United States Environmental Protection Agency

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A Division of ERG

Life Cycle Assessment and Cost Analysis of Mixed Wastewater and Graywater Distributed Treatment for Water Reuse in San Francisco

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AWWA Sustainable Water Management Conference
April 2, 2019
Tucson, AZ

Office of Research and Development
National Exposure Research Laboratory
National Risk Management Research Laboratory

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Research Background:

Urban communities such as San Francisco have adopted ordinances requiring all new commercial, mixed-use or multi-family building projects to treat on-site wastewater or graywater for non-potable reuse (NPR).

Research Question:

What are the environmental and economic costs of implementing various mixed wastewater or graywater treatment configurations for new mixed-use building-scale or district scale NPR projects?

Study Objectives

- Focus is comparative impacts of various NPR configurations for mixed wastewater and source separated graywater treatment:
  - *Aerobic membrane bioreactor (MBR)*
  - *Anaerobic MBR*
  - *Recirculating vertical flow wetland*
- Assess environmental and cost impacts at a building and district scale

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Life Cycle Approach

- Assess cradle-to-grave impacts for all processes, products, and services associated with the system for the following metrics:
  - Cost [U.S. Dollars 2016]
  - Global climate change potential [kg CO2 equivalent (eq.)]
  - Eutrophication potential [kg N. eq]
  - Cumulative energy demand [MJ (renewable and non-renewable)]
  - Particulate matter formation potential [kg PM2.5 eq.]
  - Smog formation potential [kg O_3 eq.]
  - Acidification potential [kg SO_2 eq.]
  - Water use [cubic meters water]
  - Fossil depletion potential [kg oil eq.]
- Standardize to functional unit of treatment of one cubic meter of either municipal wastewater or graywater with the specified influent wastewater characteristics

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Reuse Scenarios Analyzed

		Mixed Wastewater		Separated Graywater	
		Large Mixed Use (Office/Residential)	District	Large Mixed Use (Office/Residential)	District
Total Flow Rate	0.025 MGD	✓		✓	
	0.05 MGD		✓		✓
Flow Rate of Water Treated	0.016 MGD			✓	
	0.025 MGD	✓			
	0.031 MGD				✓
	0.05 MGD		✓		
Sewer Connection	Sewered	✓	✓	✓	✓
	Unsewered		✓		
People Served*		**1,100**	**2,250**	**1,100**	**2,250**
Building Footprint (Roof Area)		**20,000**	**156,000**	**20,000**	**156,000**
Building Area Served (sq. ft)		**380,000**	**755,000**	**380,000**	**755,000**

* includes residents and office workers.

Fraction of Treated Water Reused On-Site

Representative of buildings with average efficiency appliances

Representative of buildings with high efficiency appliances

Wastewater Scenario	Building Configuration	High reuse	Low reuse
Mixed Wastewater	Mixed Use Building	72%	35%
	District	72%	35%
Separated Graywater	Mixed Use Building	100%	55%
	District	100%	57%

*Note: Assume fraction of treated water estimated for on-site reuse displaces treated drinking water

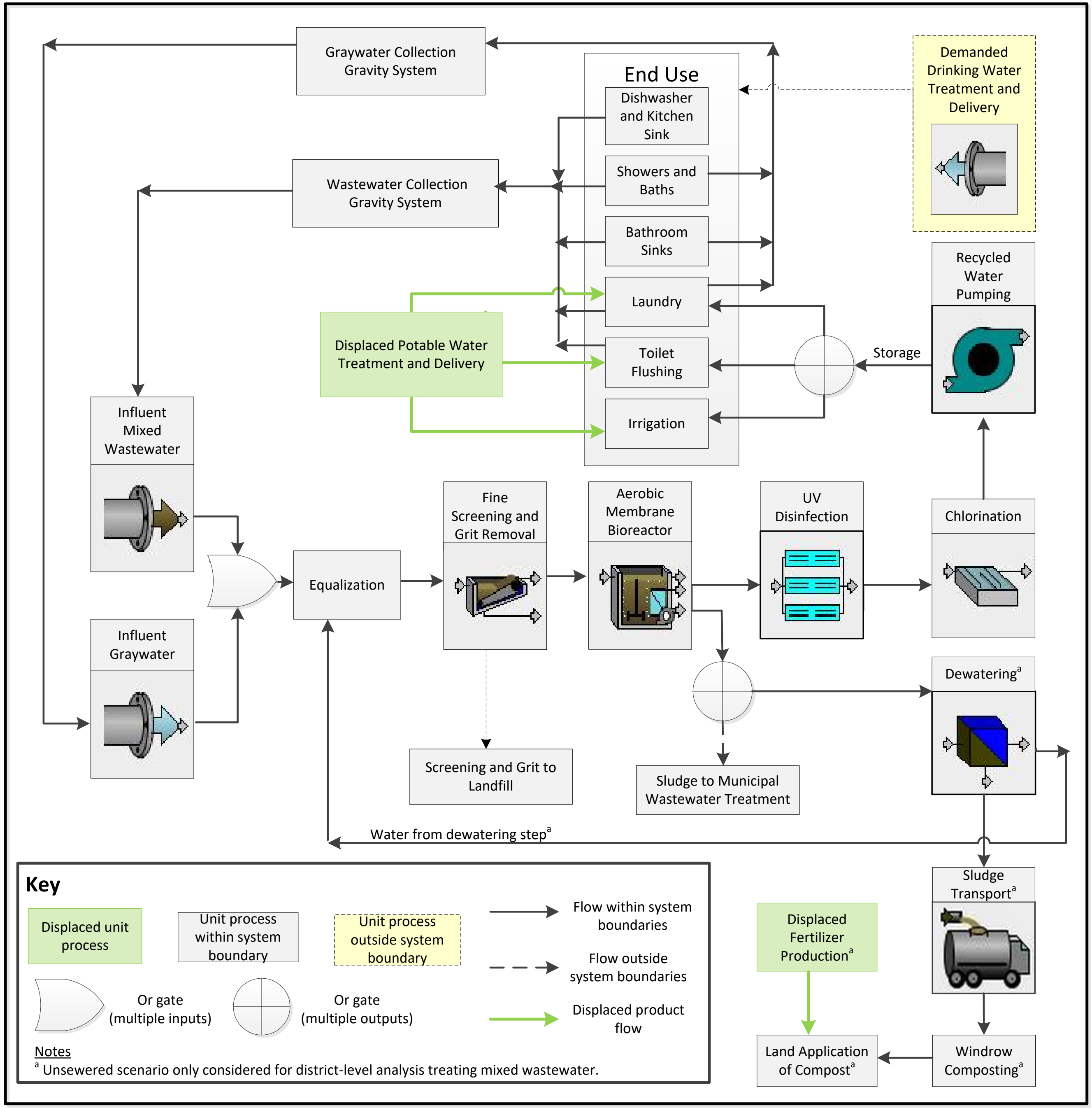
Influent and Effluent Characteristics

		Influent Values		Target Effluent Quality
Water Quality Characteristics		Mixed WW	Separated GW	Both
Characteristic	Unit	Medium Strength (Residential & District)[a]	Low Pollutant Load with Laundry[a]	Effluent Quality for Unrestricted Urban Use
Suspended Solids	mg/L	220	94	<5
Volatile Solids	%	80	47	-
$cBOD_5$	mg/L	203	167	-
BOD_5	mg/L	236	194	<10
Soluble BOD_5	mg/L	144	116	-
Soluble $cBOD_5$	mg/L	124	100	-
COD	mg/L	508	333	-
Soluble COD	mg/L	203	153	-
TKN	mgN/L	35	8.5	-
Soluble TKN	mgN/L	21	6.9	-
Ammonia	mgN/L	20	1.9	-
Total Phosphorus	mgP/L	5.6	1.1	-
Nitrite	mgN/L	0	0	-
Nitrate	mgN/L	0	0.64	-
Average Summer	deg C	23	30	-
Average Winter	deg C	23	30	-
Chlorine Residual	mg/L	n/a	n/a	0.5-2.5

