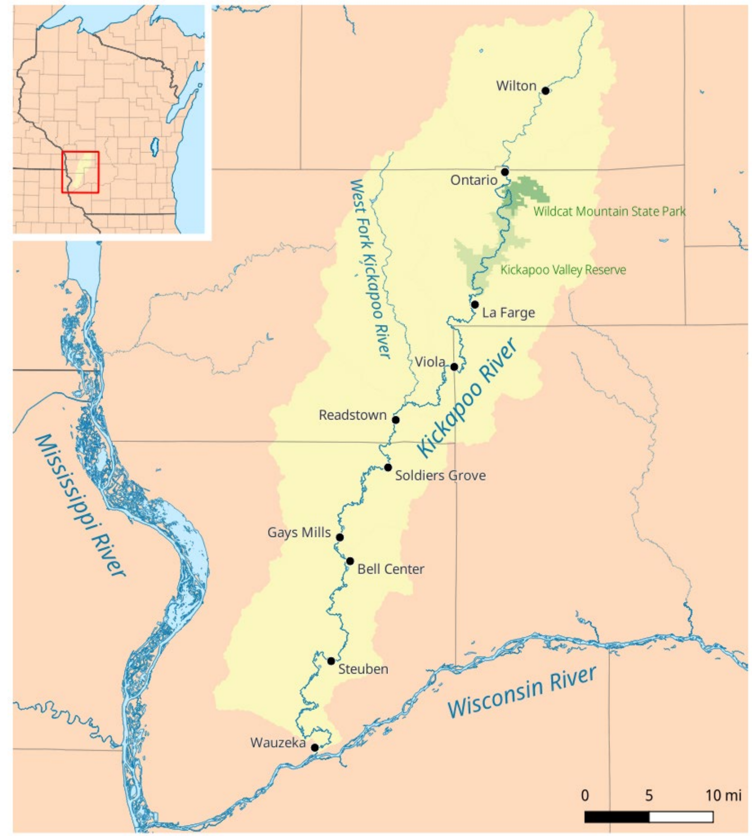
Total Emergy Comparison between Different Nutrient Removal and Recovery Technology



Kickapoo River Watershed Integrated Study

- Nutrient compliance
- Flood risk
- Non-point source pollution from ag land
- Groundwater/aquifer recharge

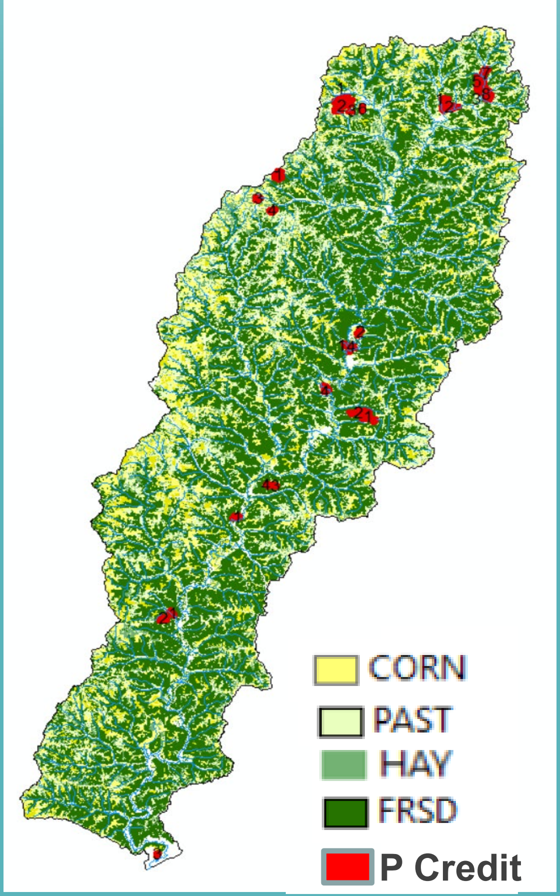




• WWTF

Overview of WWTPs in Kickapoo Watershed

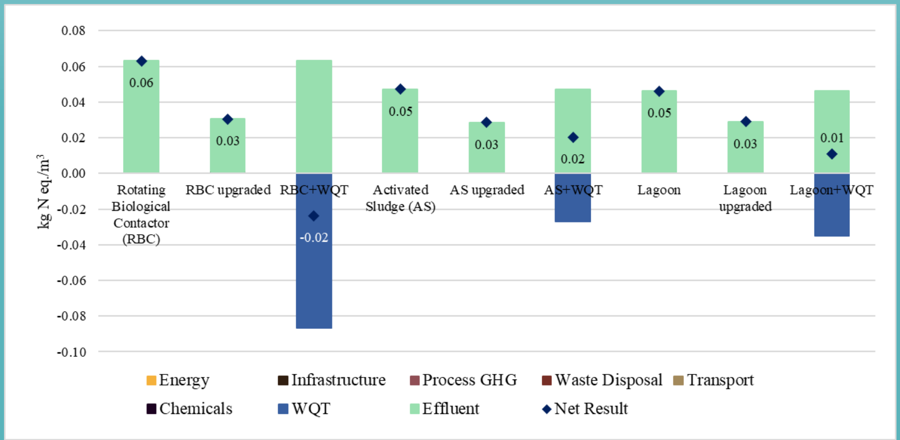
Facility Name	Population Served	Biological Process	2016-2020 Average[11] Average Flow (Design flow)	2016-2020 Average[11] Effluent P Concentration	WQBEL
			MGD	mg/L	mg/L
ONTARIO WWTF[1]	554	RBC	0.041 (0.086)	4.6	0.075
VIOLA WWTF[2]	699	Aerated Lagoon	0.084 (0.10)	2.5	0.1
READSTOWN WWTF[3]	415	not available	0.091 (0.094)	1.0	0.1
SOLDIERS GROVE WWTF[4]	592	Activated Sludge	0.046 (0.114)	3.7	0.1
GAYS MILLS WWTF[5]	504	Activated Sludge	0.073 (0.087)	1.9	0.1
WAUZEKA WWTF[6]	250	Activated Sludge	0.051 (0.08)	2.7	0.1
WILTON WWTF[7]	504	Aerated Lagoon	0.043 (0.089)	5.6	0.075
LA FARGE WWTF[8]	746	Activated Sludge	0.149 (0.172)	0.57	0.1
NORWALK WWTF[9]	638	Activated Sludge	0.048 (0.138)	3.0	0.075
VPP GROUP WWTF[10]	not available	not available	0.061 (0.081)	0.03	0.075



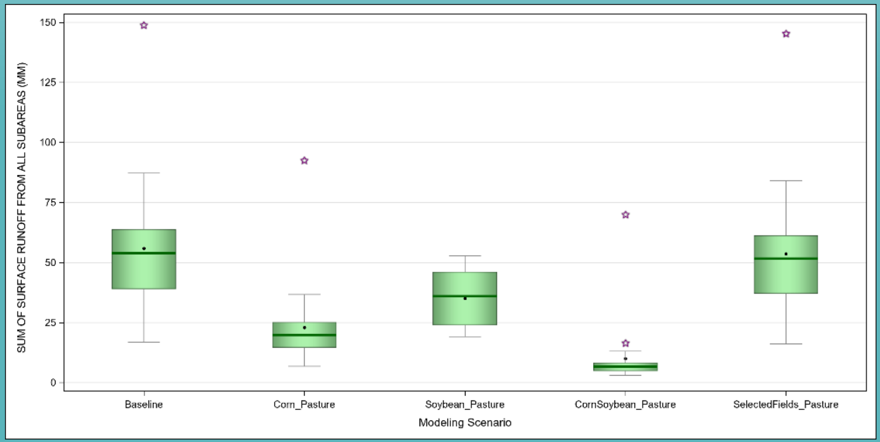
Sources: 1 - (Davy Engineering Co. 2016b), 2 - (Delta 3 Engineering 2016), 3 - (Delta 3 Engineering 2018a), 4 - (Davy Engineering Co. 2018), 5 - (Davy Engineering Co. 2019), 6 - (Delta 3 Engineering 2018b), 7 - (Delta 3 Engineering 2017; Delta 3 Engineering 2019), 8 - (MSA 2017), 9 - (Davy Engineering Co. 2016a), 10 - (McMahon 2016), 11 - (Hartenbower 2021)
Acronyms: P – phosphorus, WQBEL – water quality based effluent limit, MGD – million gallons per day, WWTF – wastewater treatment facility

Integrated Watershed Management of Kickapoo

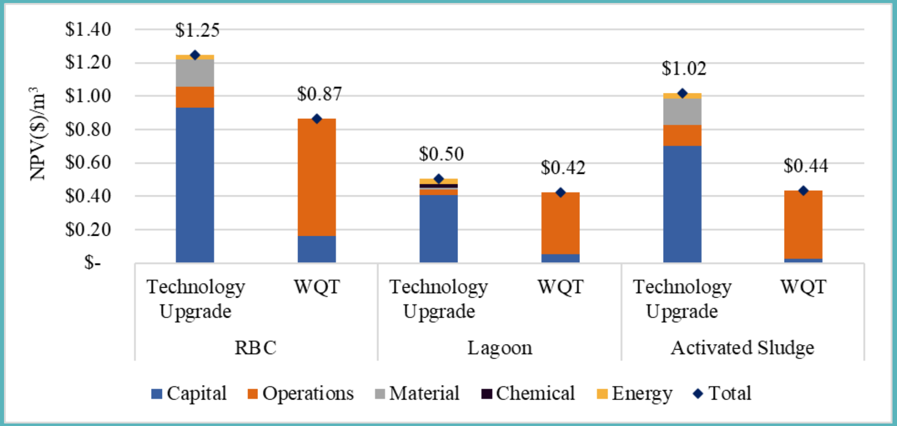
Eutrophication Impact (Nutrient Pollution)



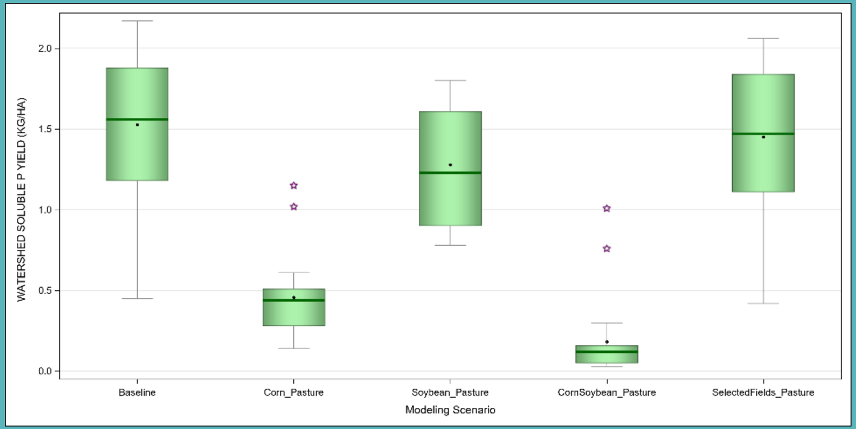
Surface Runoff



Life Cycle Cost Comparison



Soluble P Yields



Preliminary Results. Do Not Reproduce.

