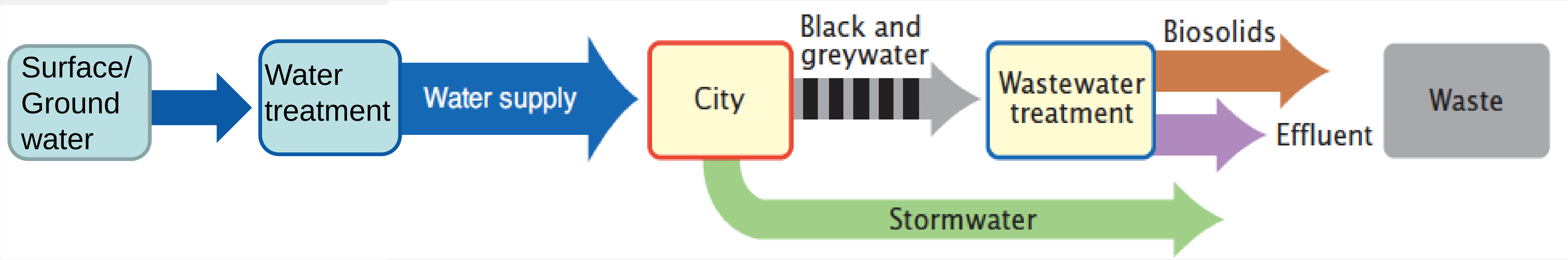
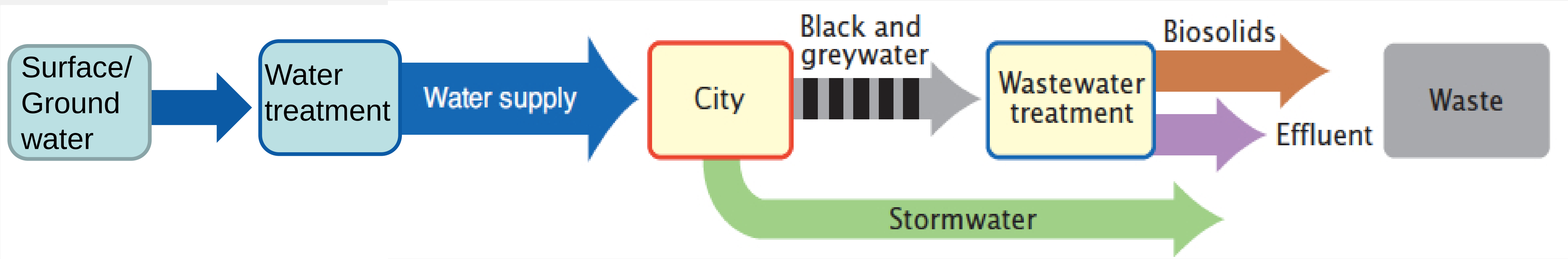
Solving for Pattern: Integrated Sustainability Assessment of Alternative Centralized and Decentralized Water Service Options

Jay L Garland, US EPA Office of Research & Development


Current Water and Wastewater System



Current Water and Wastewater System



- Imbalanced nutrient cycle instead of nutrient recovery
- Energy consumption instead of production
- Not resilient to climate change

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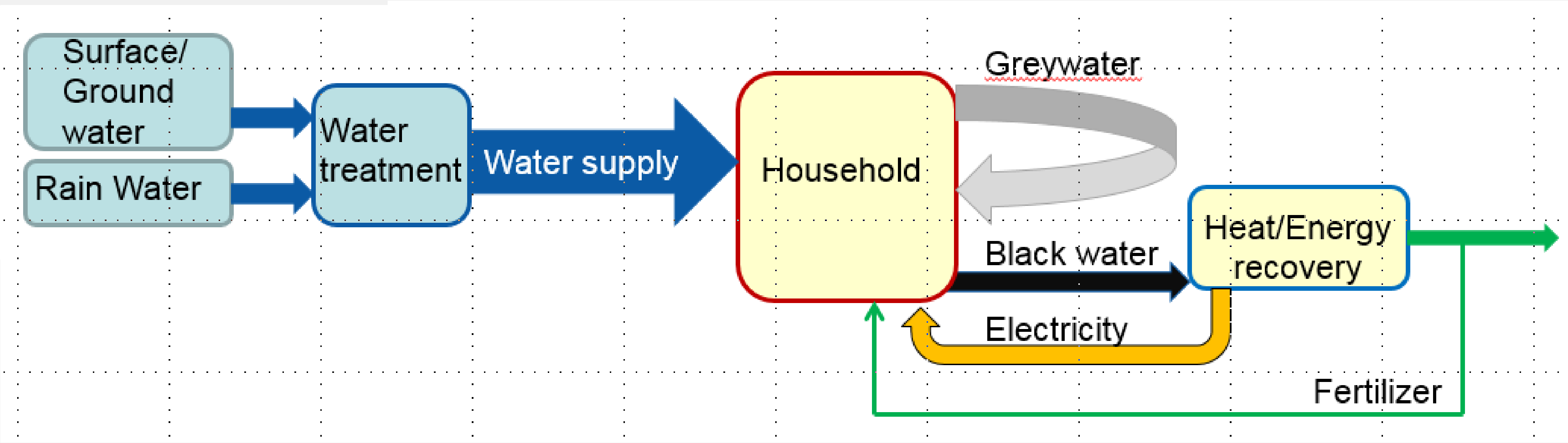
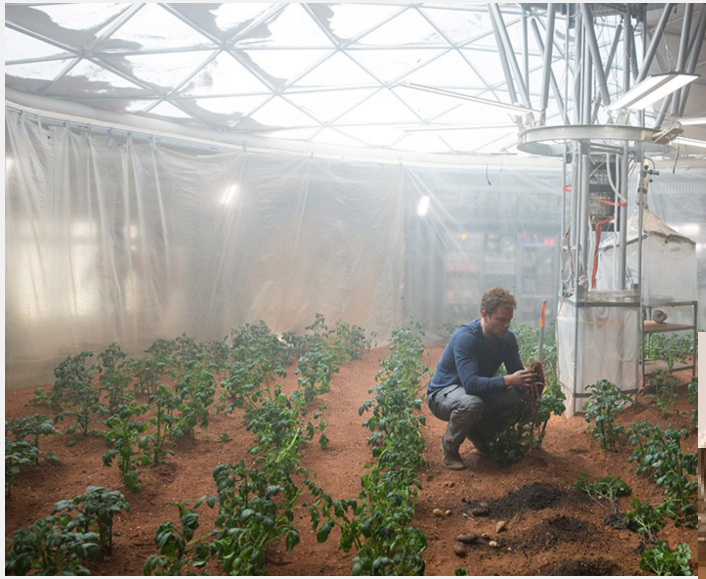
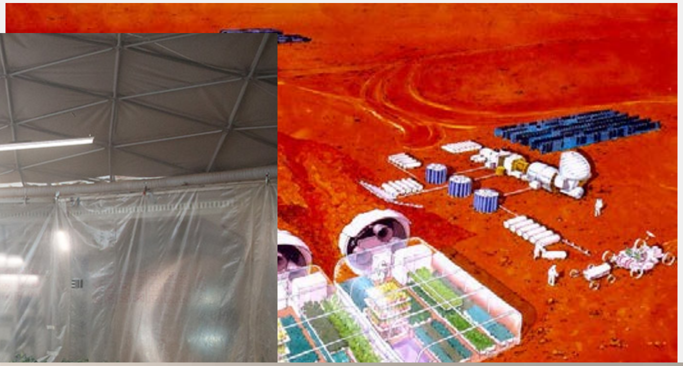
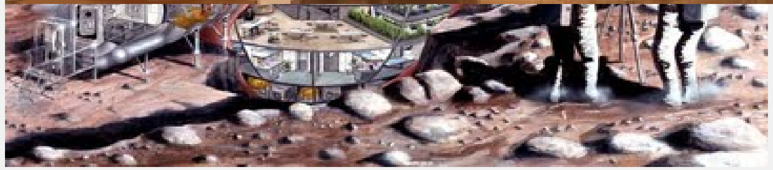
Future Water and Wastewater System



My Extraterrestrial Bias



"If we knew how to live on Mars, we'd know how to reduce our footprint on Earth. Space colonization is the Rosetta stone for earthly sustainability because it's entirely about living in the absence of ecosystem services. The Moon, Mars and the asteroids are a great experimental laboratory that we're ignoring at our own peril."