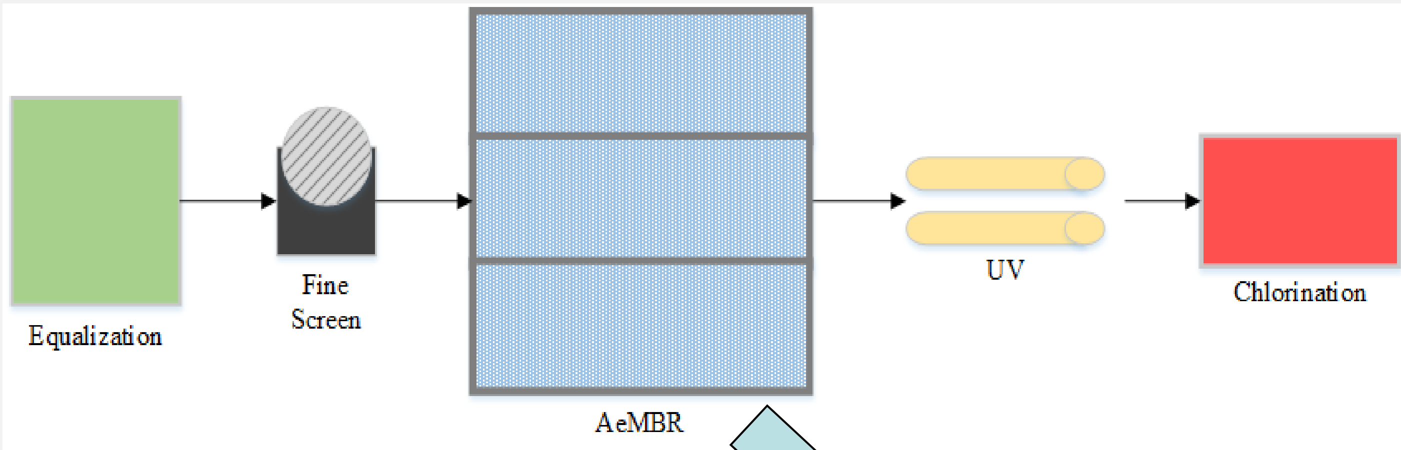
- Separated graywater in U.S.: wastewater from bathroom faucets, showers, baths, and laundry.
- Mixed wastewater: modeled as medium strength domestic.
- Treatment systems meet log reduction targets for NPR of mixed wastewater & graywater.

Full System Diagram

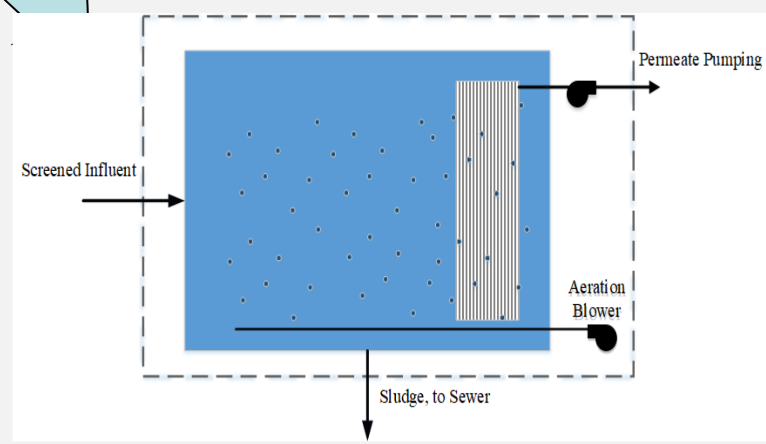
- Building scale system connected to sewer
- Unsewered scenario considered for district mixed wastewater treatment



Aerobic MBR (AeMBR)

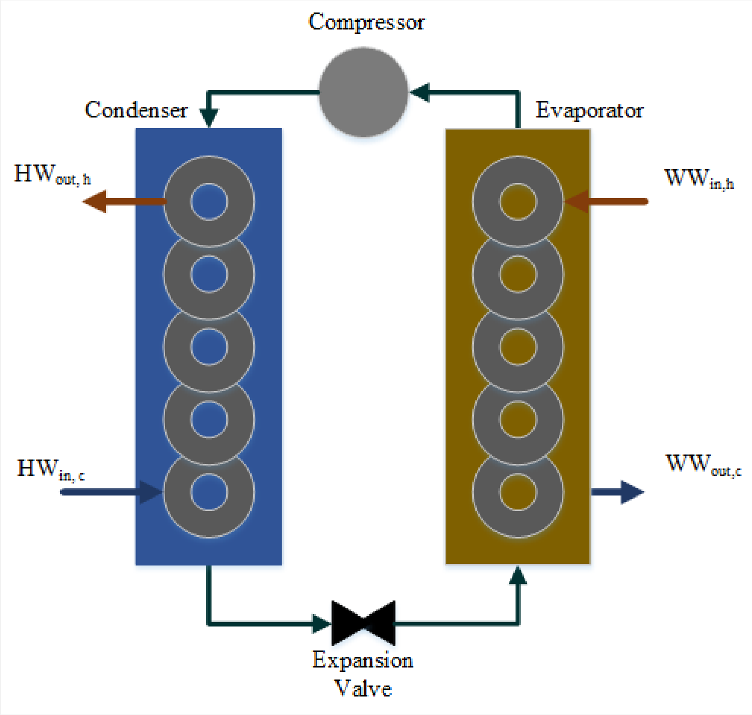


- Baseline technology – commercially available.
- model was primarily based on modeling simulations in CAPDETWorks™ design and costing software and GPS-X™

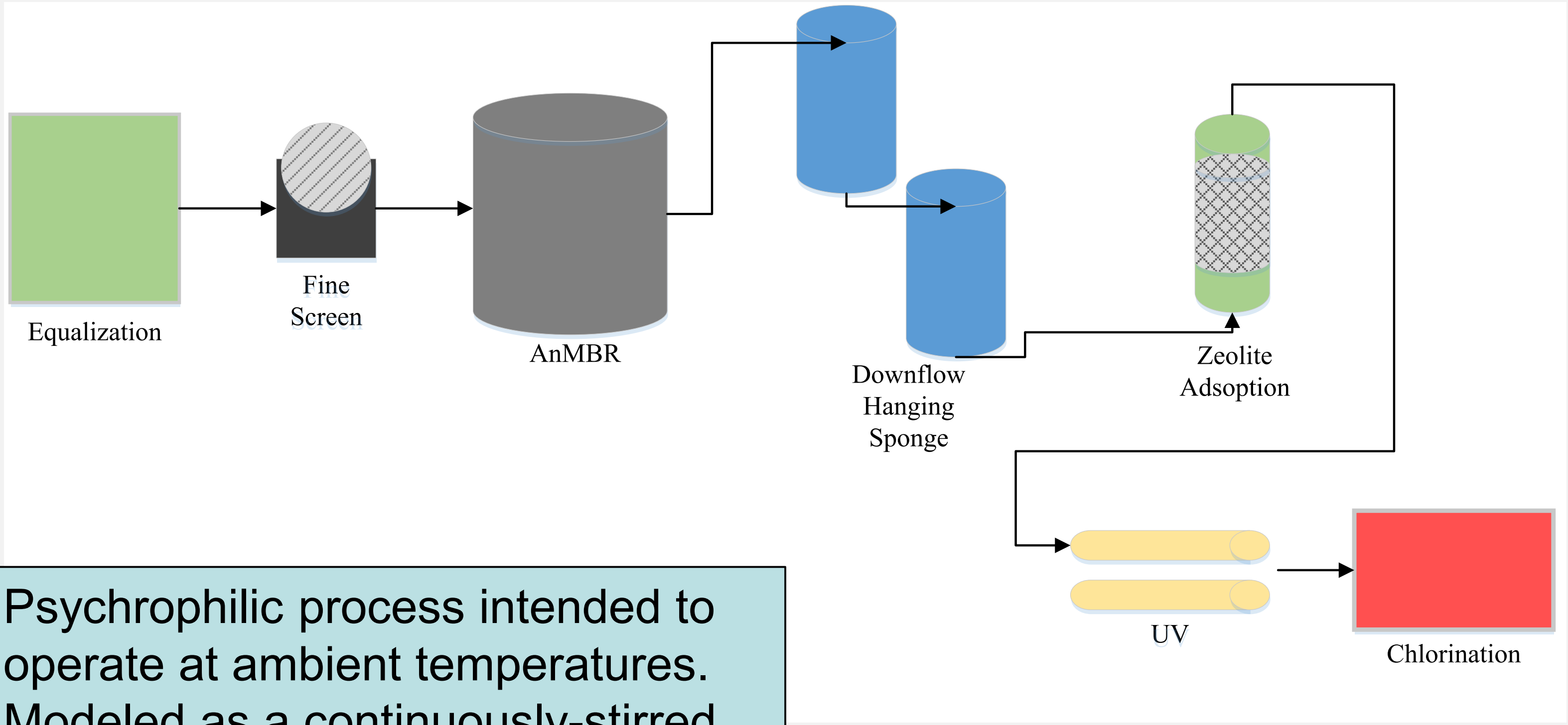


Thermal Recovery for AeMBR

- Low-grade heat from the mixed wastewater and graywater is recovered using a water-to-water heat pump prior to AeMBR treatment
- Filtered graywater and wastewater is pumped into a heat exchanger