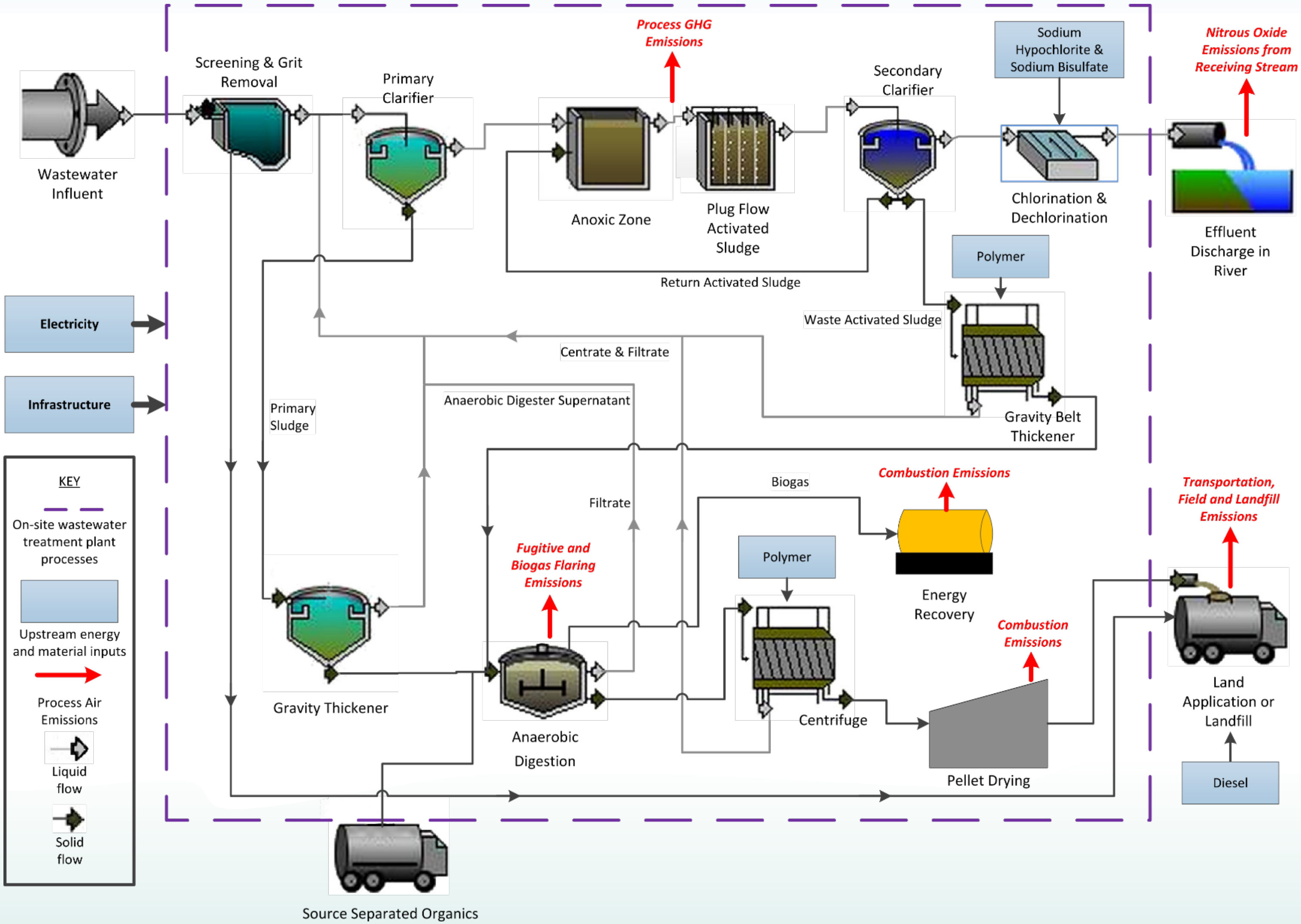
- Tools and metrics: emergy and LCA (life cycle assessment)
- System analyses examples
  - Nutrient recovery and removal
  - **Energy recovery**
  - Water reuse
  - City of Tomorrow

Study Objectives

Assess environmental and cost impact of:

- Expanding anaerobic digester (AD) capacity for food waste co-digestion.
- Installing combined heat and power (CHP).
- Variable digester performance.
- Avoided waste scenarios.

Process Flow Diagram

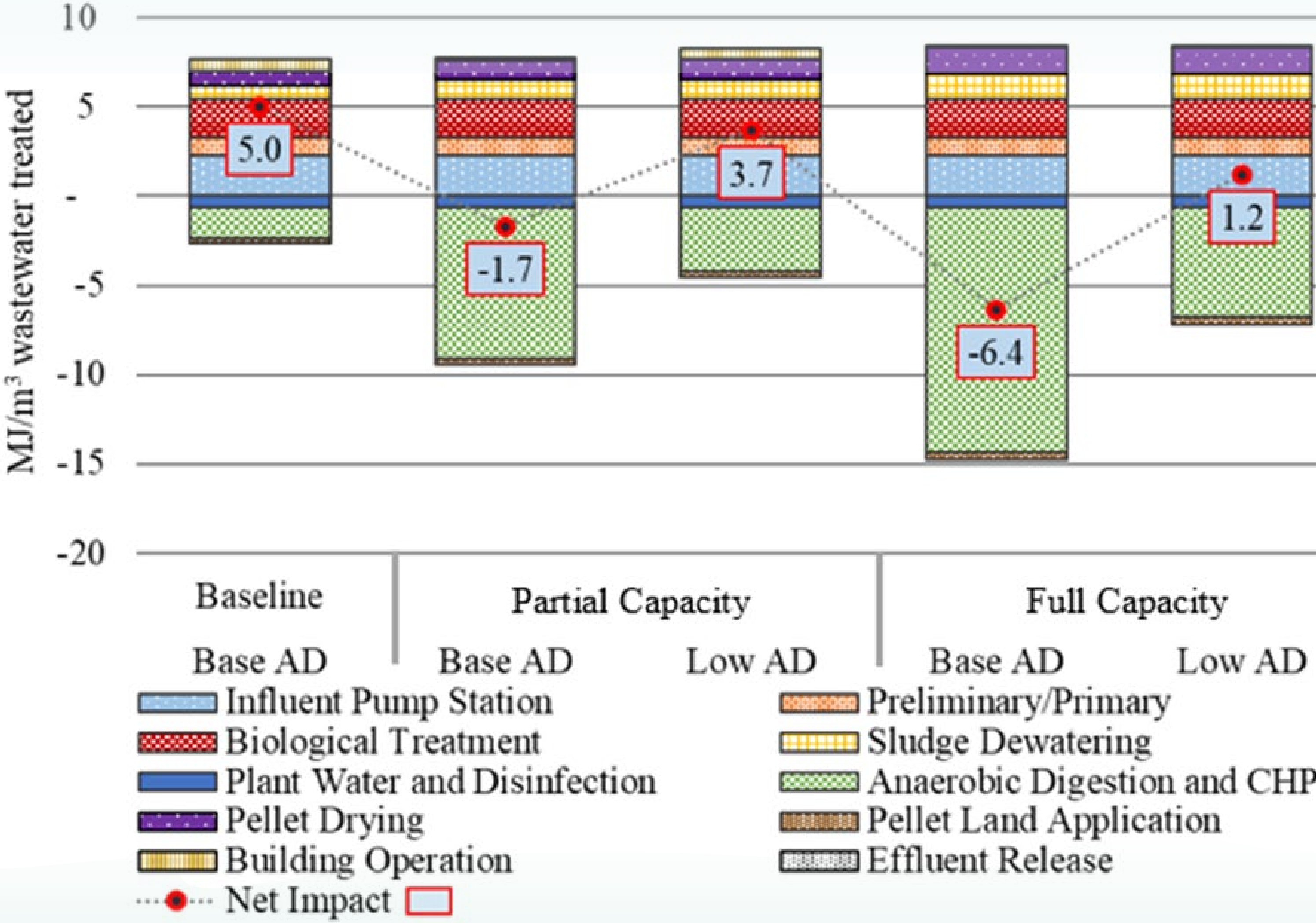


Waste Scenarios Analyzed

	Scenario	Waste Type	Quantity (gpd)
	All Scenarios	Septage	80,000
		Municipal Solids*	8,000
	Scenario 1: Base (2016)	Primary & WAS	172,000
		SSO	-
Partial Capacity	**Scenario 2: 50% SSO Capacity**	Primary & WAS	179,000
		SSO	46,000
Full Capacity	**Scenario 3: 100% SSO Capacity**	Primary & WAS	188,000
		SSO	92,000

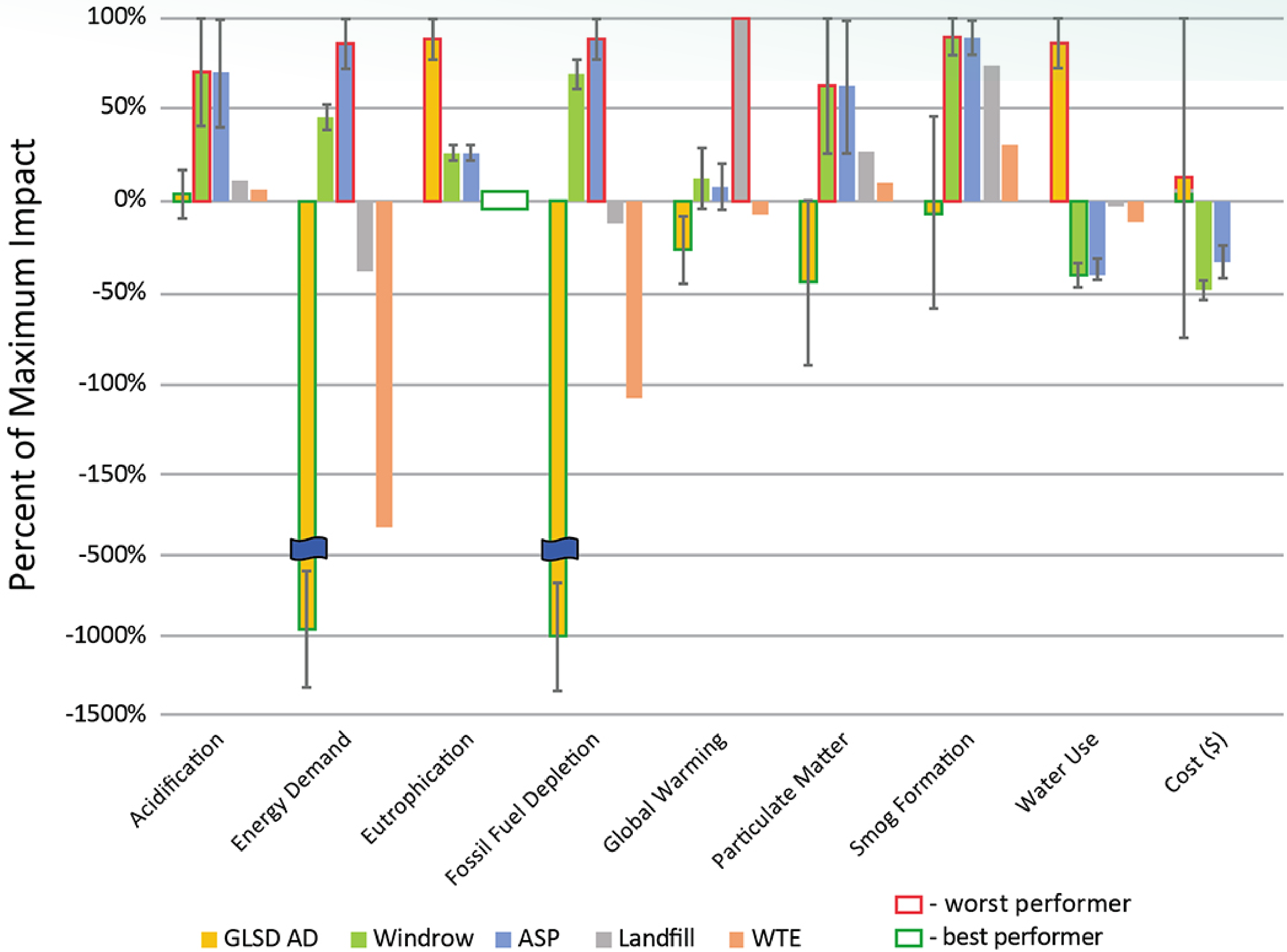
***Municipal Solids:** Trucked in primary and waste activated sludge.