Karl Schroeder

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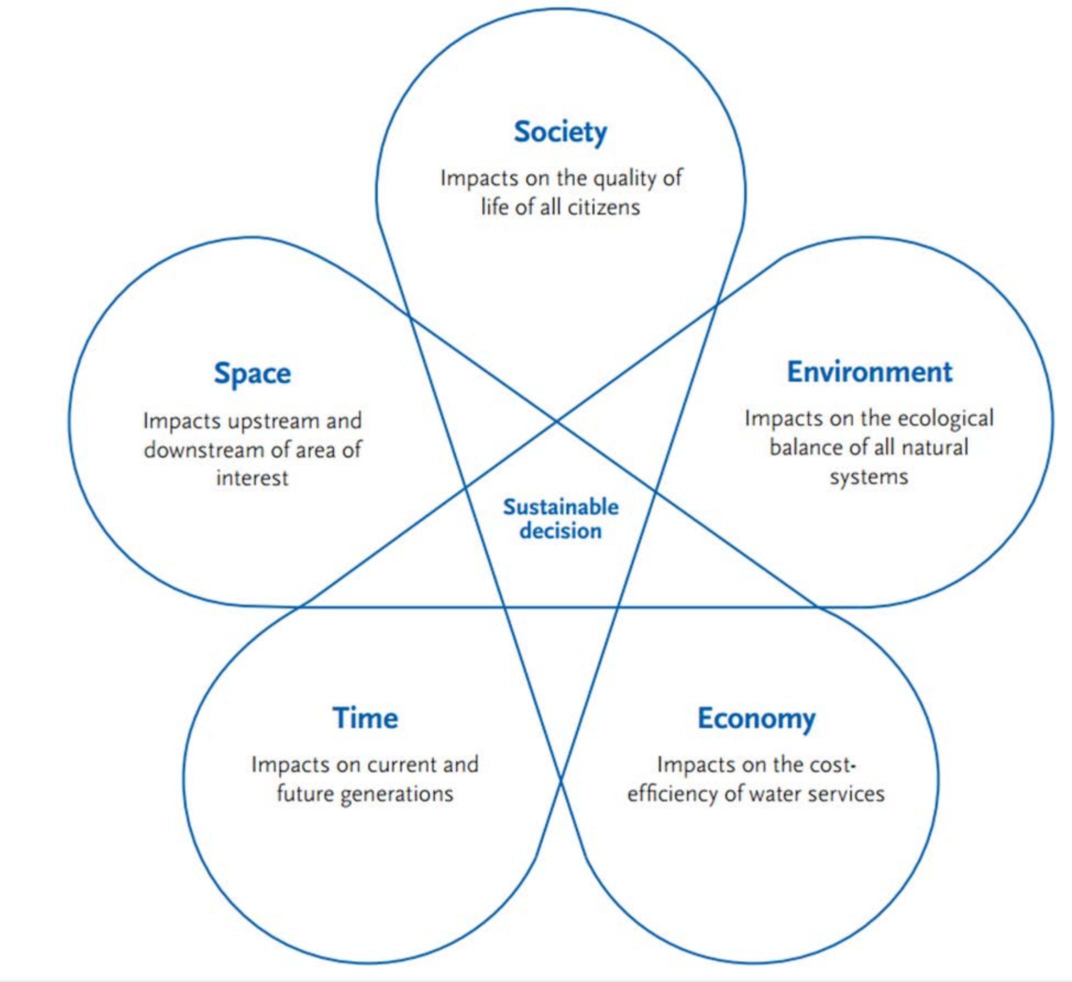
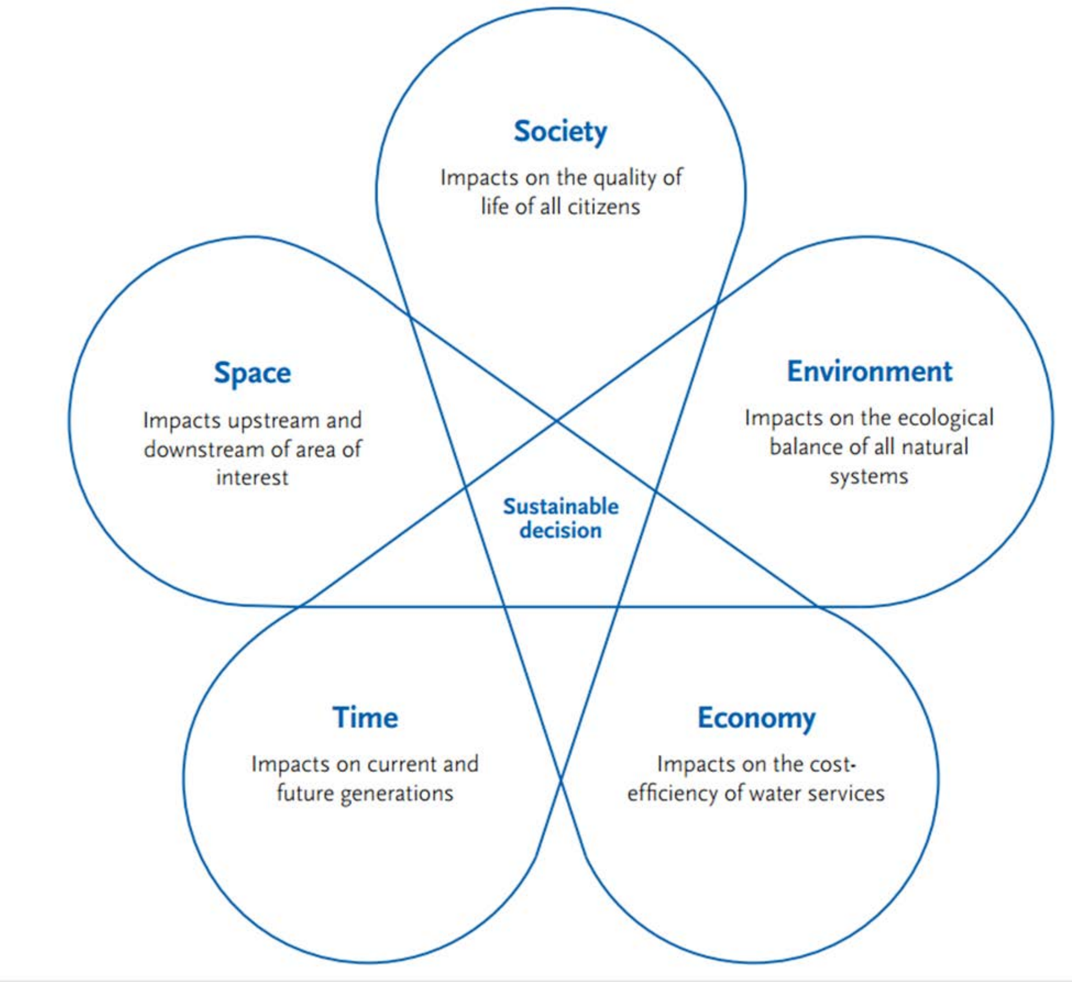
Considerations for a sustainable decision



The SWITCH Training Kit prepared within the framework of the European research project SWITCH (2006 to 2011) ww.switchurbanwater.eu

Sustainability metrics for water systems



Society
Human health impact
Environment
Life cycle energy use
Life cycle global warming potential
Life cycle eutrophication potential
Economy
Equivalent annual cost
Society/Environment/Economy
Technical resilience

Xue, X.; *et al.*, Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches. *Water Research* 2015, 77, 155-169.