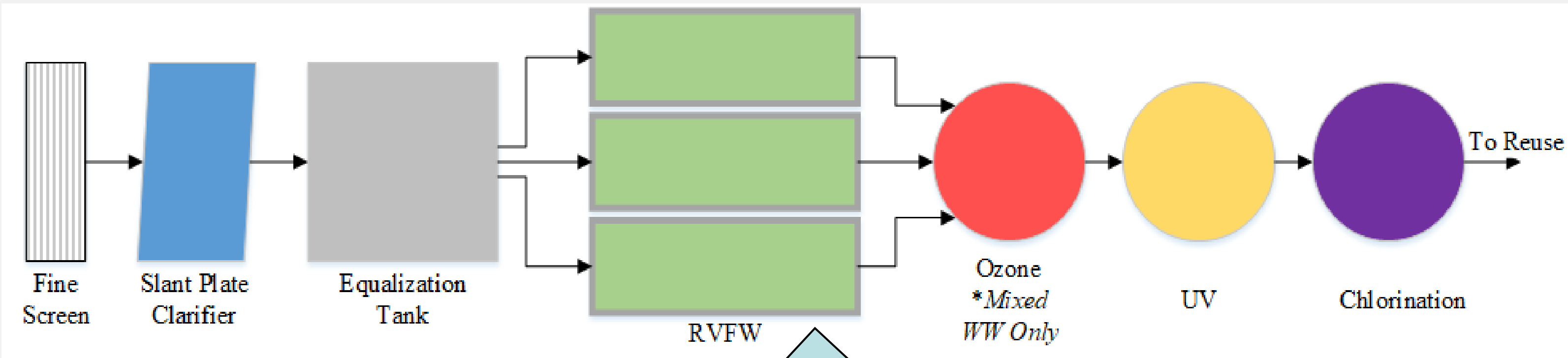
Anaerobic MBR (AnMBR)

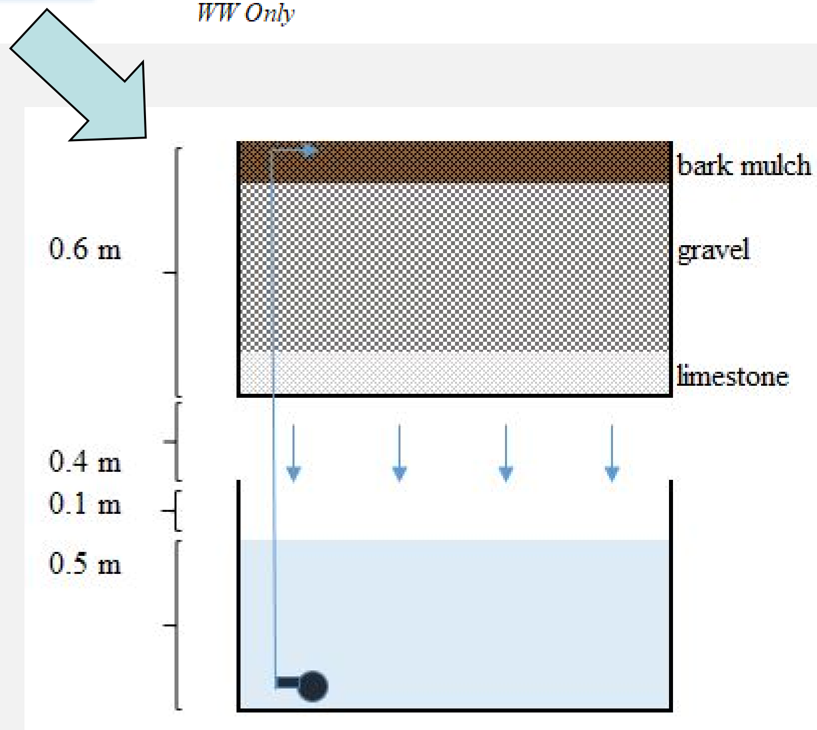


- Psychrophilic process intended to operate at ambient temperatures.
- Modeled as a continuously-stirred tank reactor.
- Continuous biogas sparging used in baseline.
- Recovered biogas used for heating purposes.

- Permeate methane recovered with downflow-hanging sponge.
- Zeolite adsorption modeled to decrease ammonia levels and establish chlorine residual.

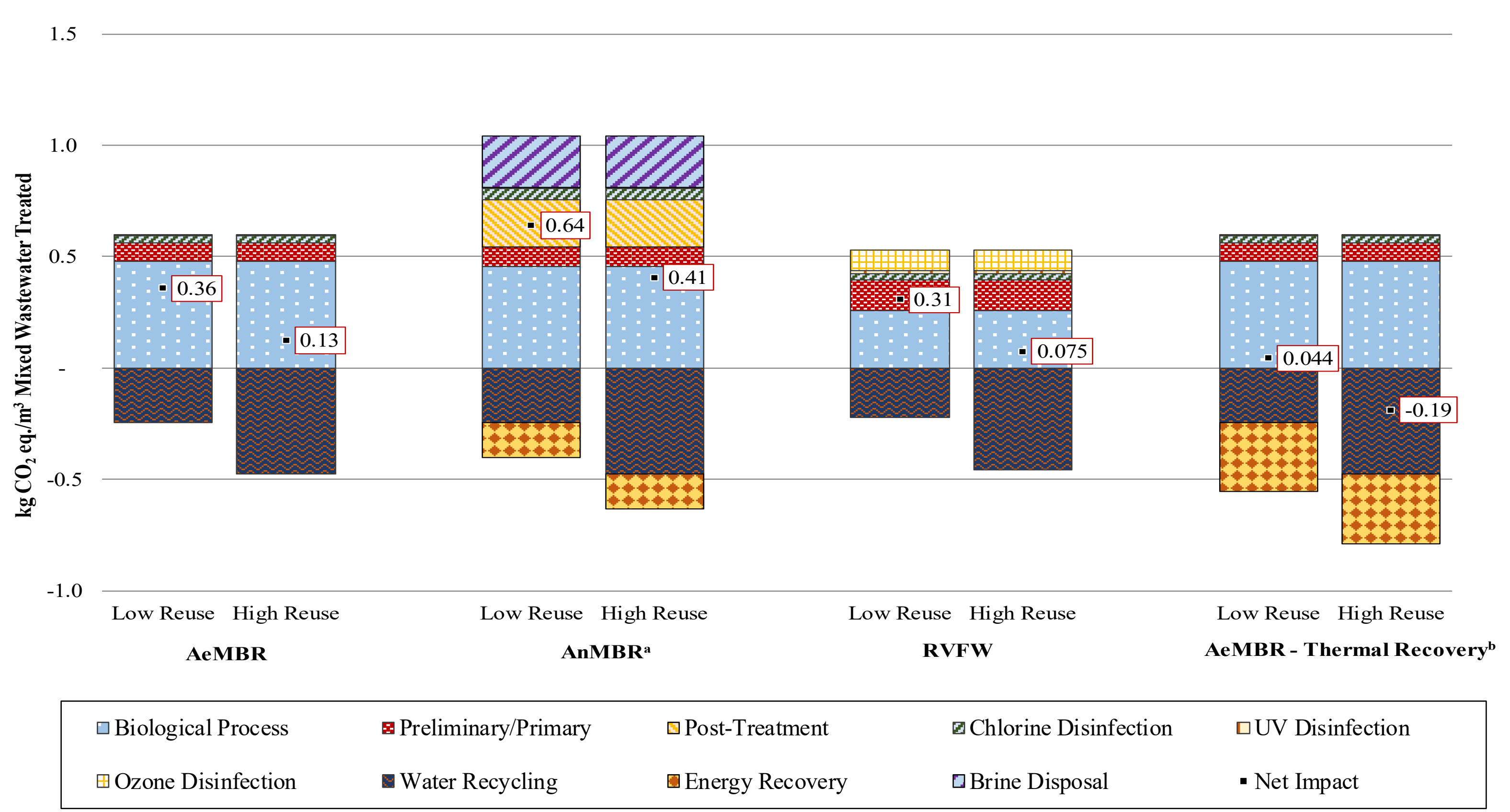
Recirculating Vertical Flow Wetland (RVFW)