Cumulative Energy Demand



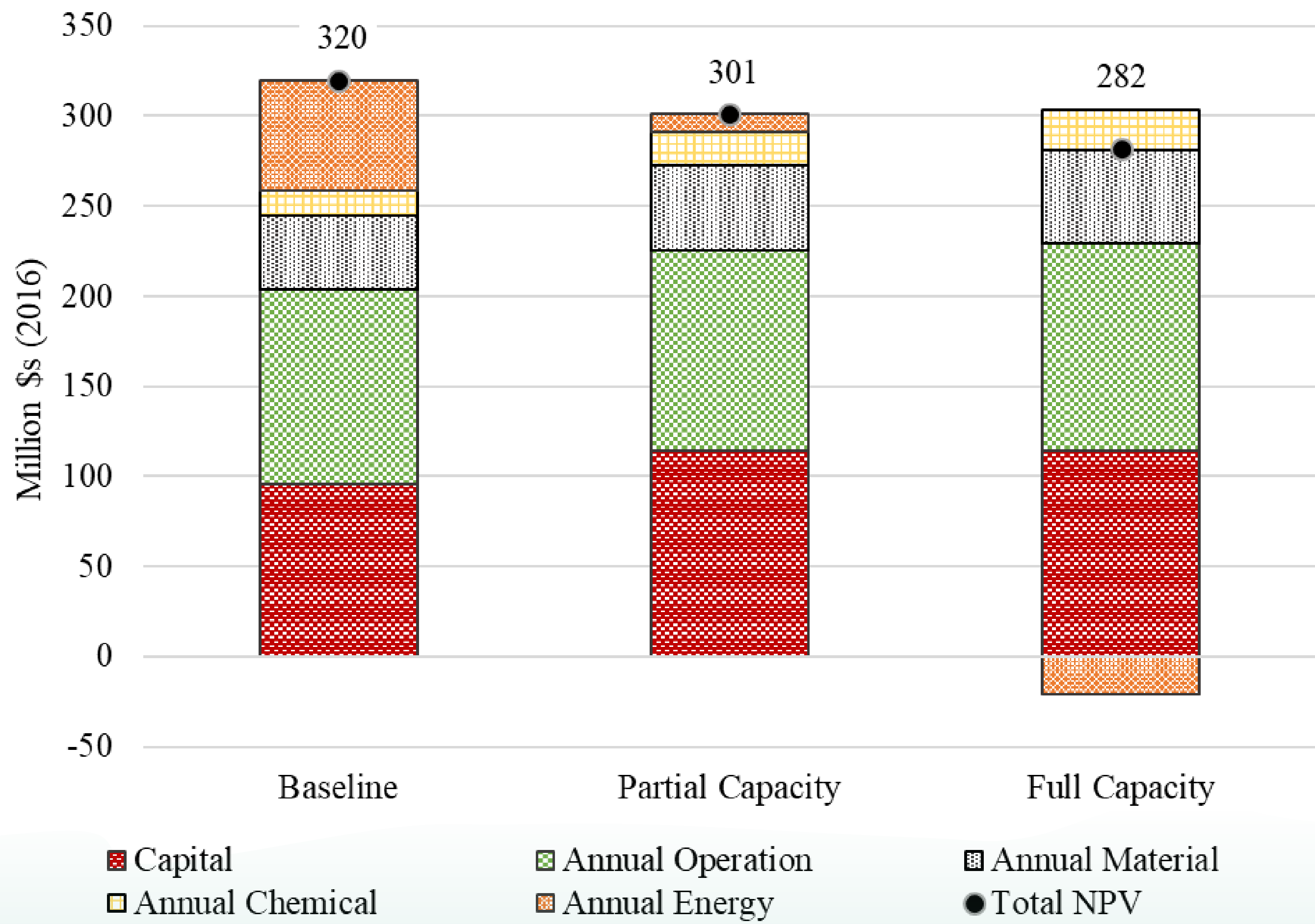
(Base AD Results by Treatment Group)

End-of-Life Process Impacts



Cost Analysis Results

Indicate a 7 and 14 year payback period for the investment in AD and CHP systems for the full and partial capacity scenarios.



- Tools and metrics: emergy and LCA (life cycle assessment)
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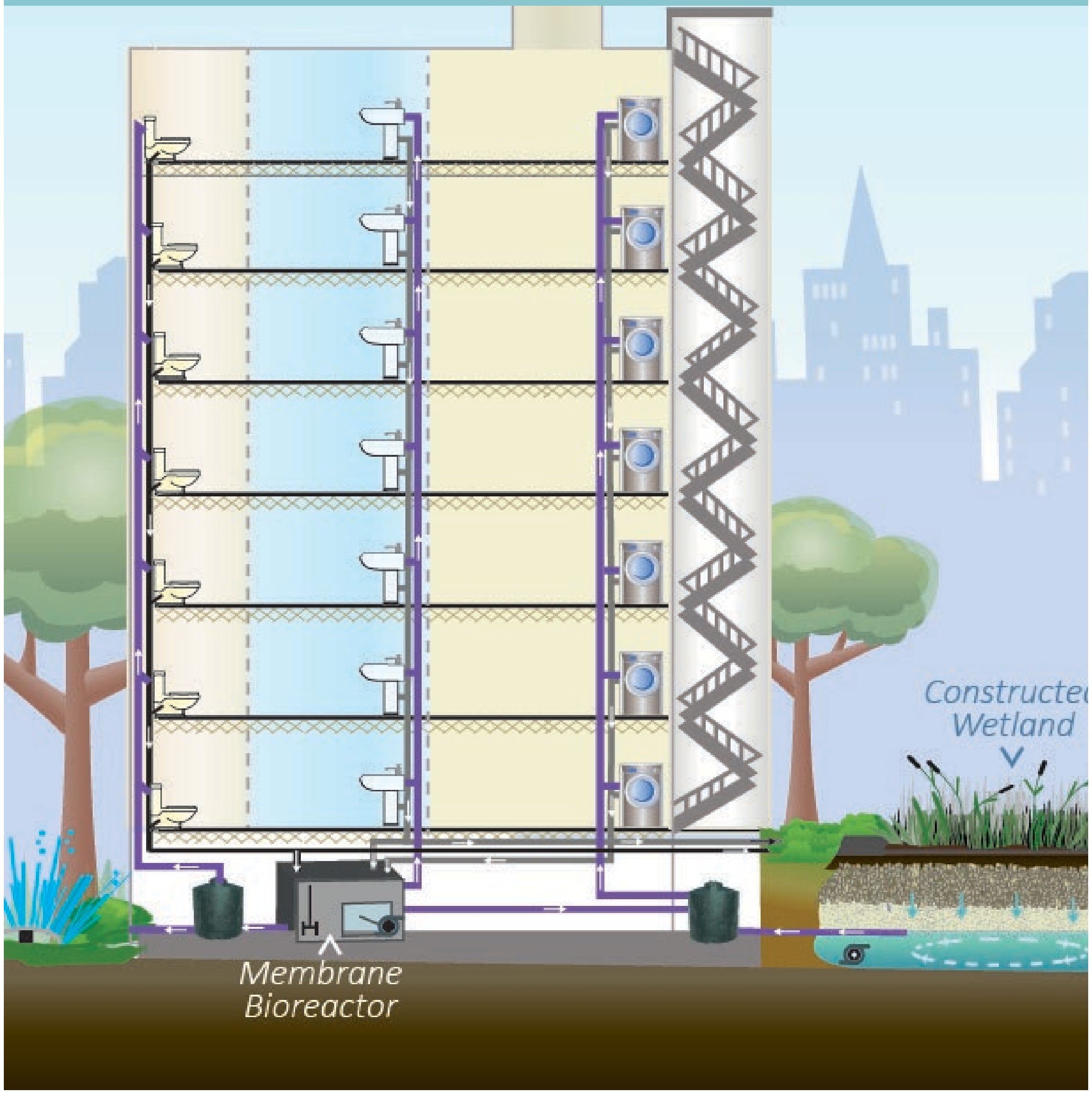
  - City of Tomorrow

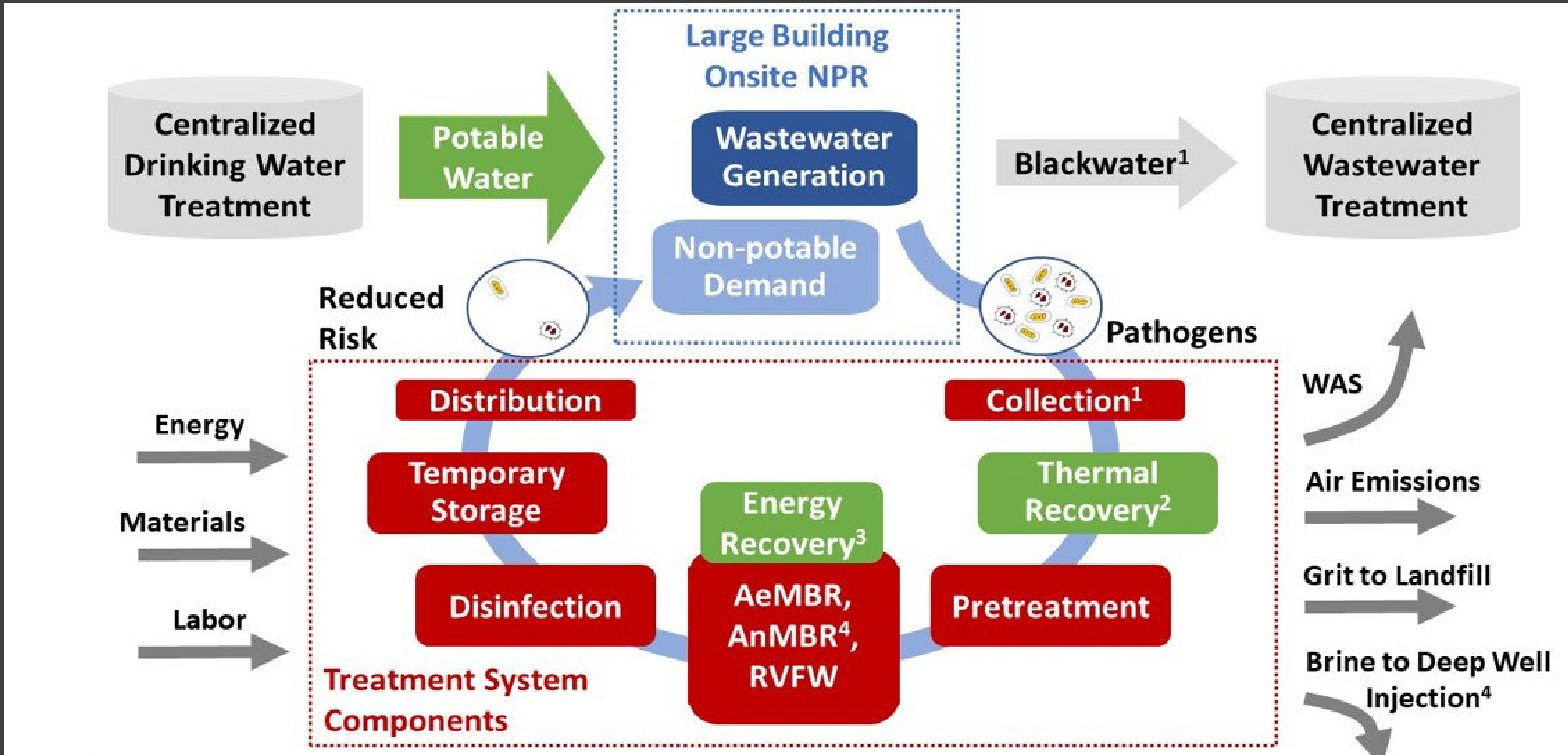
Project Background



Project team has completed several life cycle assessment (LCA) and cost studies on decentralized NPR configurations