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Wendell Berry

(by Greg Newbold)

Such solutions always involve a definition of the problem that is either false or so narrow as to be virtually false. The whole problem must be solved, not just some handily identifiable and simplifiable aspect of it. A bad solution is bad, then, because it acts destructively upon the larger patterns in which it is contained… A bad solution solves for a single purpose or goal, such as increased production. And it is typical of such solutions that they achieve stupendous increases in production at exorbitant biological and social costs.

from the essay, *Solving For Pattern*,

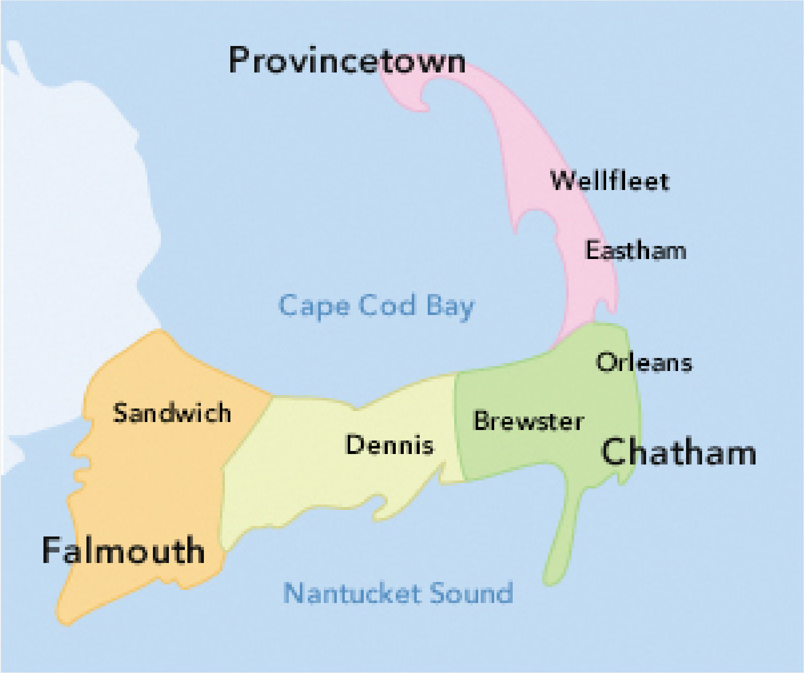
Contributors

- Mary Schoen, Soller Environmental
- Cissy Ma, US EPA
- Jennifer Cashdollar, US EPA
- Troy Hawkins, Enviance
- Xiaobo Xue, Oak Ridge Institute For Science and Education (now SUNY-Albany)
- Nicholas Ashbolt, University of Alberta
- Alison Wood, University of Texas
- Mike Blackhurst, University of Texas
- Desmond Lawler, University of Texas

Objectives

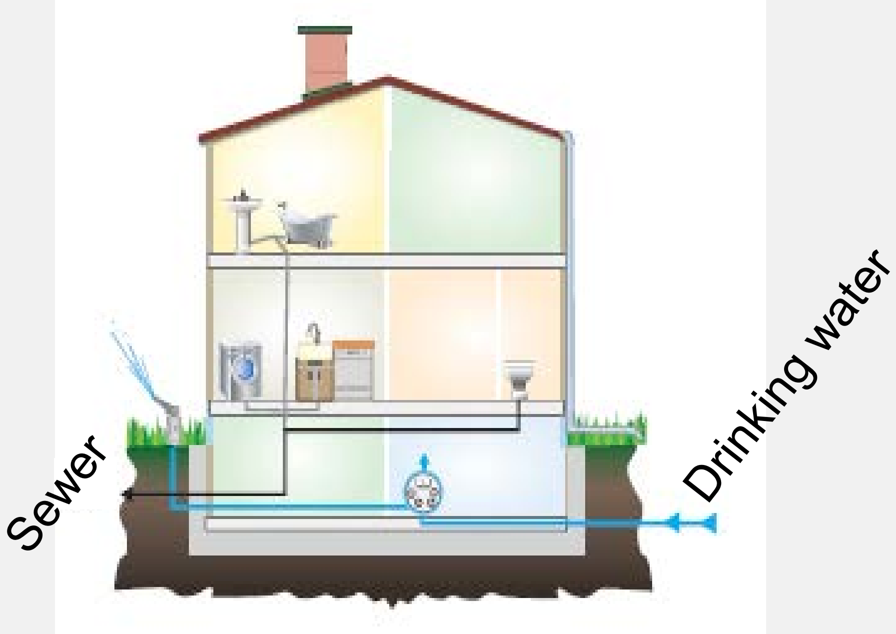
- Use the sustainability metrics to compare the sustainability of community water system options
- Identify important knowledge gaps in the calculation of the sustainability metrics for community water systems

Cape Cod: A region preparing for change



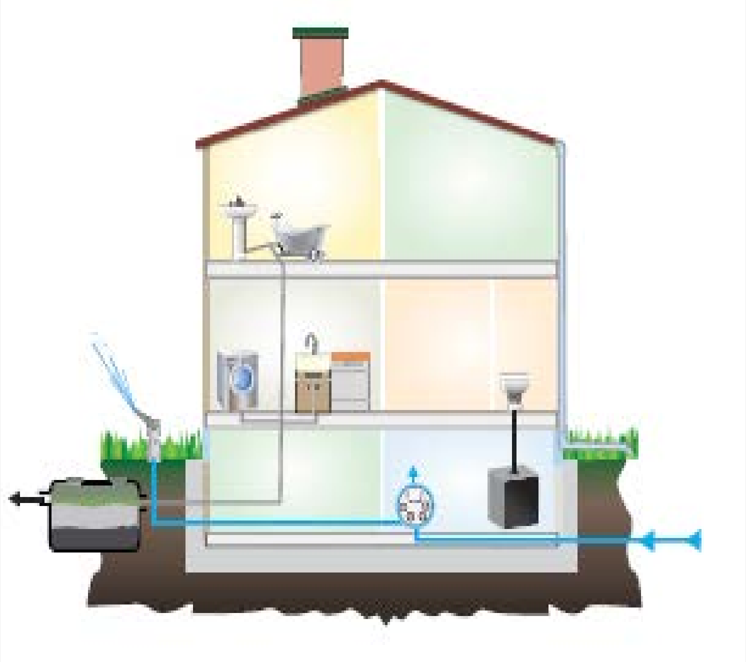
- Environmental damage due to eutrophication from septic leakage
- Regional effort to develop wastewater plan in response to eutrophication
- Stakeholder involvement- citizens, Cape Cod Commission, EPA Region 1, EPA ORD, local non-profits
- Opportunity for EPA ORD to evaluate community options using different metrics

Option 1: Centralized



- Conventional drinking water
- Conventional wastewater treatment

Option 2: Composting toilet / septic



- Conventional drinking water
- Composting toilet, with greywater to septic system
- Compost transported out of the watershed

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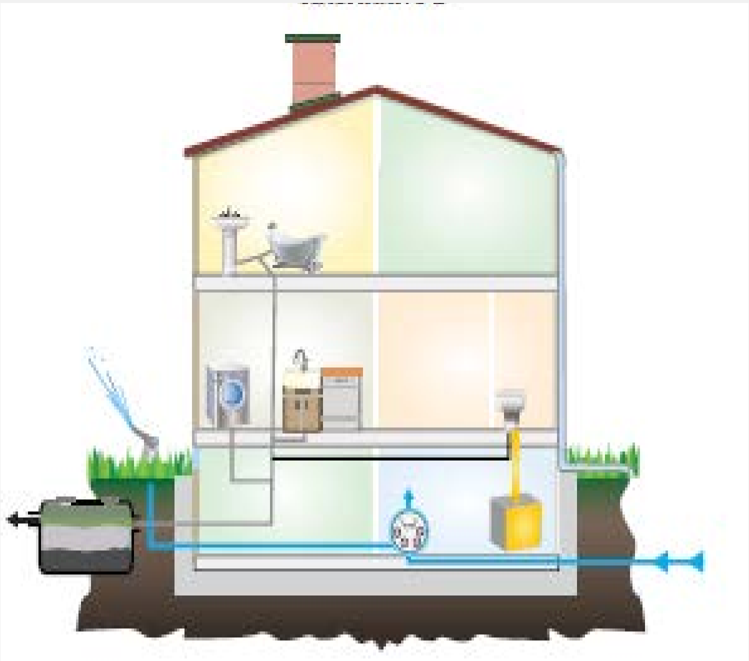
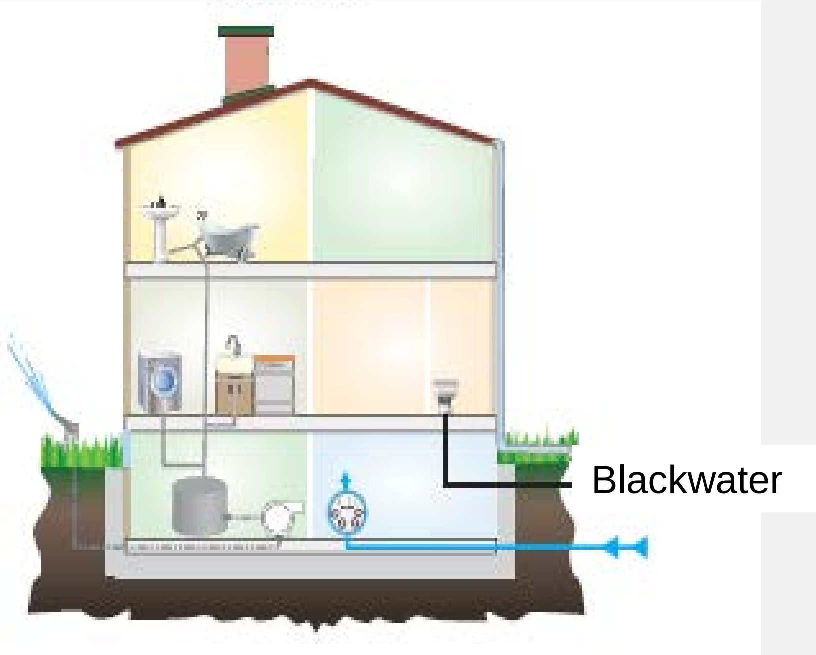
Option 3: Urine diversion toilet / septic