Utilizes active pumping to achieve a high recirculation rate, limiting land area requirements

Life Cycle Impacts for Building Scale Mixed Wastewater Treatment Technologies (Global Warming Potential)



[a] AnMBR results modeled with continuous biogas sparging.
[b] Thermal recovery modeled as providing heat to a natural gas-based building hot water heater.
Note: Low reuse = high efficiency appliances, 35% of treated water is recycled; High reuse = average efficiency appliances, 72% of treated water is recycled

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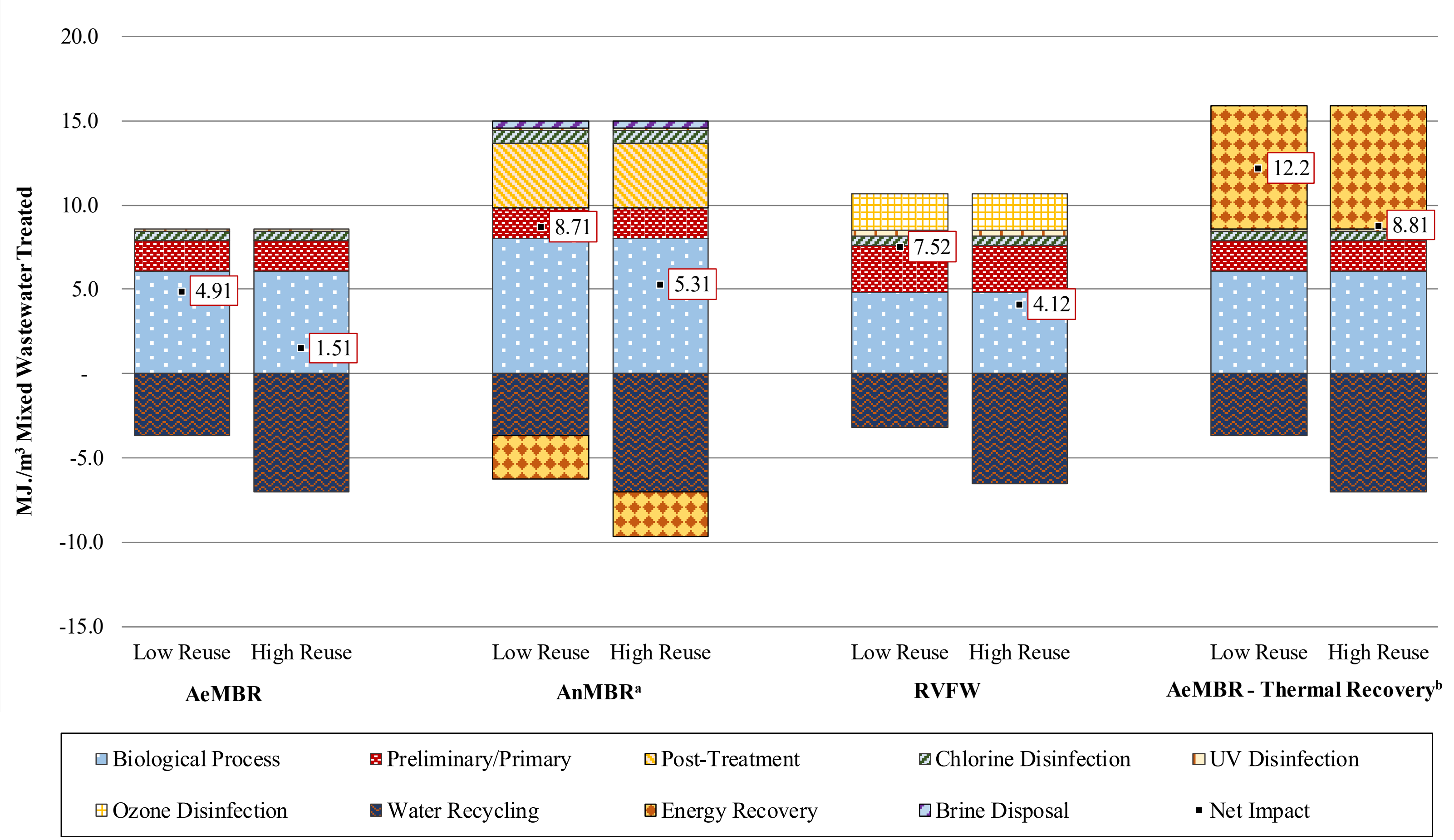
Life Cycle Impacts for Building Scale Mixed Wastewater Treatment Technologies (Cumulative Energy Demand)



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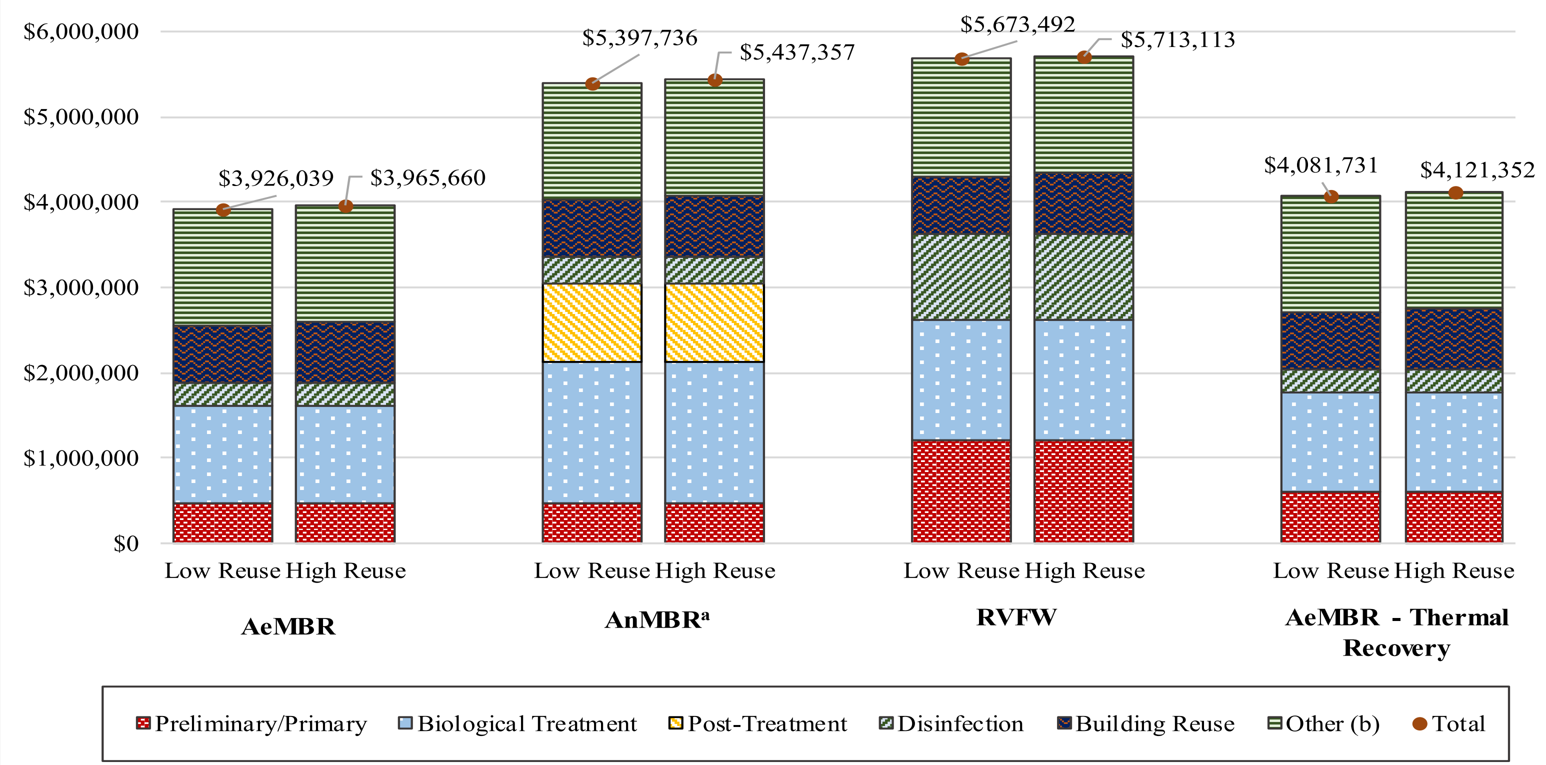
Net Present Value for Building Scale Mixed Wastewater Treatment Technologies (by Life Cycle Stage)



[a] AnMBR results modeled with continuous biogas sparging.
[b] Other = administrative costs.