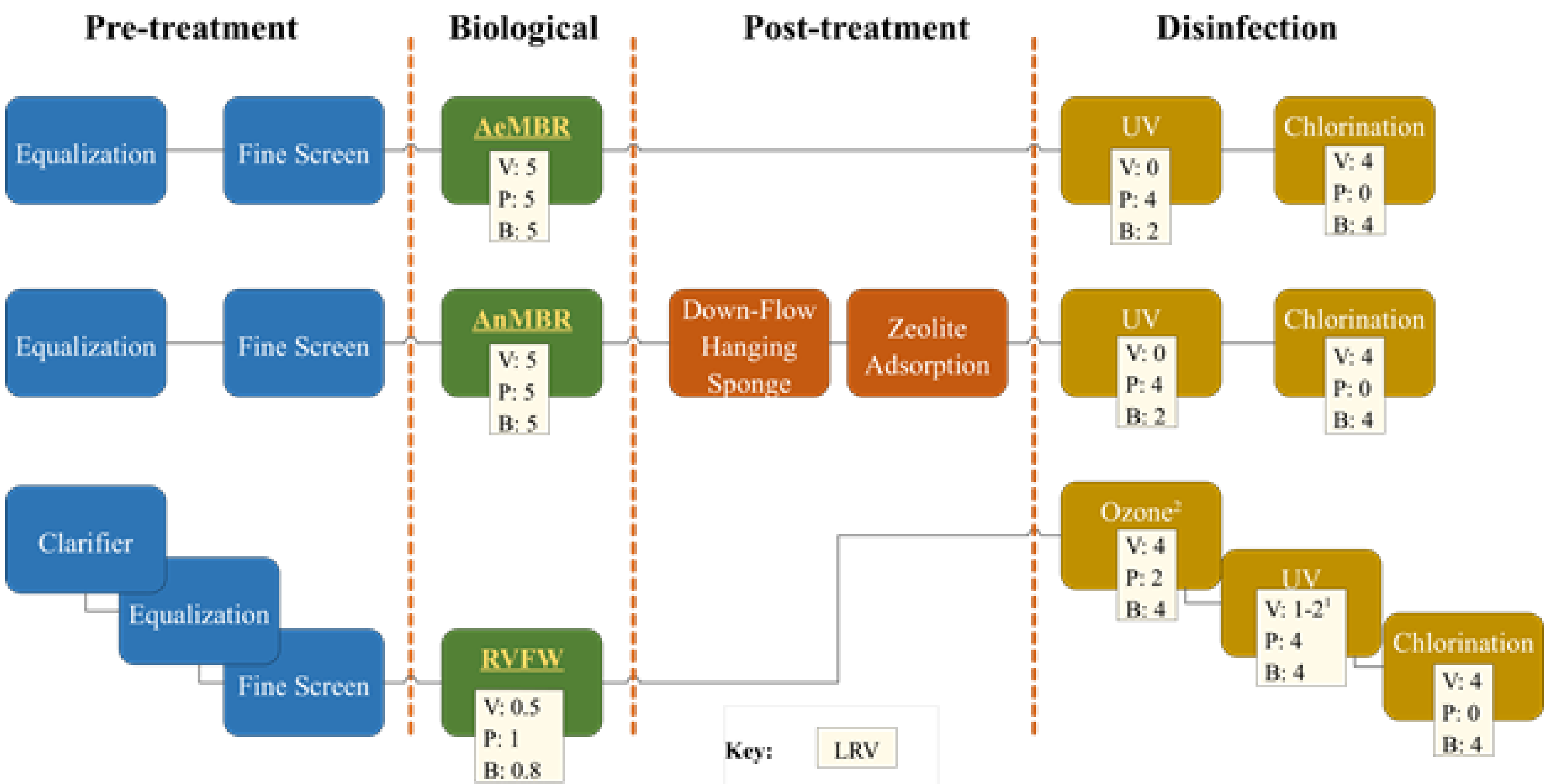
Latest study focused on large urban buildings in San Francisco, treating mixed wastewater or source separated graywater with aerobic membrane bioreactor (MBR)

Work expanded to an EPA web-based calculator



Life Cycle Approach

Analyze cost and environmental impact of systems treating mixed wastewater and source separated graywater for onsite NPR (0.01-0.016 MGD). Integrated results with microbial risk assessment.

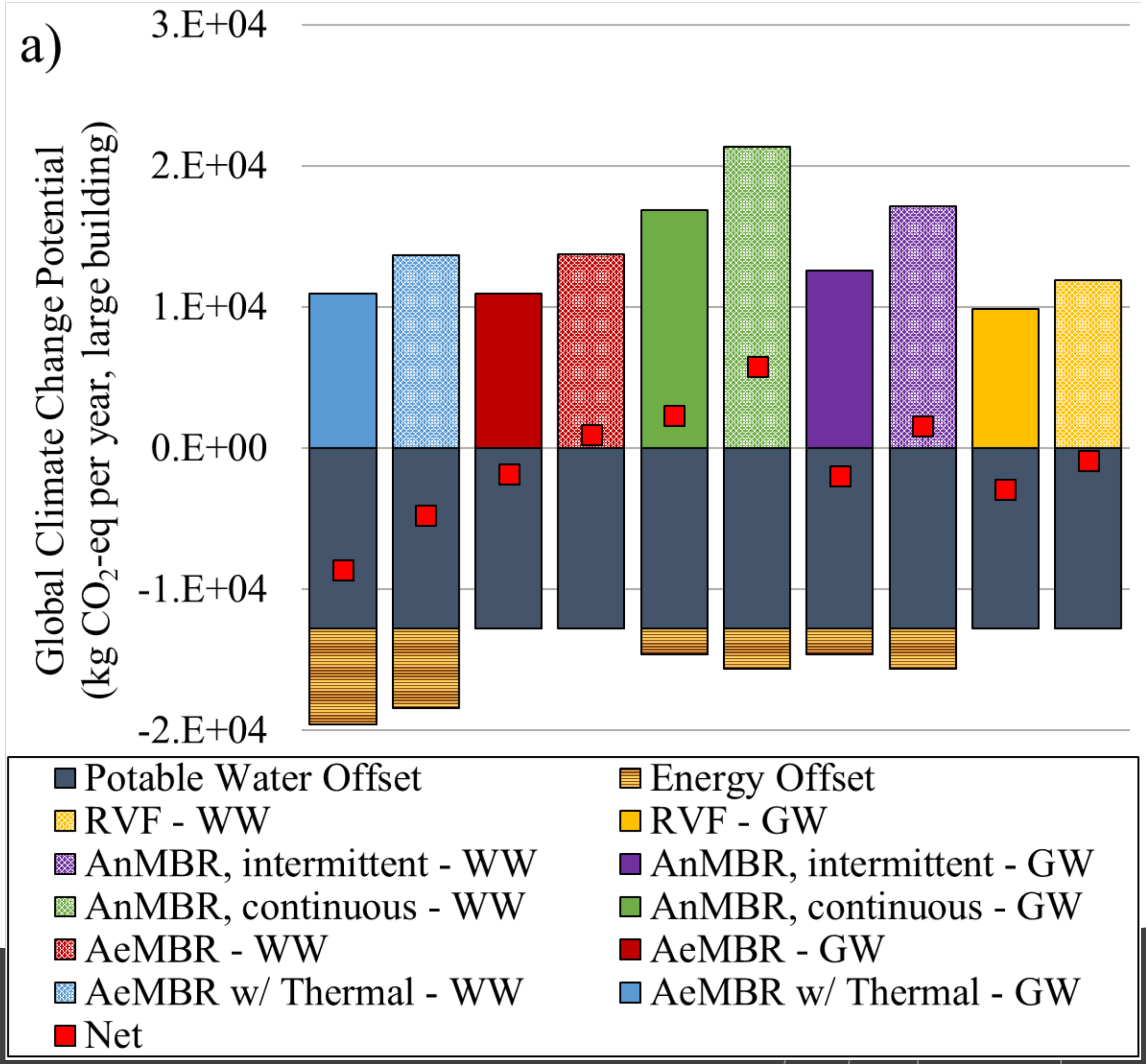


[1] UV virus LRV varies due to application of different UV doses for mixed WW and GW RVFWs.