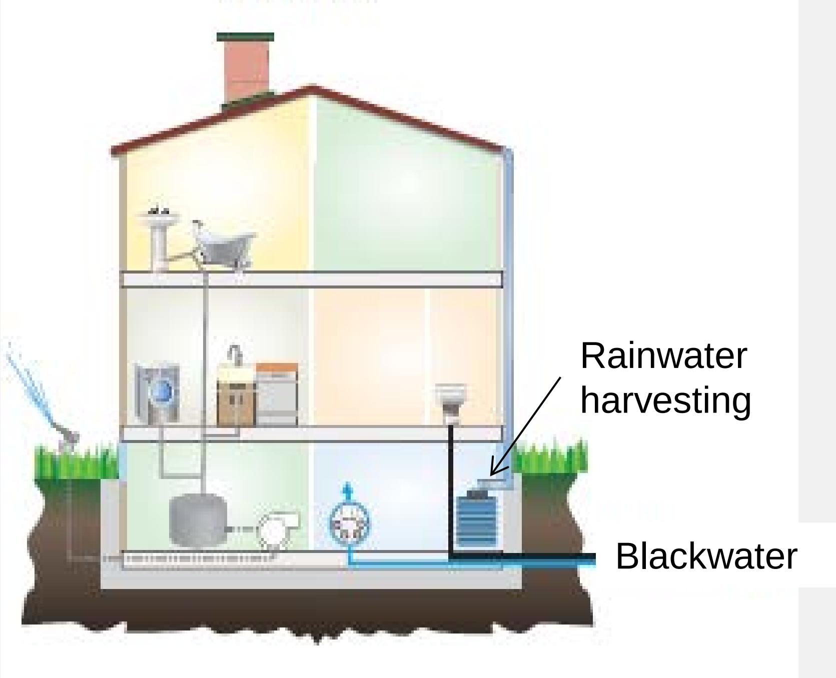
- Conventional drinking water
- Urine diversion toilet, with greywater and solids to septic system
- Urine transported out of the watershed

Option 4: Energy recovery / greywater reuse



- Conventional drinking water
- Blackwater pressure sewer to energy recovery digester
- Digestate used as soil amendment in watershed
- Greywater reuse for nonpotable purposes

Option 5: Energy recovery / greywater and rainwater reuse



- Conventional drinking water
- Blackwater pressure sewer to energy recovery digester
- Digestate used as a soil amendment in the watershed
- Greywater reuse and rainwater reuse for shower

Take a guess…

1. Which option is the most/least expensive for each household?
2. Will the reuse options have relatively higher human health risk?
3. Will the septic options have more nutrient releases in the watershed?
4. Will the energy recovery options have lower energy use and greenhouse gas production?
5. Overall, which option is worst/best based on these metrics?

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Equivalent Annual Cost

- Objective: Quantify monetary costs and benefit
- Tool: Life cycle costing
- Treatment of variability/uncertainty: Deterministic with separate sensitivity analysis
- Reference: Wood, A.; *et al.*, Cost-effectiveness of nitrogen mitigation by alternative household wastewater management technologies. Journal of environmental management 2015, 150, 344-354.

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Equivalent Annual Cost

- Based on the current scenario in Falmouth, MA
  - Population and housing from 2010 census
  - Existing infrastructure and waste systems (retrofit)
- Includes installation and O&M costs
- Assumes no salvage value
- Assumes no benefit from potential sale of urine, compost, or digestate
- Costs from white and grey literature, vendor information