Low reuse = high efficiency appliances, 35% of treated water is recycled
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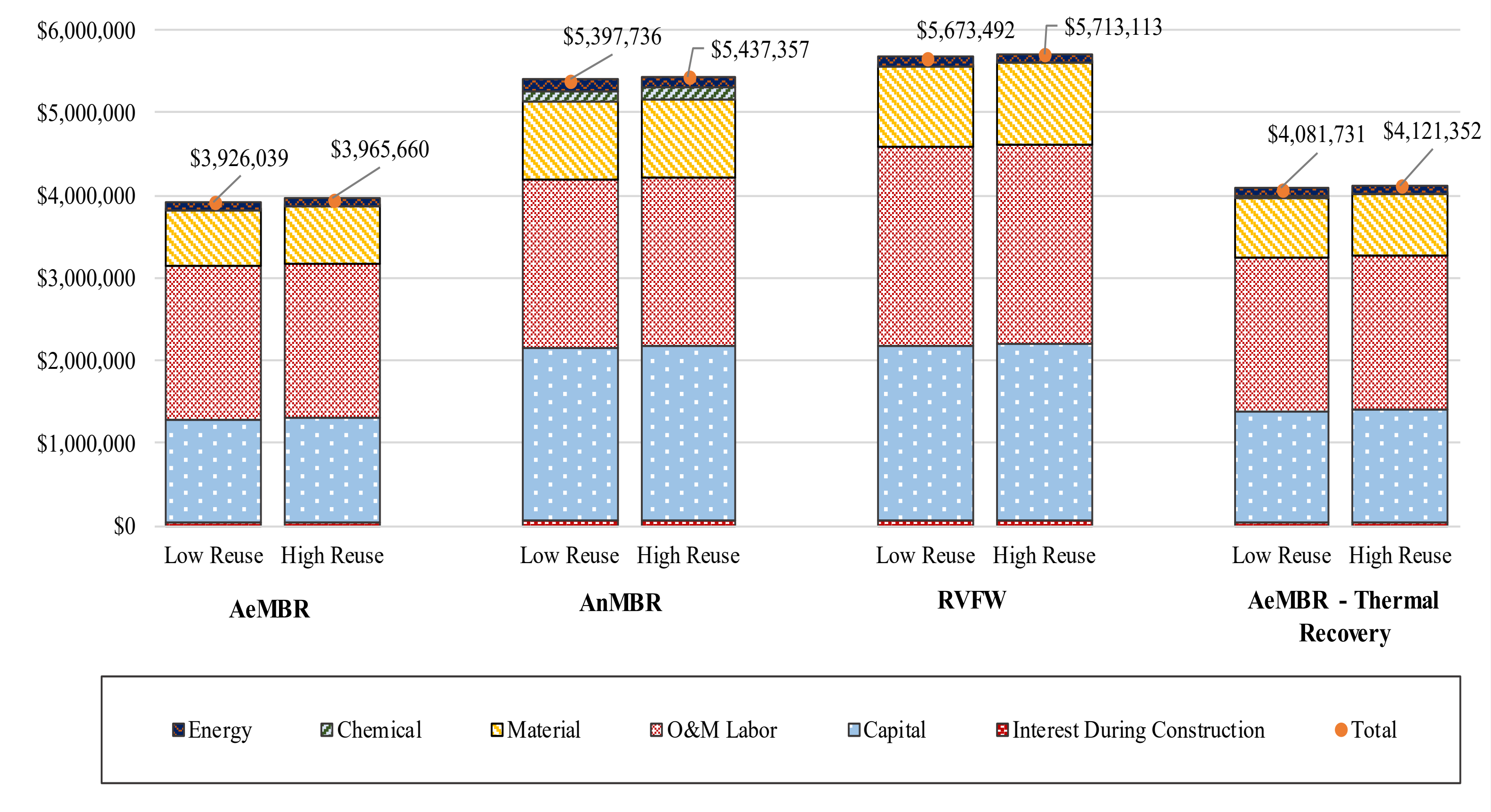
Net Present Value for Building Scale Mixed Wastewater Treatment Technologies (by Cost Category)



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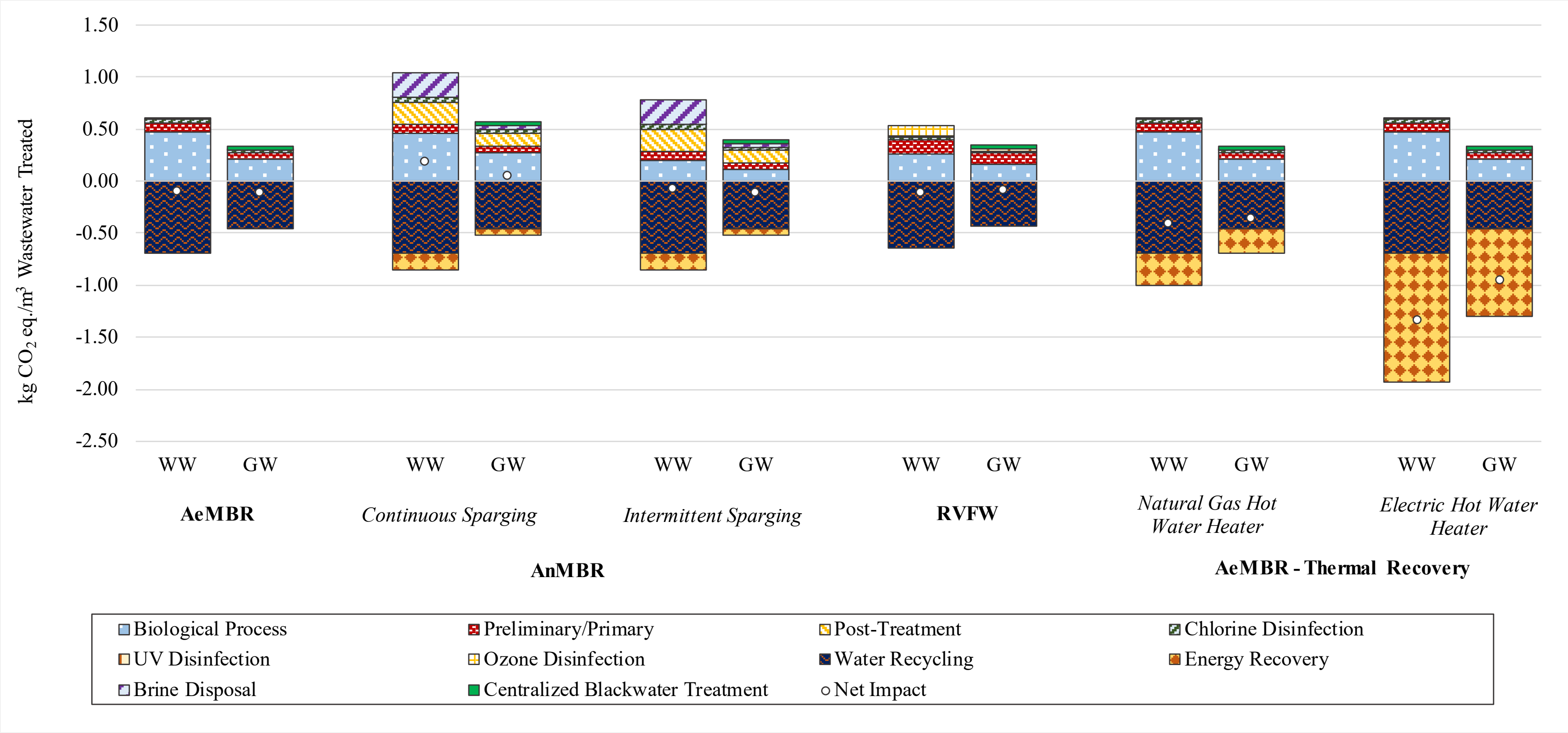
Full Utilization of Treated Water – Mixed Wastewater and Graywater (Global Warming Potential)



*Note: Net water savings is 1.21 m^3/m^3 wastewater treated for mixed wastewater and 0.79 m^3/m^3 wastewater treated for graywater. For mixed wastewater, able to achieve > 1 m^3 water savings as also avoiding water losses in distribution system. This slide includes centralized WRRF blackwater treatment (not included in previous GW slides).