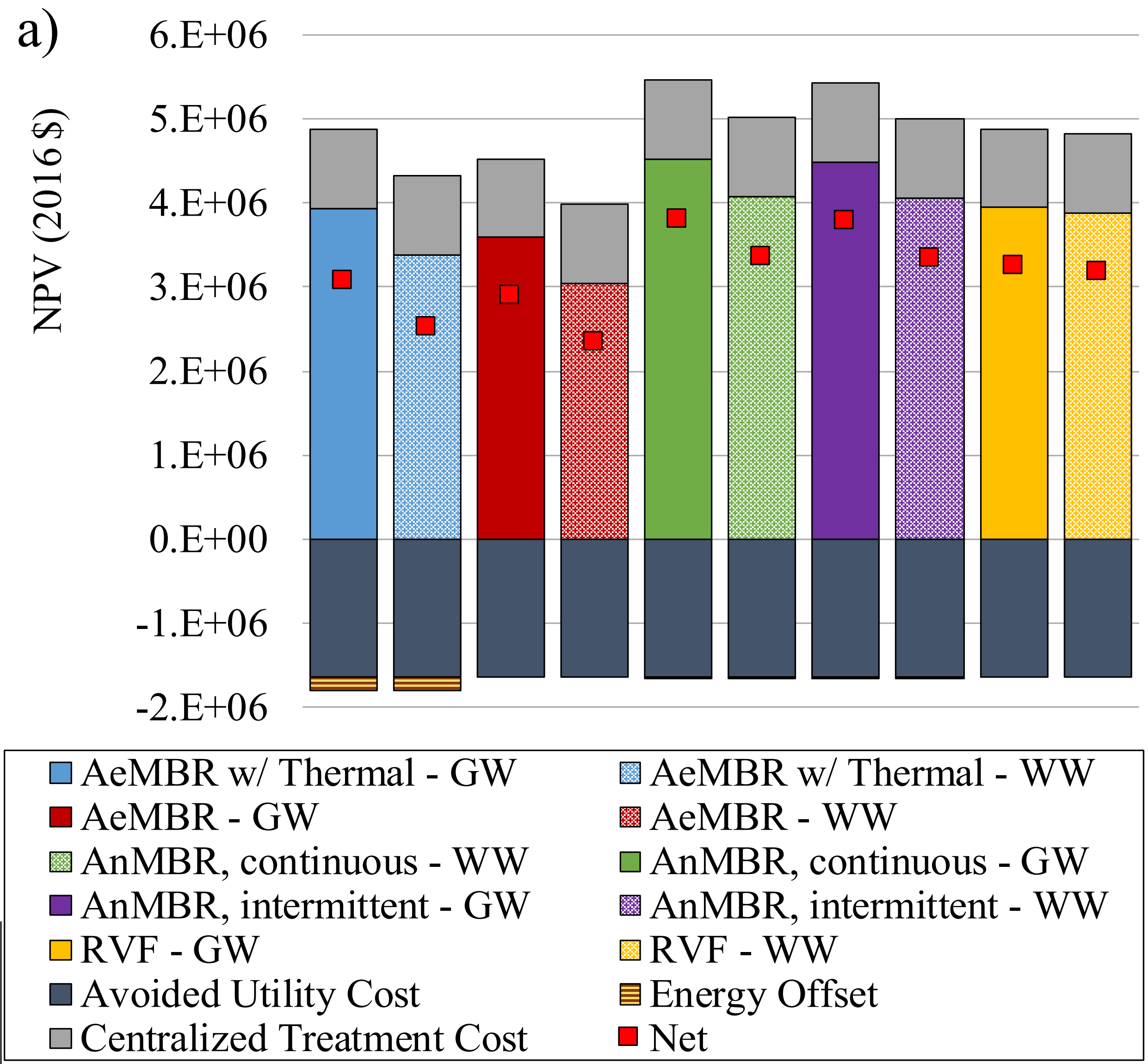
[2] The ozone disinfection process only applies to the RVFW system treating mixed wastewater.

Life Cycle Approach

Analyze cost and environmental impact of systems treating mixed wastewater and source separated graywater for onsite NPR (0.01-0.016 MGD). Integrated results with microbial risk assessment.



Global Warming Potential



From Arden et al. 2020

System Cost (Net Present Value)

Non-Potable Environmental and Economic Water Reuse (NEWR) Calculator

EPA United States Environmental Protection Agency

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Non-Potable Environmental and Economic Water Reuse (NEWR) Calculator

Identify Source Water Options for Non-Potable Reuse

The Non-Potable Environmental and Economic Water Reuse (NEWR) Calculator is a simple to use web-based tool for screening-level assessments of source water options for any urban building location across the United States that is considering onsite non-potable reuse.

On this Page

Access NEWR

Platform and Compatibility

NEWR is a single page web application that requires an internet connection and JavaScript enabled in the browser. The web-based application can be used on desktop devices and on mobile devices, such as smartphones and tablets. It is compatible using modern browsers with Windows and Mac operating systems.

Disclaimer: Any mention of trade names, manufacturers, or products does not imply an endorsement by EPA. EPA and its employees do not endorse commercial products, services, or enterprises.

Calculator Goal

NEWR – Non-potable Environmental and Economic Water Reuse Calculator

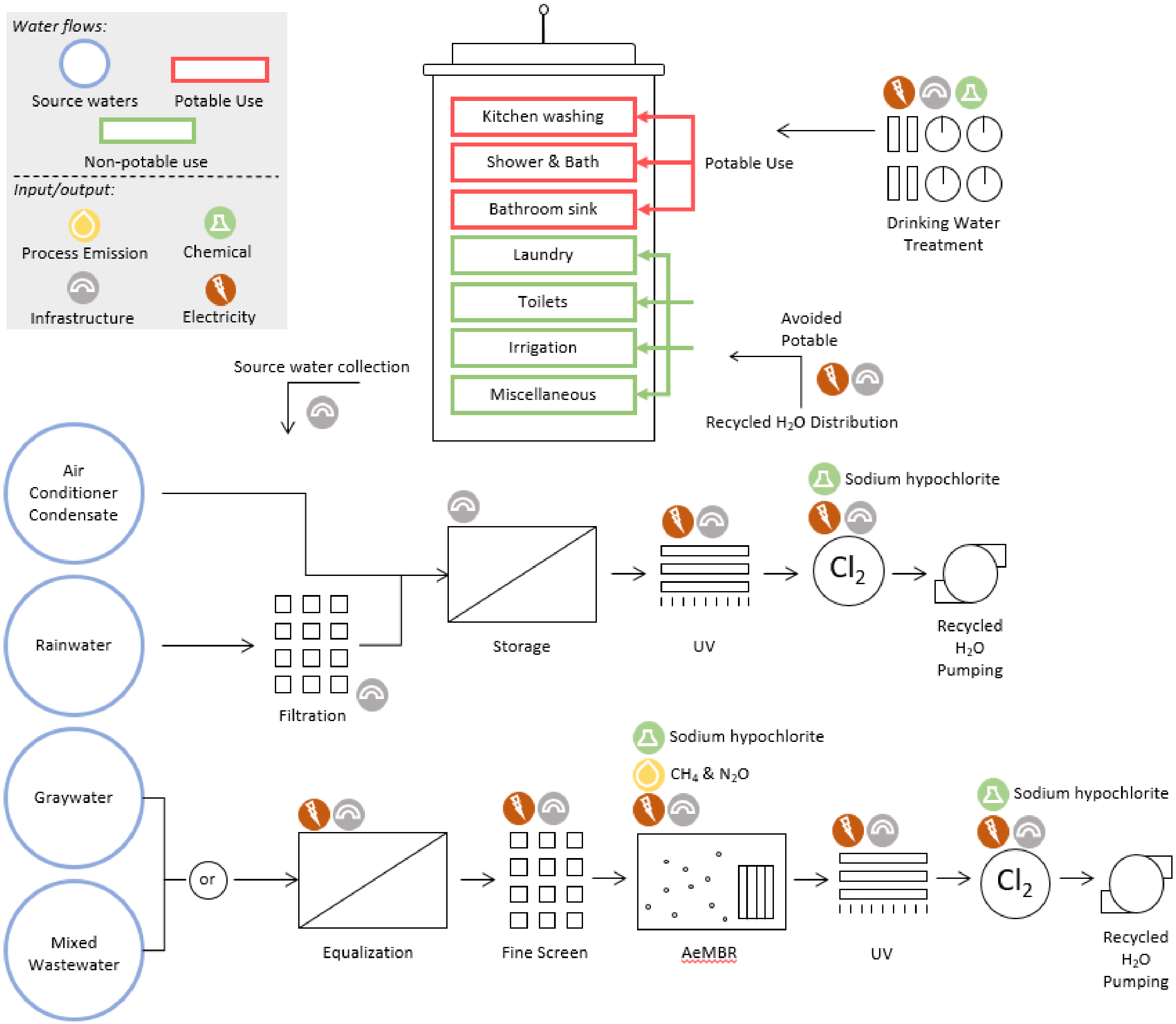
- Build on previous LCA and cost studies on NPR options for urban case studies and create a simple calculator to develop screening-level assessments for any large building location across the US.
- Research Questions: What is the most environmentally and cost-effective source water(s) to meet large building non-potable water needs?
  - As a function of location
  - As a function of building type/size

System Types

- The calculator assesses the following system types:
  - Rainwater Harvesting
  - Air Conditioning Condensate Harvesting
  - Graywater Aerobic Membrane Bioreactor
  - Mixed Wastewater Aerobic Membrane Bioreactor

- All systems designed to meet NPR log reduction targets
- Option for recovery of thermal energy for hot water heating

System Types



Intended Audience

- Building developers can use the calculator as an initial screening tool prior to a more detailed engineering design analysis
- Urban communities interested in implementing NPR at the building-scale
- Research scientists investigating NPR options

User Entry: Location

Non-Potable Reuse Building-Scale Calculator

Specify ZIP Code

Enter a 5 digit ZIP Code to start: 55403

The Non-Potable Reuse (NPR) Building-Scale Calculator can help identify environmentally and cost effective options for on-site NPR based on user selected geography, building specifications, source water type, and end use. Follow the prompts to explore building-scale NPR opportunities in your region. The Calculator is intended for buildings with 50 or more residential and/or office occupants.

Next

User Entry: Building Characterization

Non-Potable Reuse Building-Scale Calculator

Building Characterization

Select Building Type ⓘ

- (•) Mixed Use (30% commercial, 70% residential)
- ( ) Residential
- ( ) Commercial

Specify # Building Occupants ⓘ

- (•) Large Building (1100)
- ( ) Medium Building (550)
- ( ) Small Building (110)
- ( ) Number of Occupants (recommended minimum value is 50)

Specify # Floors in Building ⓘ

4

Enter Building Footprint ⓘ

20000

Previous

Next

User Entry: Source Water Characterization

Non-Potable Reuse Building-Scale Calculator

Source Water Characterization

Select Source Water Option ⓘ

- [x] Rainwater

Enter portion of the building footprint that is allocated to rainwater harvesting:

20000

- [x] Air Conditioning Condensate
- [x] Wastewater

Incorporate Thermal Recovery Unit? ⓘ

- (•) Yes, Natural Gas Hot Water Heater
- ( ) Yes, Electric Hot Water Heater
- ( ) No

Select Wastewater Collection Type ⓘ

- ( ) Mixed Wastewater (treated with Aerobic MBR)
- (•) Separated Graywater (treated with Aerobic MBR)

Specify Building Water Use Efficiency ⓘ

- (•) High Efficiency
- ( ) Standard Efficiency

Previous

Next

User Entry: End Use Characterization

Non-Potable Reuse Building-Scale Calculator

End Use Characterization

Select Recycled Water Use Type ⓘ

- [x] Toilet Flushing
- [x] Outdoor Irrigation

High Water Use ⓘ

1000

Medium Water Use ⓘ

Enter irrigated area in sf

Low Water Use ⓘ

Enter irrigated area in sf

- [x] Laundry
- [ ] Other (gpd)

Does Recycled Water Displace Drinking Water? ⓘ

- (•) Yes
- ( ) No

Define Energy Use of Drinking Water Treatment ⓘ

- ( ) Zip Code Default
- ( ) Lower Energy Demand
- ( ) Higher Energy Demand
- (•) Custom

Define Characteristics of Water Service Utility ⓘ

Water Type	Acquisition Efficiency
Default	Default
Regional Topography	**Distribution Efficiency**
Default	Default
Treatment System Energy Use	**Network Leakage**
Average	Default - 18.7%

Previous

Calculate

Optional inclusion for any 'Other' end use of recycled water

Optional customization of avoided drinking water impacts

Results: Zip Code Data

Non-Potable Reuse Building-Scale Calculator Results

Show data entered

New Calculation

ZIP Code Data	Water Availability & Demand	Global Warming Potential	Total Energy Demand	Fossil Fuel Depletion	Water Consumption	Water Scarcity	Cost (Net Present Value)	Methods & Resources