Take a guess…

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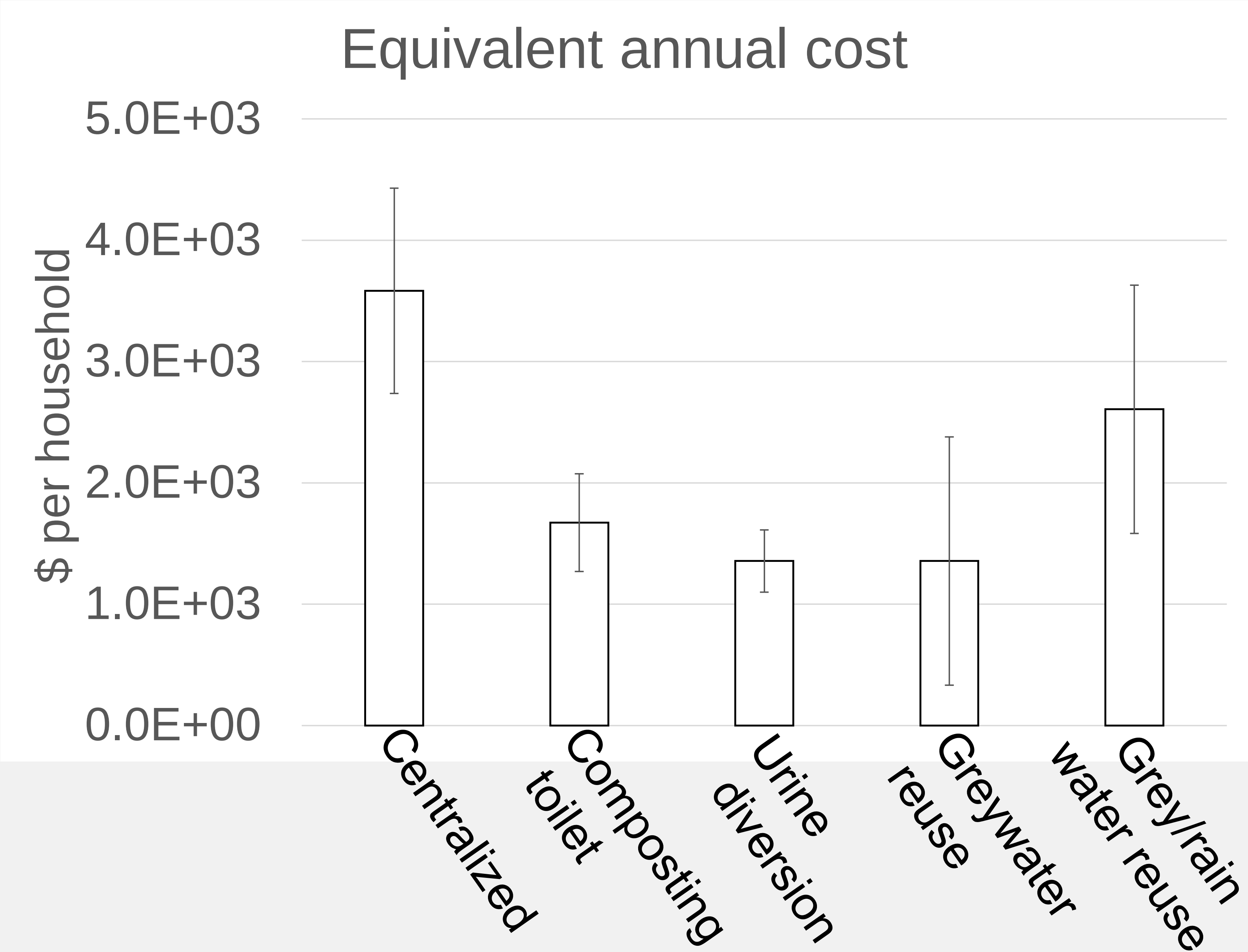
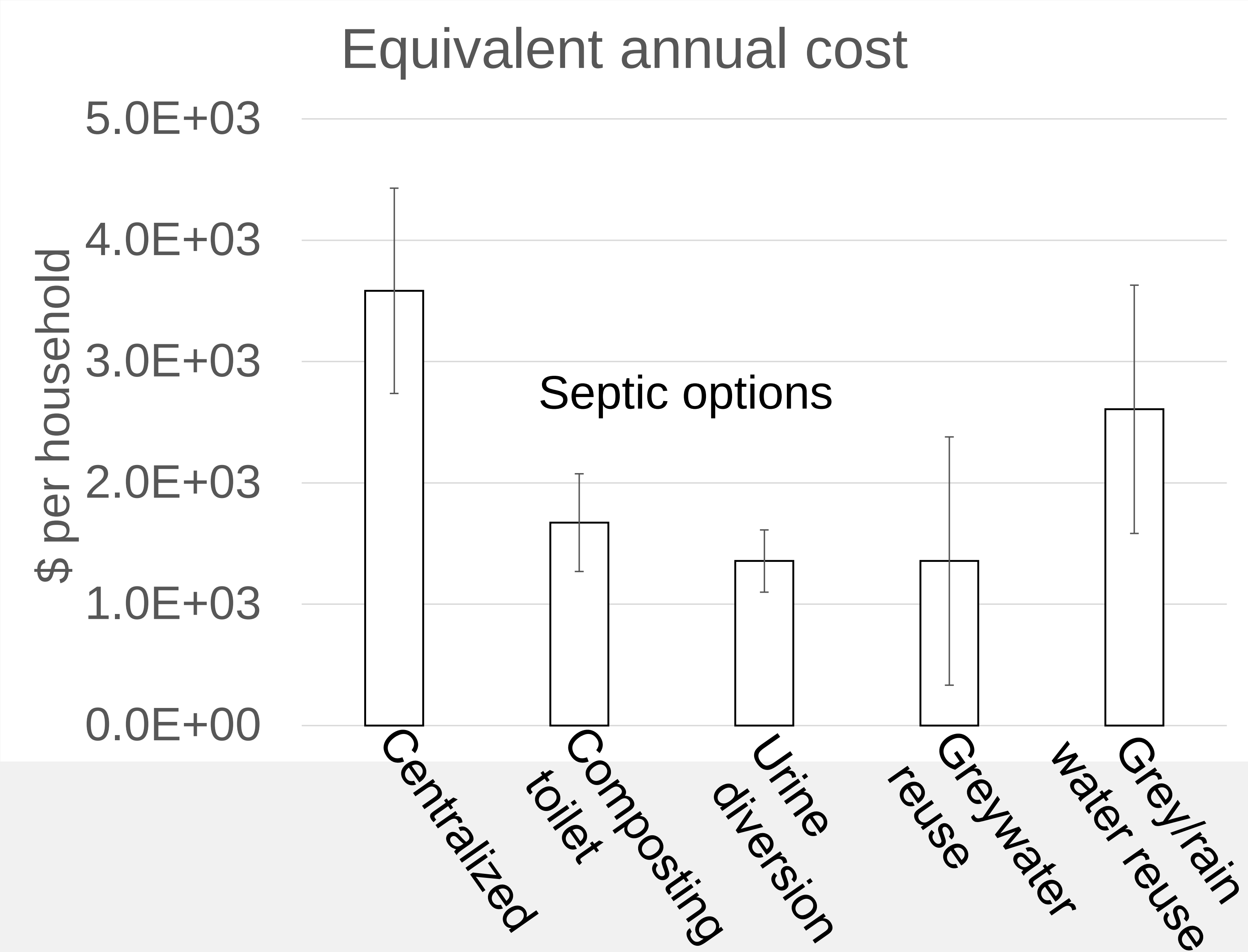

Equivalent annual cost
$ per household
5.0E+03
4.0E+03
3.0E+03
2.0E+03
1.0E+03
0.0E+00
Centralized
Composting toilet
Urine diversion
Greywater reuse
Grey/rain water reuse