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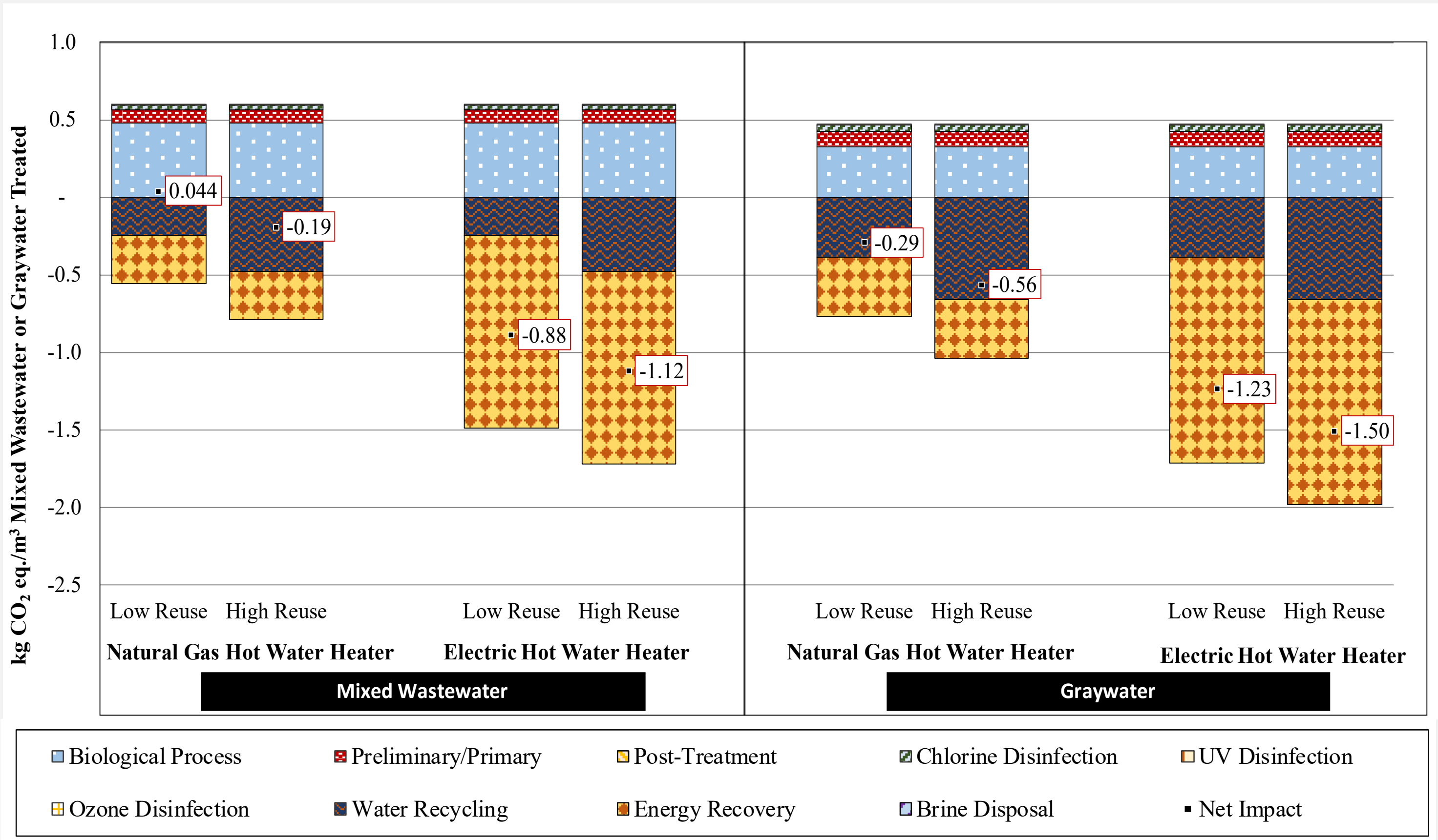
Thermal Energy Recovery - Sensitivity Analysis (Global Warming Potential)



Low reuse = high efficiency appliances, 35% (Mixed WW) or 55% (GW) of treated water is recycled
High reuse = average efficiency appliances, 72% (Mixed WW) or 100% (GW) of treated water is recycled

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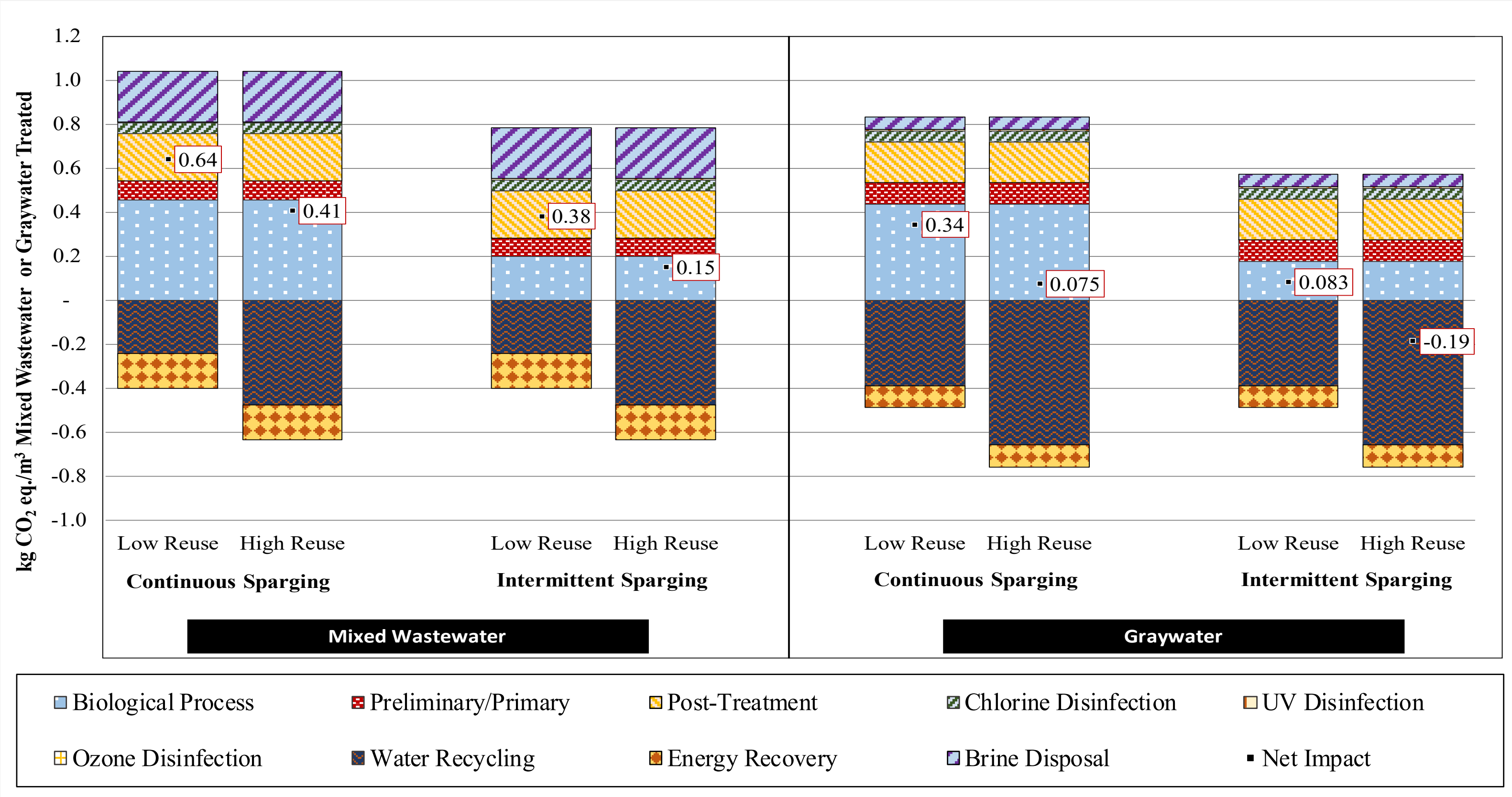
AnMBR Biogas Sparging - Sensitivity Analysis (Global Warming Potential)