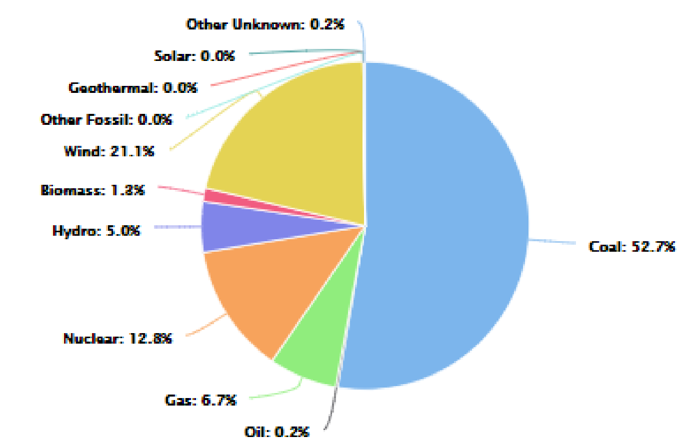
ZIP Code Data for 55403

Month	Rainfall (inches)	AC Condensate Harvesting Potential (gal/cfm)	Reference Evapotranspiration (inches)
January	0.00	0	0.6695
February	0.00	0	0.9285
March	0.00	0.0011	2.1945
April	0.00	0.0188	3.8789
May	3.46	0.1343	5.4589
June	4.25	0.8455	5.9582
July	3.98	1.5081	6.4559
August	3.98	1.2179	5.4194
September	2.99	0.675	4.0626
October	2.09	0.0147	2.6382
November	0.00	0.0008	1.2239
December	0.00	0	0.5977

Water Scarcity Factor	1.28	
Natural Gas Rate	0.30	$/1000 cf
Electricity Rate	0.12	$/kWh
Water Supply Rate	0.01	$/1000 gallons

eGRID Subregion - MRO West

Electric Grid Resource Mix



Results: Water Availability and Demand

Non-Potable Reuse Building-Scale Calculator Results

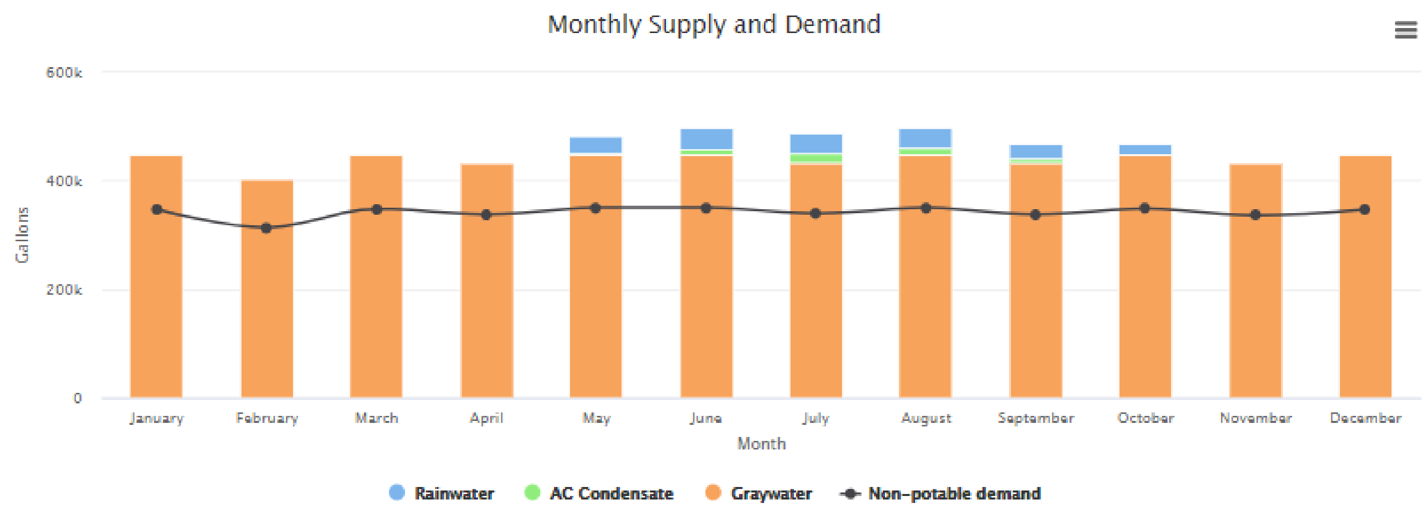
Show data entered

New Calculation

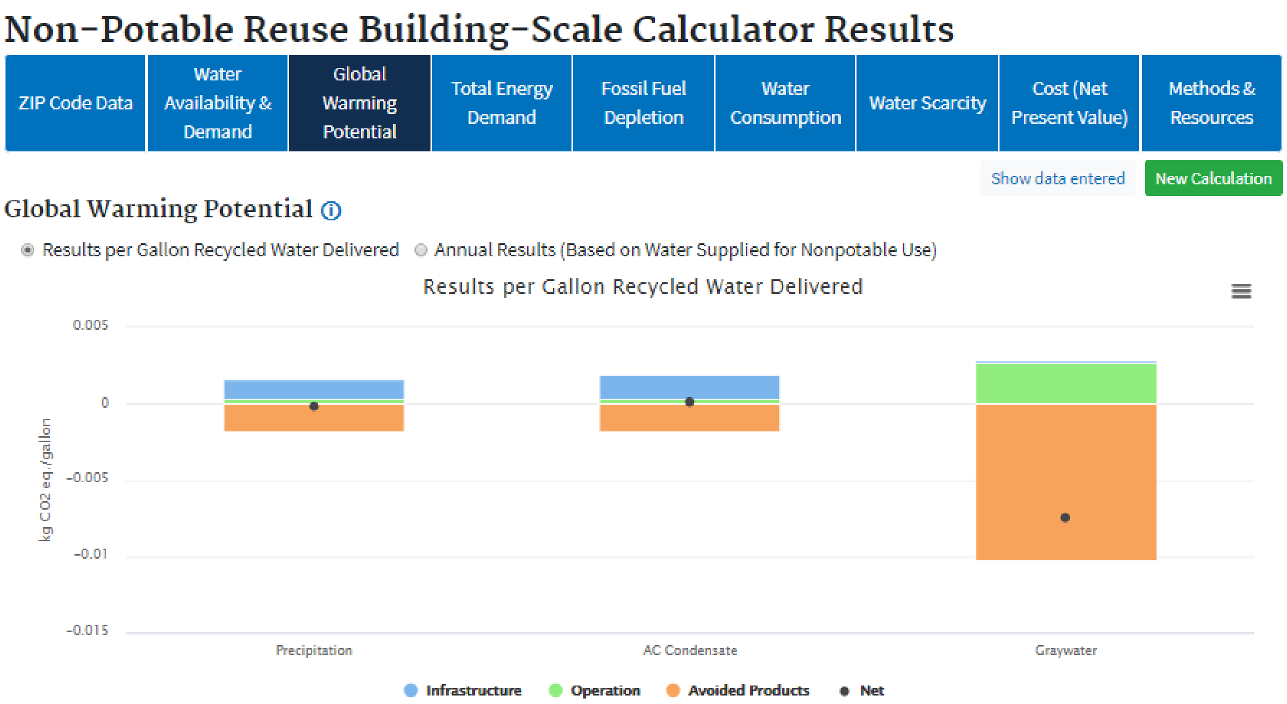
ZIP Code Data	Water Availability & Demand	Global Warming Potential	Total Energy Demand	Fossil Fuel Depletion	Water Consumption	Water Scarcity	Cost (Net Present Value)	Methods & Resources

Water Availability & Demand

○ By Source Water Type ◉ Combined Source Water Types



Results: Global Warming Potential (per gallon)

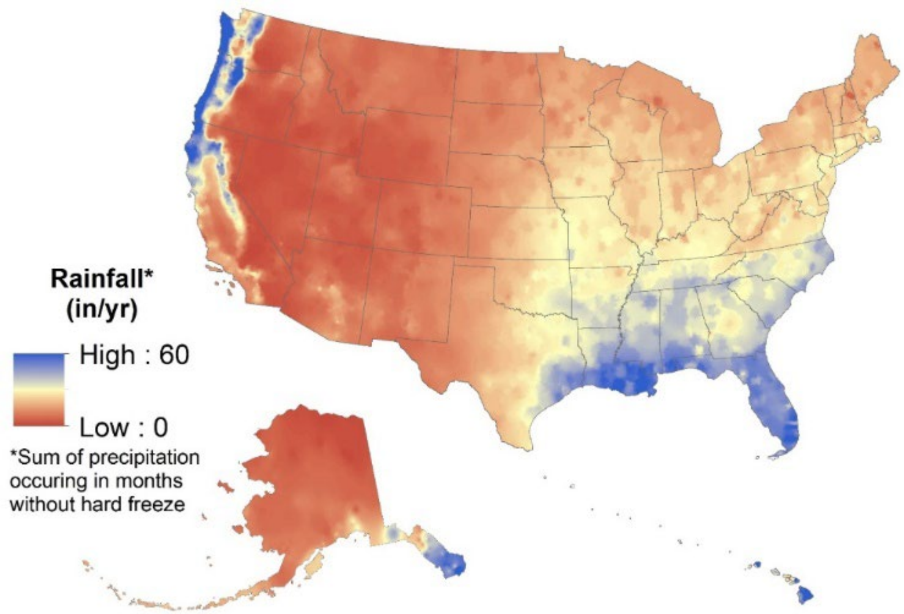


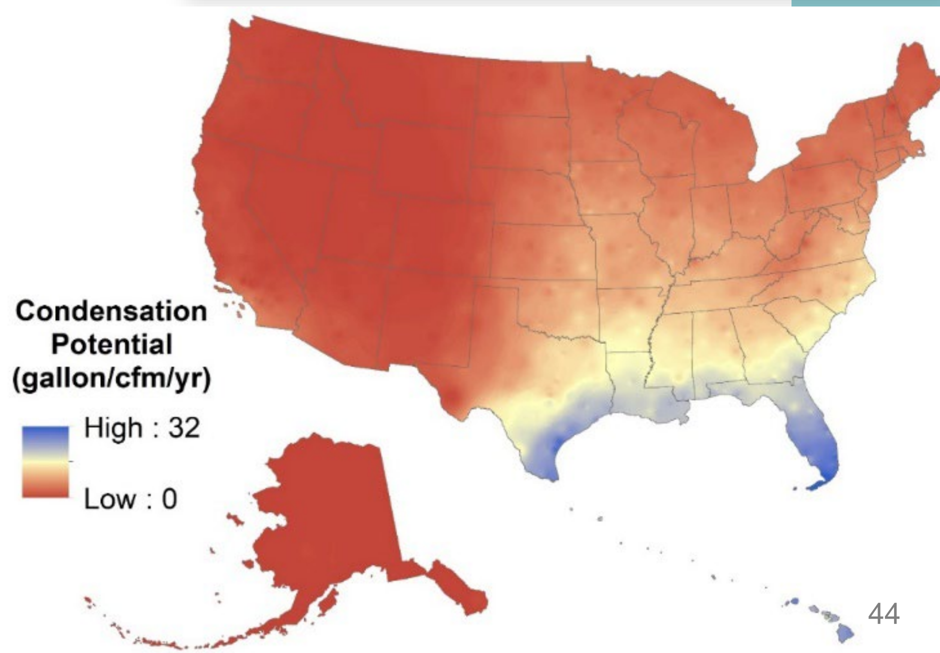
Infrastructure = all capital equipment for treatment, collection, and distribution
Operation = electricity and chemicals for treatment and disinfection
Avoided products = displaced drinking water requirements and hot water heating requirements (MBR with thermal recovery)