Equivalent annual cost
$ per household
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Septic options
Centralized
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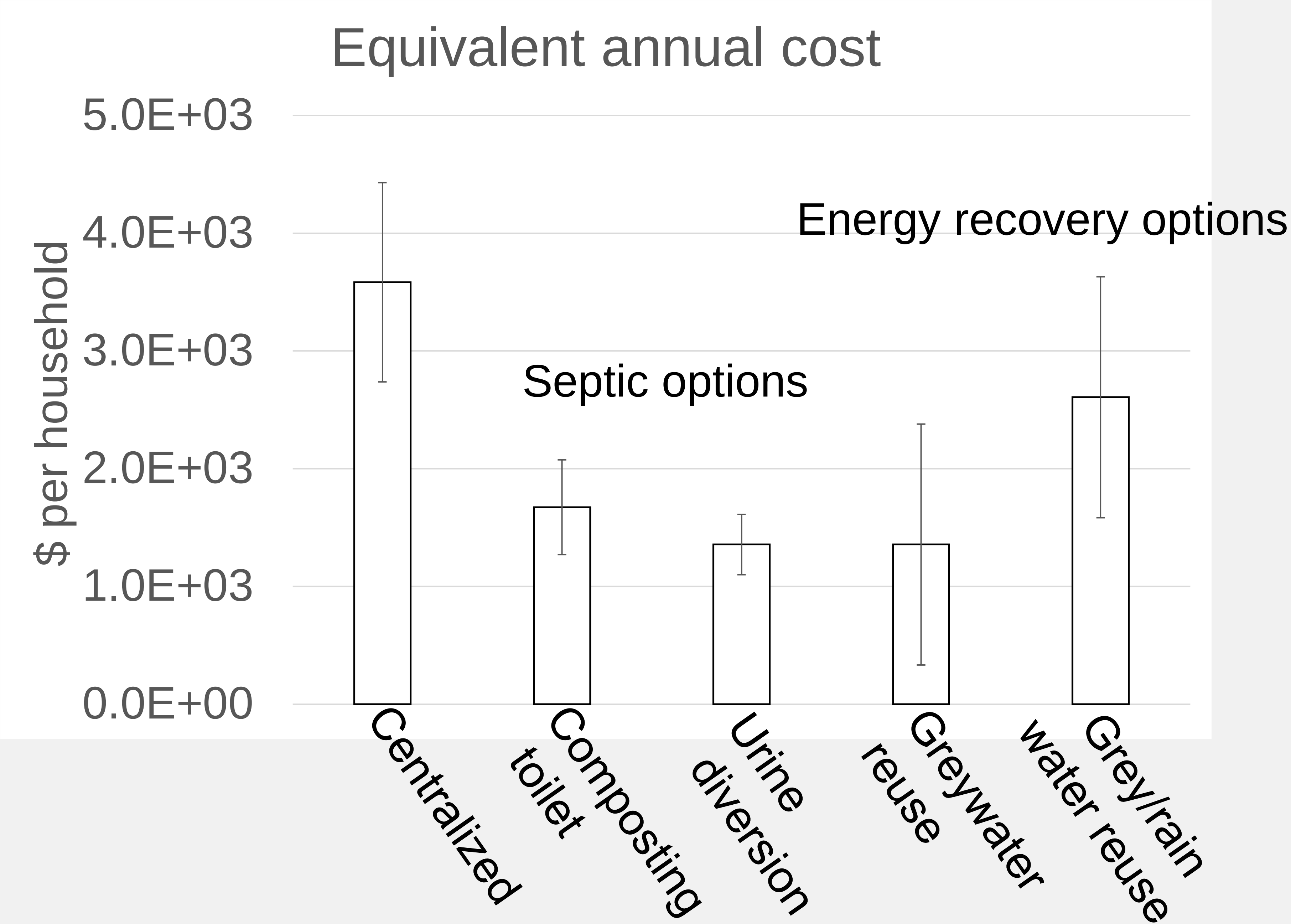
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4.0E+03
3.0E+03
2.0E+03
1.0E+03
0.0E+00
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Centralized
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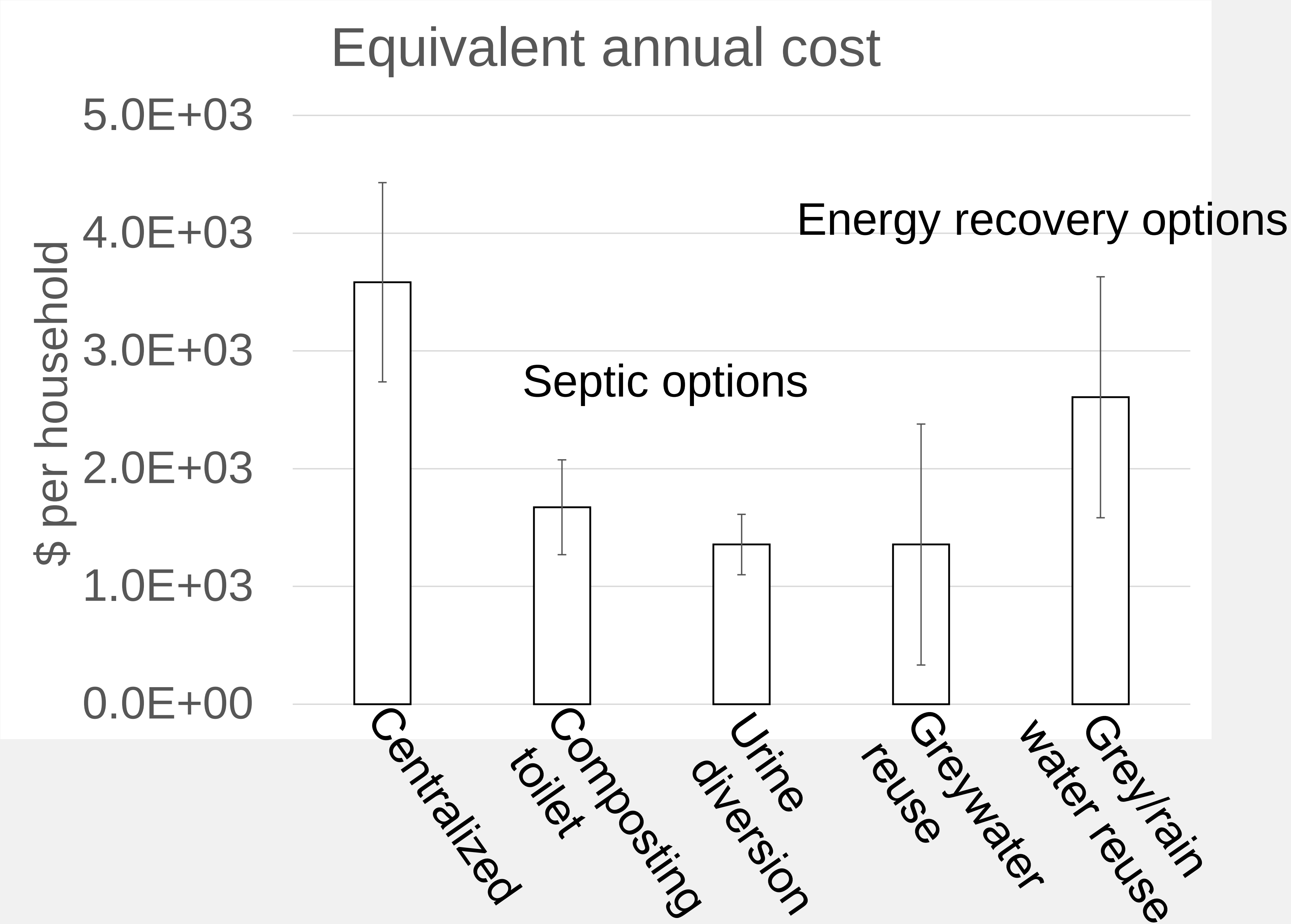