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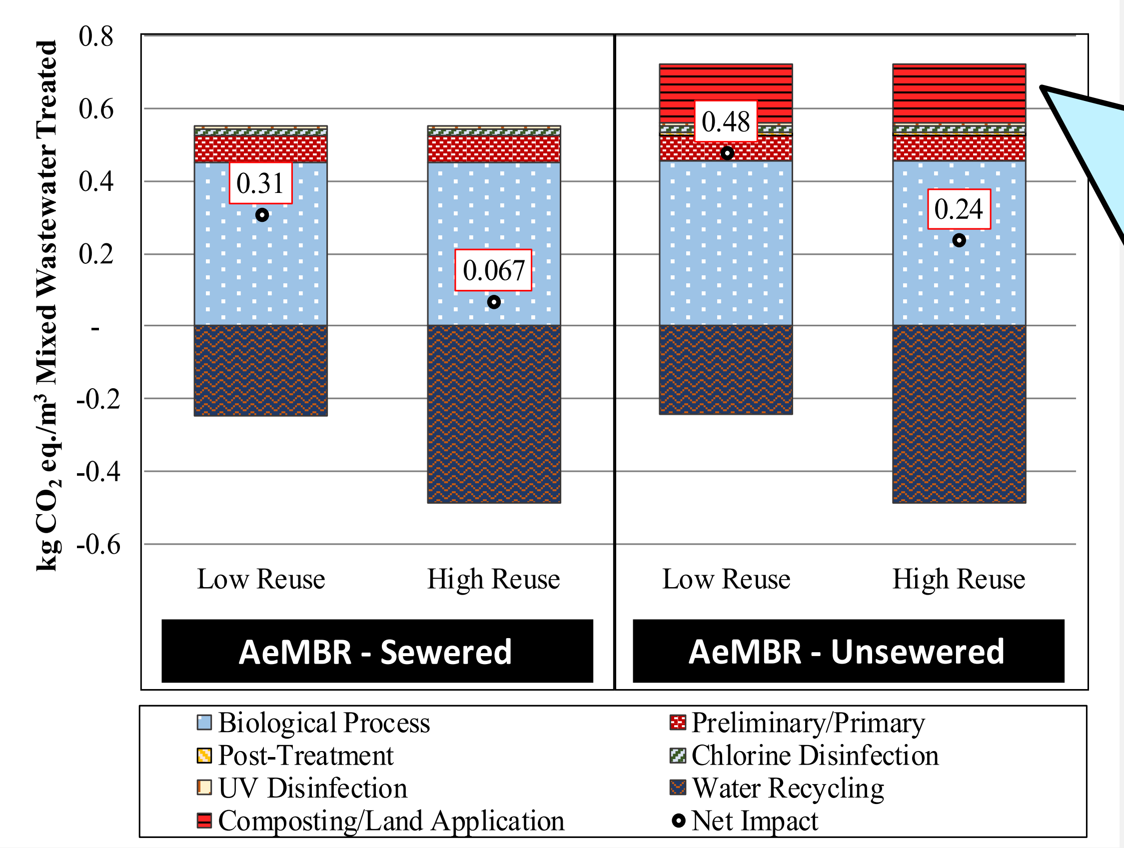
Life Cycle Impacts for District Scale Mixed Wastewater Treatment Technologies (Global Warming Potential)



On-site biosolids dewatering, trucking to facility (130 km), windrow composting, land application and avoided fertilizer production

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So, does it make sense?

- Clear environmental benefits of displacing drinking water
- Graywater and mixed wastewater treatment net environmental impacts similar if able to find uses for all treated water
  - Source separated graywater systems provide sufficient recycled water quantity to meet building needs
  - Mixed wastewater systems may be more applicable if able to share water with other buildings
- Can add thermal recovery unit before AeMBR or RVFW treatment options to provide hot water heating needs
- Benefits of AnMBR energy recovery offset at the building-scale due to post-treatment steps required to establish the chlorine residual

Disclaimer

This research was part of the U.S. Environmental Protection Agency (U.S. EPA) Office of Research and Development's Safe and Sustainable Water Resources (SSWR) Program. The research was supported by U.S. EPA contract EP-C-16-0015 to Eastern Research Group, Inc. Although the information in this document has been funded by the U.S. EPA, it does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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Extra Slides

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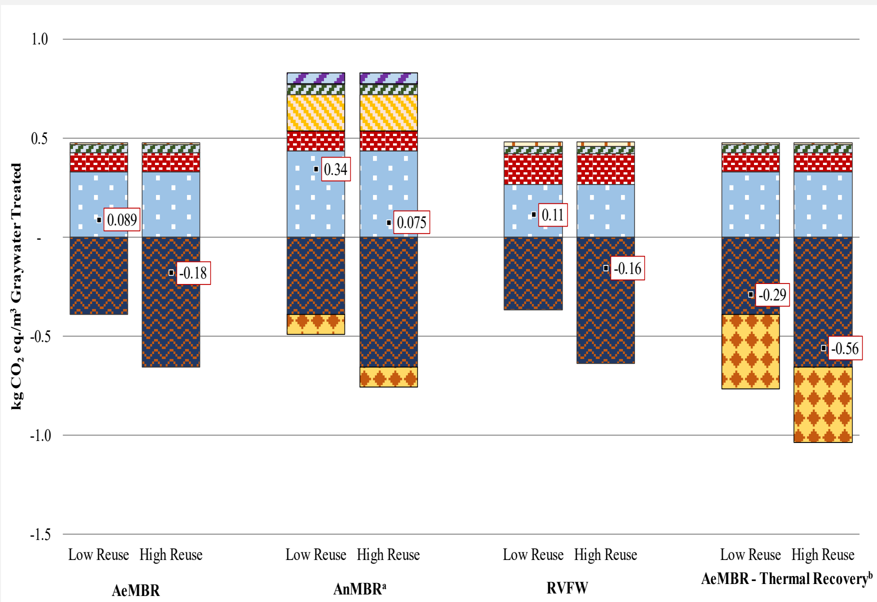
Log Reduction Targets for 10^{-4} Infection Risk Target, Non-Potable Reuse: Wastewater and Graywater

		Enteric Viruses	Parasitic Protozoa	Enteric Bacteria
Indoor Use	Domestic Wastewater	8.5	7.0	6.0
	Graywater	6.0	4.5	3.5
Unrestricted Irrigation	Domestic Wastewater	8.0	7.0	6.0
	Graywater	5.5	4.5	3.5

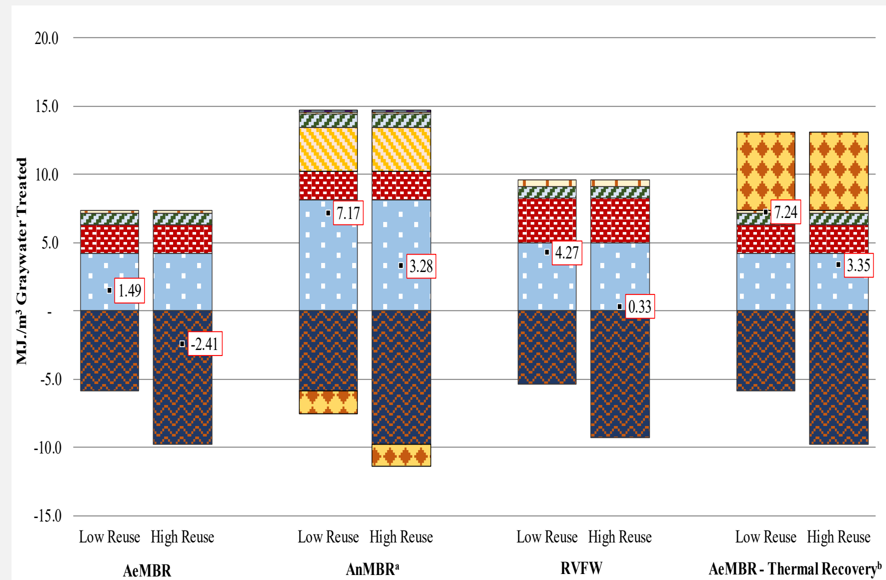
Table reproduced from Table 3-3 in (Sharvelle et al. 2017)