RWH and ACH Availability Models

- Long-term monthly data
- Filtered for hard freeze (TMY3 data, >4 consecutive hours with temperatures <28˚F)

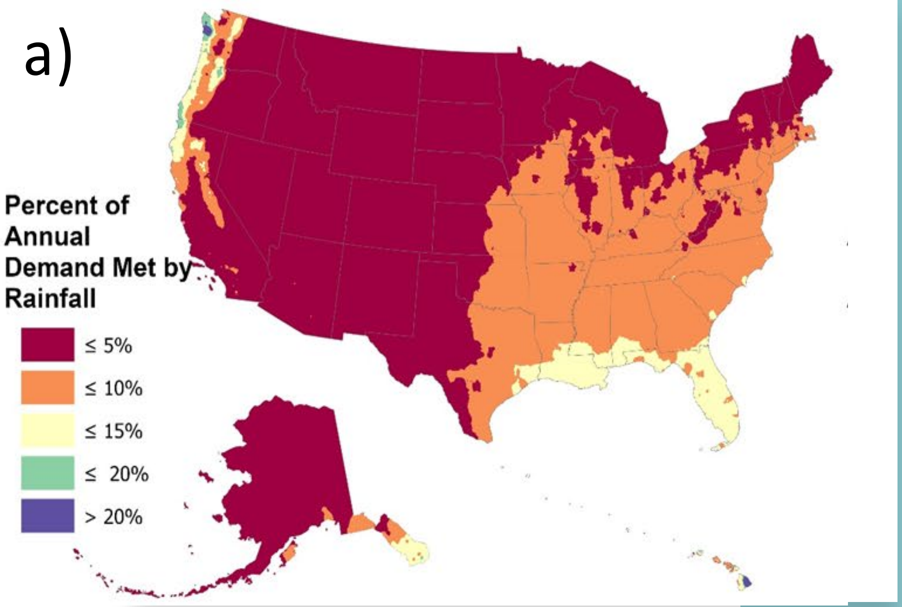
- Relative humidity (RH) model
- Function of outdoor RH, indoor RH, % outdoor air
- TMY3 data used (~2000 stations)

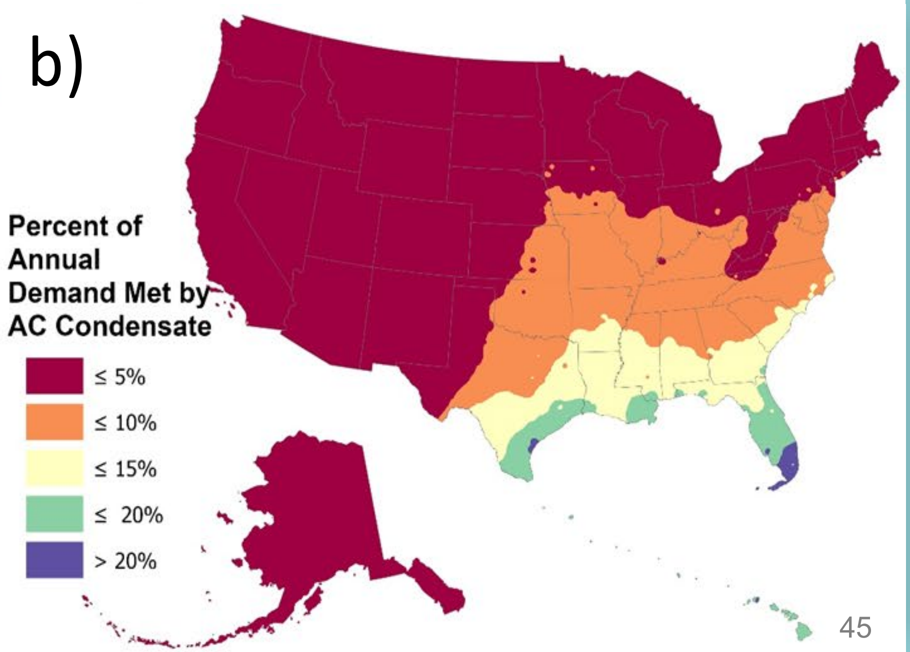




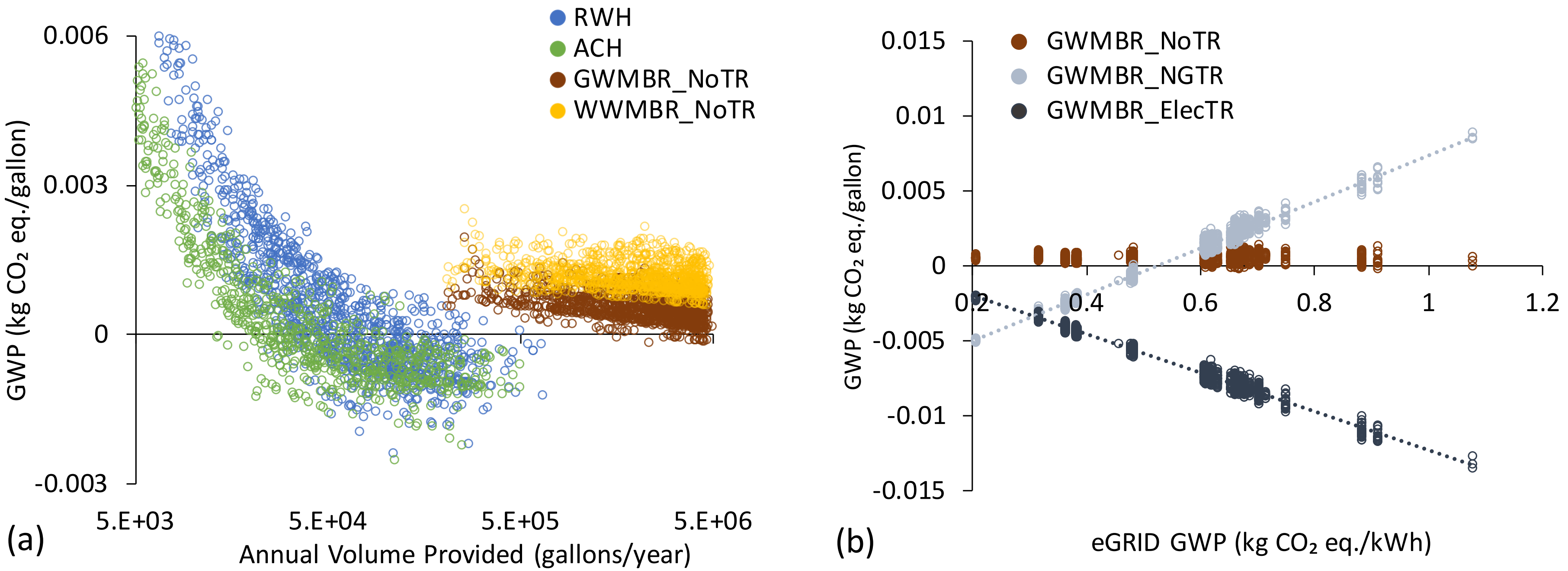
Percent of Annual Non-Potable Demand Met

Mixed WW and GW systems always meet non-potable demand under modeled conditions.



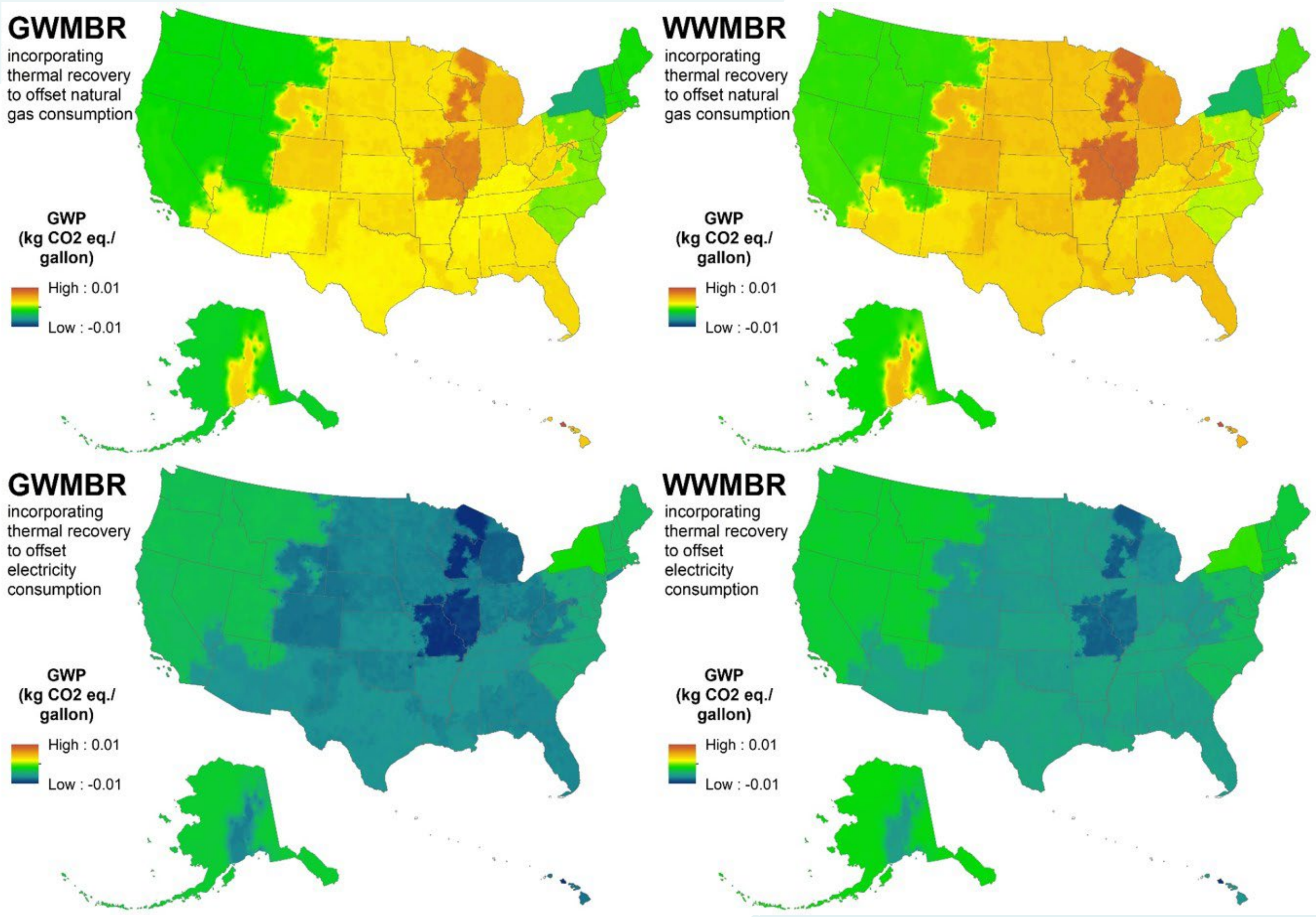


Global Warming Potential Across Source Waters, Variable Location and Building Characteristics