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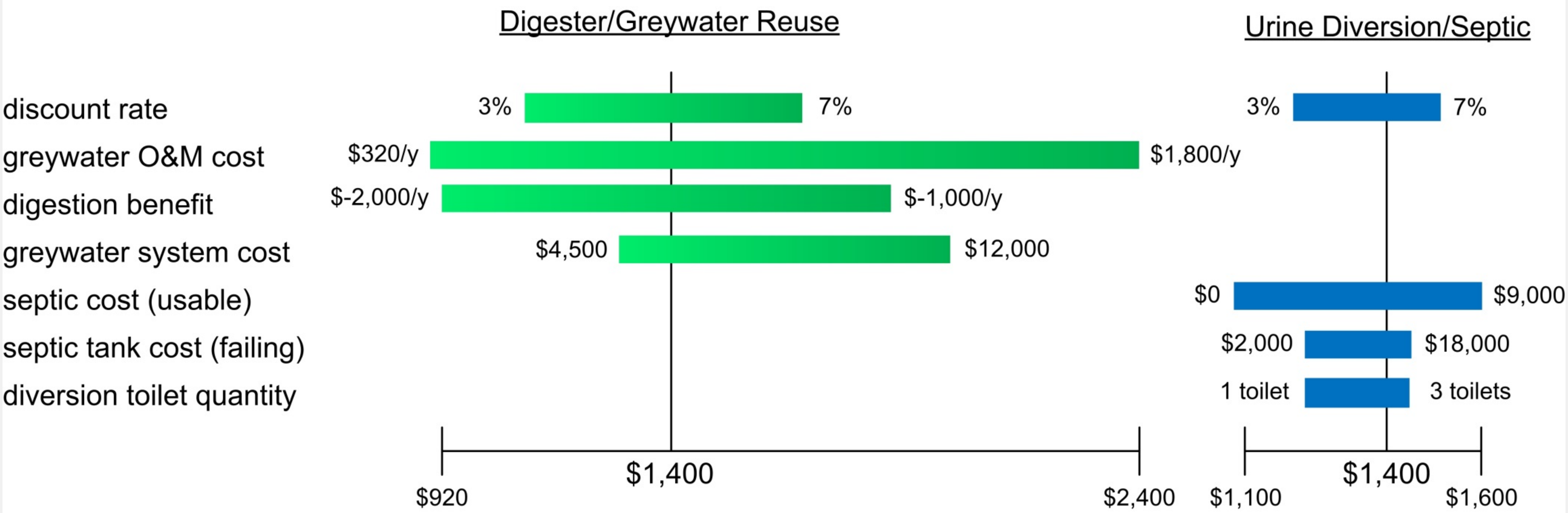
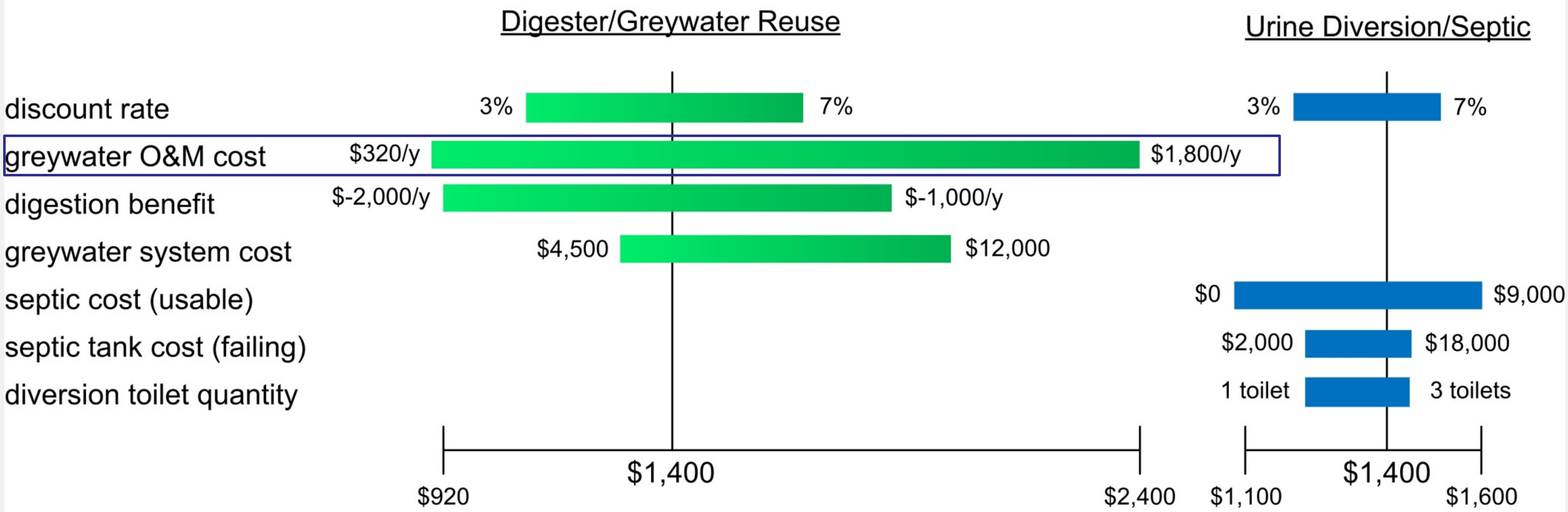
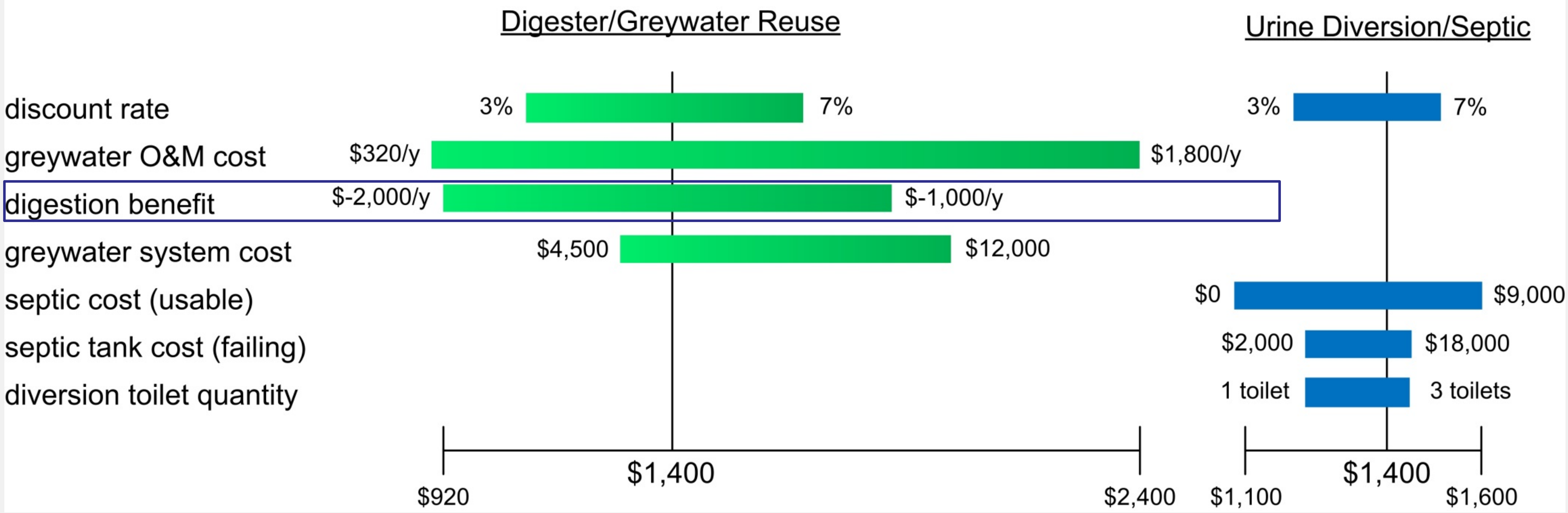
Example results



Example results



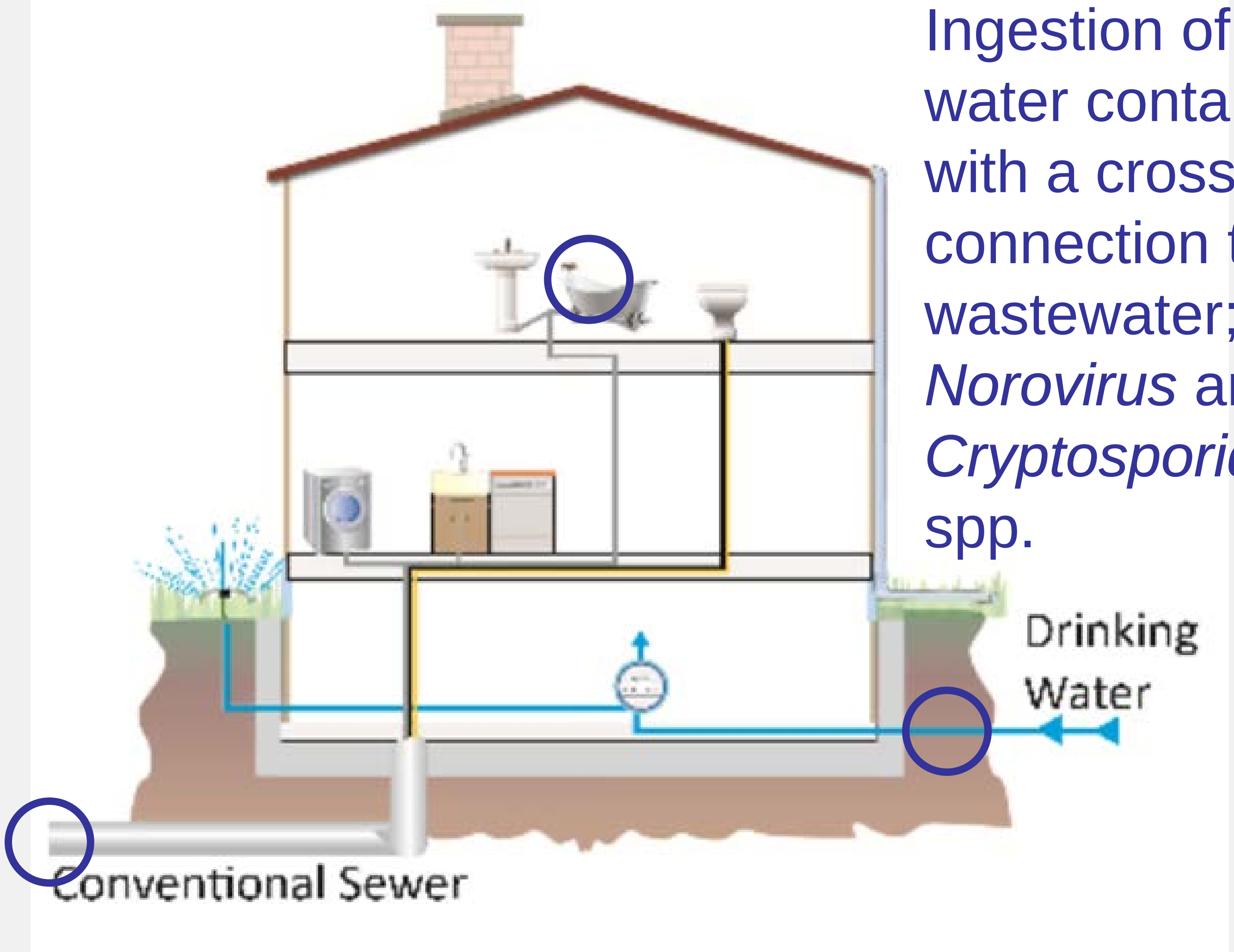
Example results



Human Health Metric

- Objective: Estimate health effects from exposures to chemical and microbial hazards using Disability Adjusted Life Years (DALYs)
- Tool: Quantitative Risk Assessment
- Treatment of variability/uncertainty: Monte Carlo analysis and separate parametric sensitivity analysis
- Reference: Schoen, M. E.; *et al.*, Comparative human health risk analysis of coastal community water and waste service options. Environmental Science & Technology 2014, 48, (16), 9728-9736.