Life Cycle Impacts for Building Scale Graywater Treatment Technologies

Global Warming Potential



Cumulative Energy Demand



Biological Process	Preliminary/Primary	Post-Treatment	Chlorine Disinfection	UV Disinfection
Ozone Disinfection	Water Recycling	Energy Recovery	Brine Disposal	▪ Net Impact

[a] AnMBR results modeled with continuous scouring.
[b] Thermal recovery modeled as providing heat to a natural gas-based building hot water heater.
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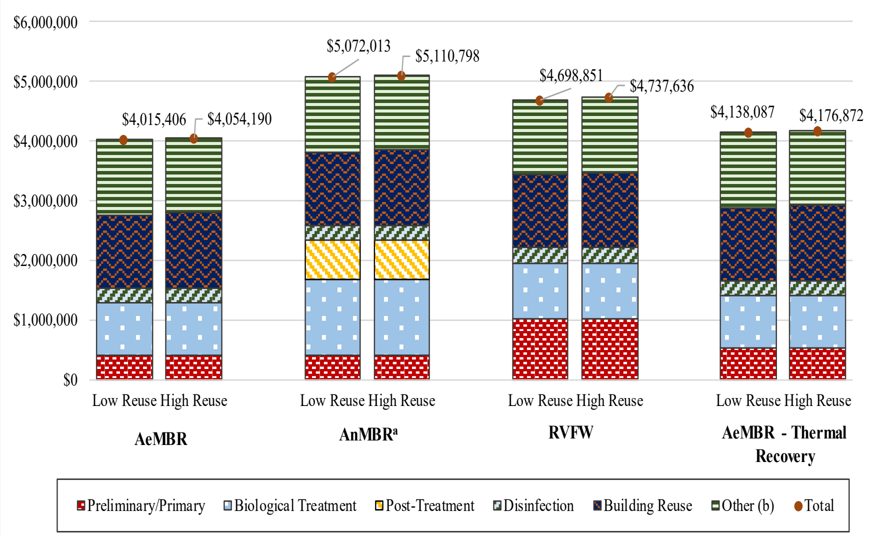
Net Present Value for Building Scale Graywater Treatment Technologies

By Life Cycle Stage



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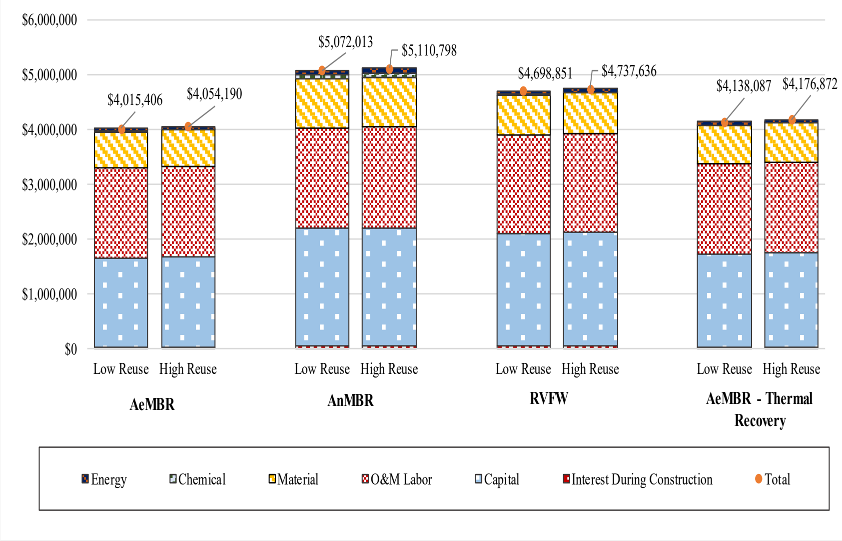
By Cost Category



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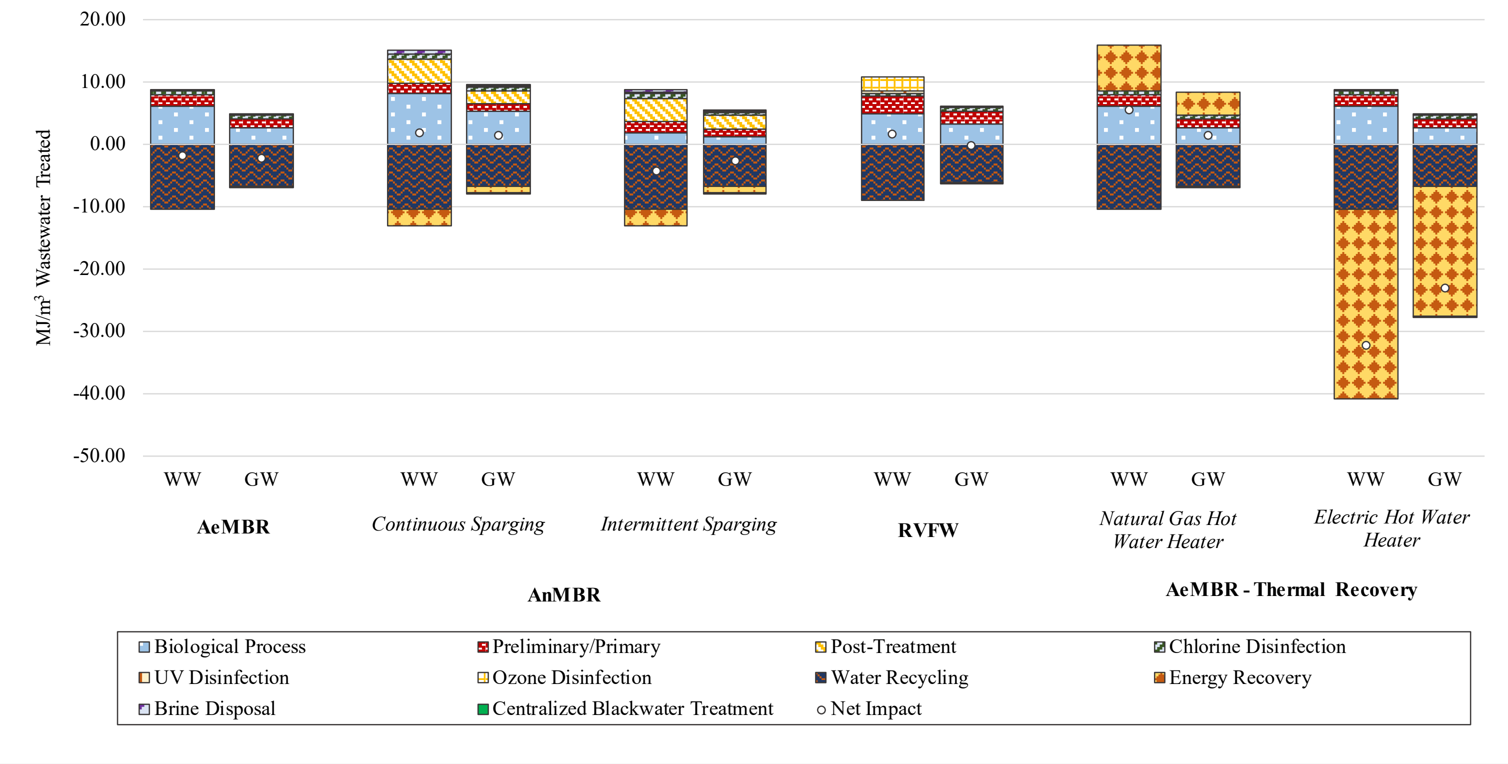
Full Utilization of Treated Water (Cumulative Energy Demand)



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