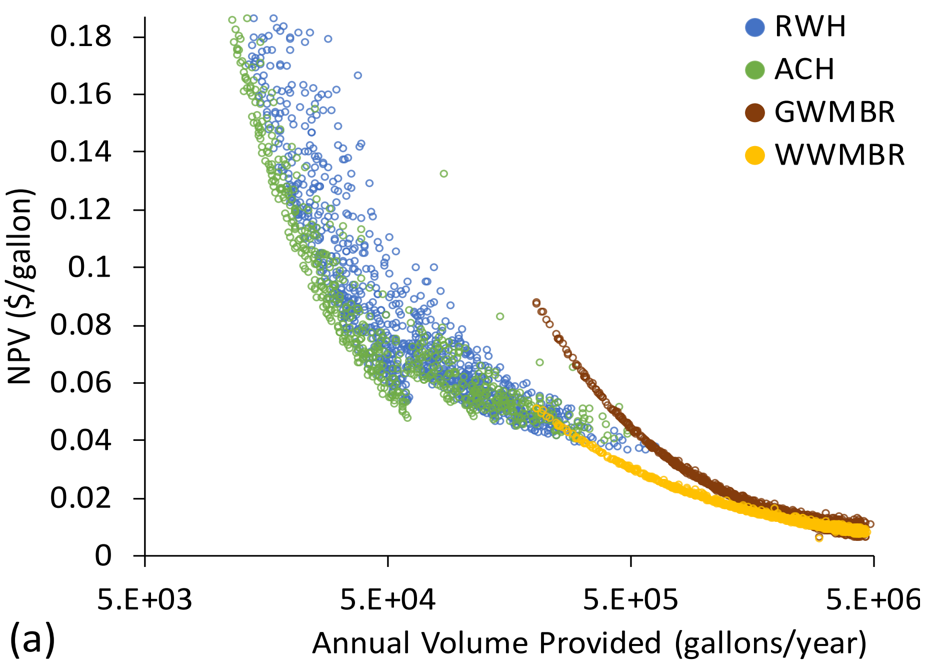


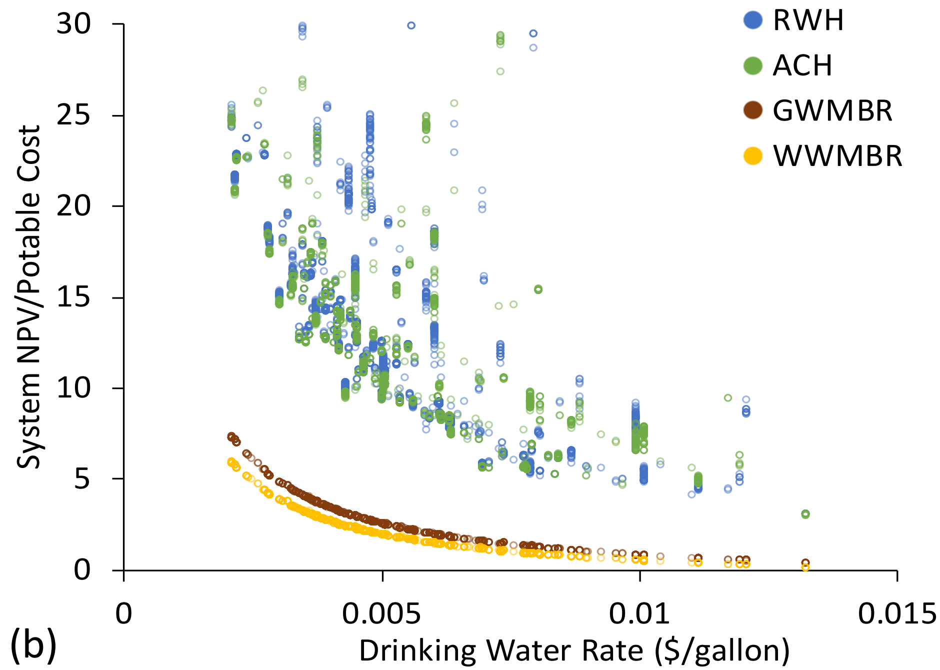
Fixed Building Global Warming Potential Across Source Waters

(With thermal recovery offsetting NG (top) and electricity (bottom))



Net Present Value Across Source Waters, Variable Location and Building Characteristics





- Tools: emergy and LCA (life cycle assessment)
- System analyses examples
  - Nutrient recovery and removal
  - Energy recovery
  - Water reuse
  - **City of Tomorrow**

New concepts

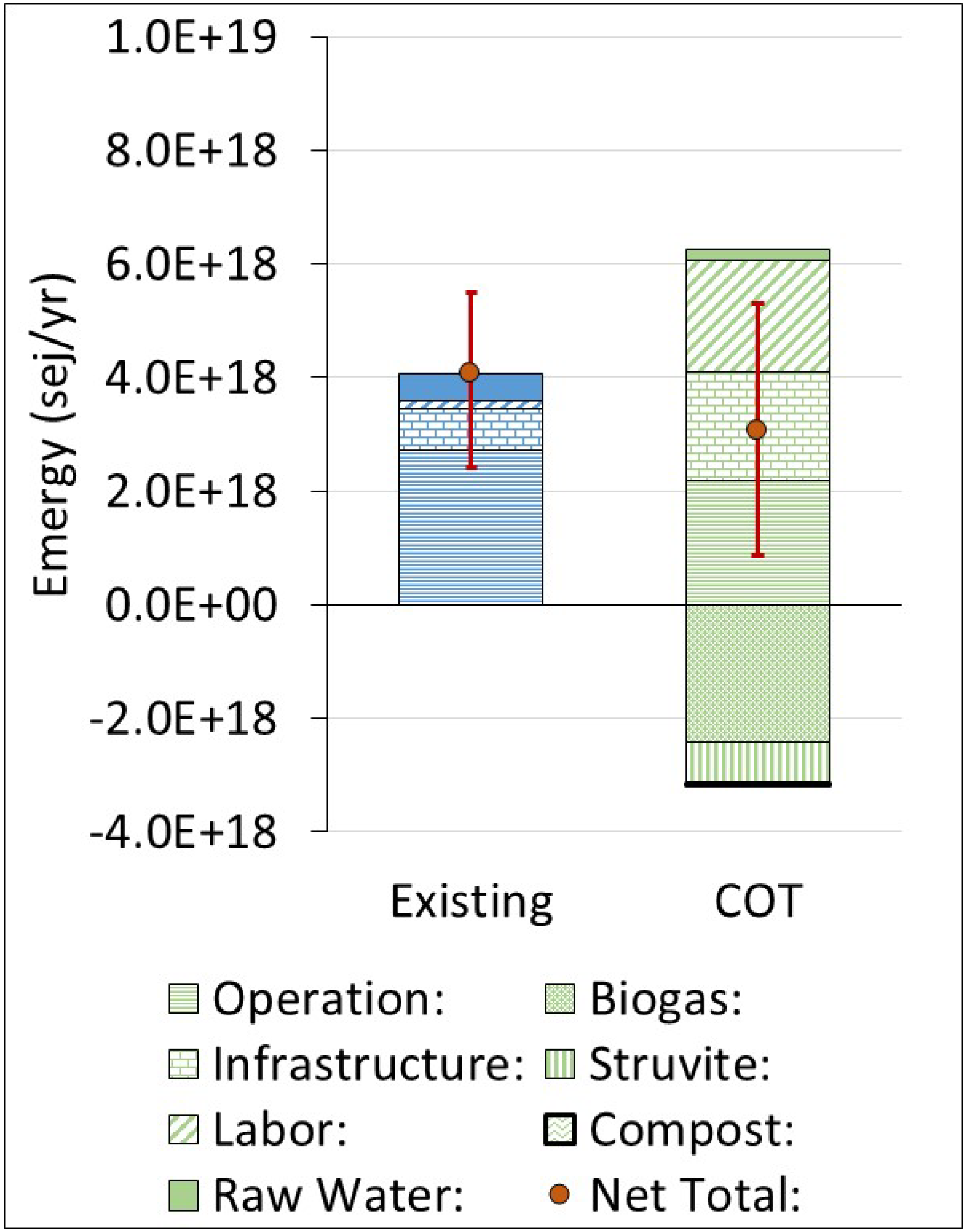
- Fit for purpose
- Source separation and resource recovery
  – Nutrient recovery
  – Energy recovery
- Decentralization

Water Systems for the City of Tomorrow

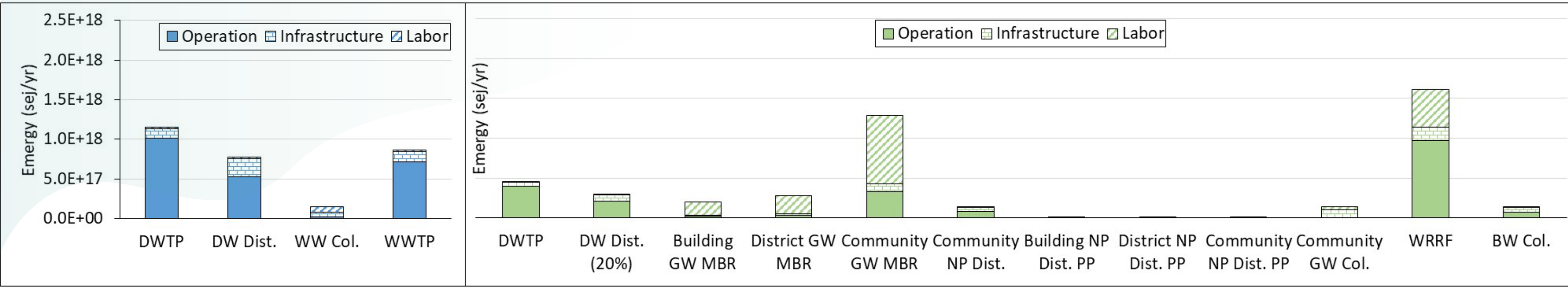
Ma, X., Xue, X., Gonzalez-Mejia, A., Garland, J., and Cashdollar, J. (2015). **"Sustainable Water Systems for the City of Tomorrow — A Conceptual Framework**." Sustainability **7**(9): 12071

Results – Emergy

- 10,000 simulations run with random selections within pre-defined range for each UEV
- Error bars represent min/max of Net Total results
- Net totals are slightly less under COT conditions
- Note large difference in labor inputs – economies of scale
- Biogas is most important resource recovery pathway



Results – Emergy



- Total emergy inputs to each major system component
- Existing system dominated by DWTP, WWTP
- COT dominated by labor to MBRs and WRRF (economies of scale)
- WRRF has relatively large resource requirements, but is responsible for production of all beneficial products (biogas, struvite, compost)

Take Home Messages

- Adopt system thinking in environmental management (water-energy nexus)
- Apply integrated assessment metrics on innovative technologies
- Design for resilience and sustainability

Questions ?

Disclaimer

The views expressed in this presentation are those of the author(s) and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency (EPA). The research described in this presentation has been funded in part by EPA under contract EP-C-15-010 to Resource Environmental Solutions and Eastern Research Group. Portions of the research were conducted by EPA and Eastern Research Group under a memorandum of understanding for cooperative research. This presentation has been reviewed in accordance with EPA policy and approved for release. Any mention of trade names, manufacturers or products does not imply an endorsement by the United States Government or the U.S. Environmental Protection Agency.