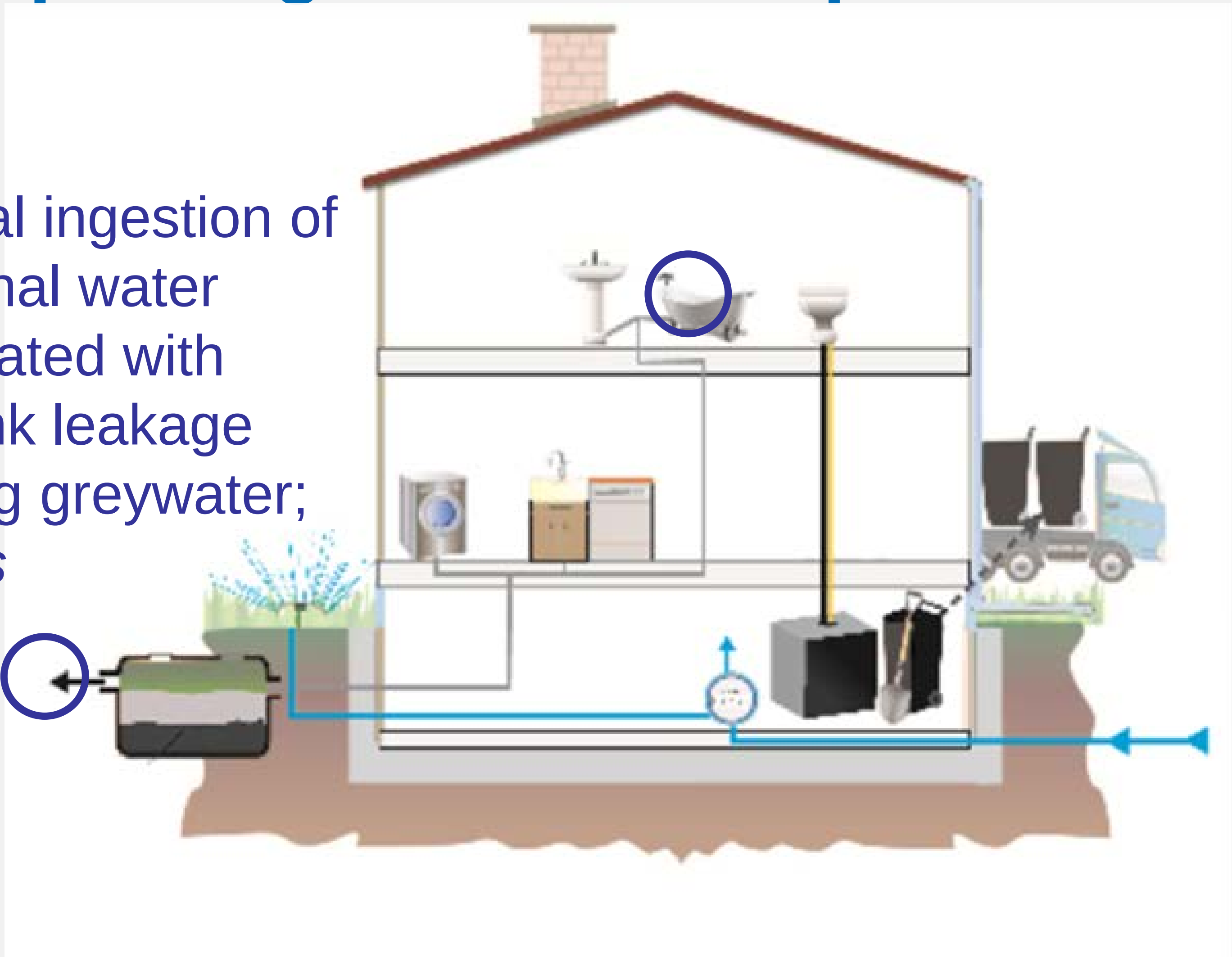
Exposure routes: Centralized



Ingestion of drinking water contaminated with a cross-connection to wastewater; *Norovirus* and *Cryptosporidium* spp.

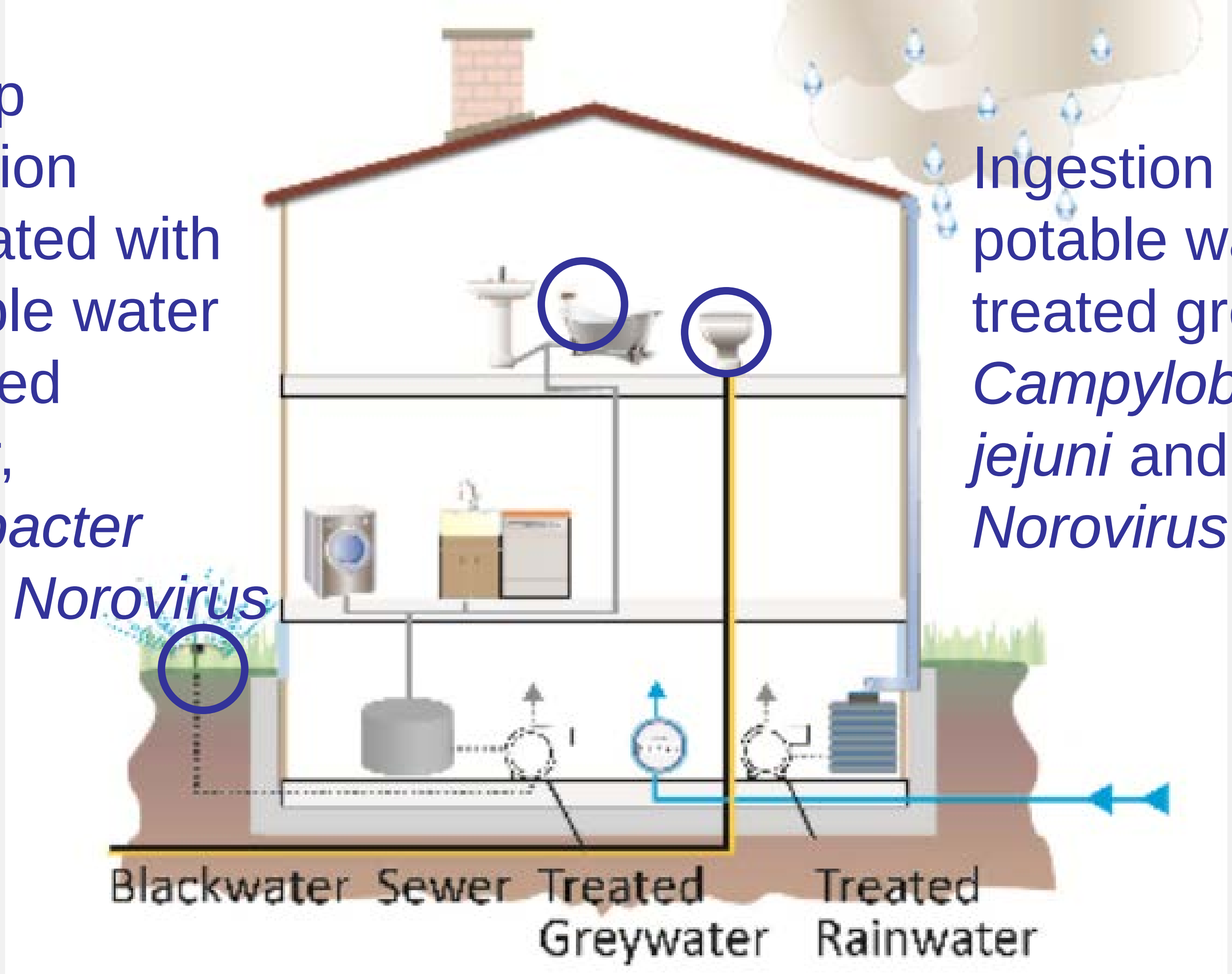
Composting toilet and septic

Accidental ingestion of recreational water contaminated with septic tank leakage containing greywater; *Norovirus*



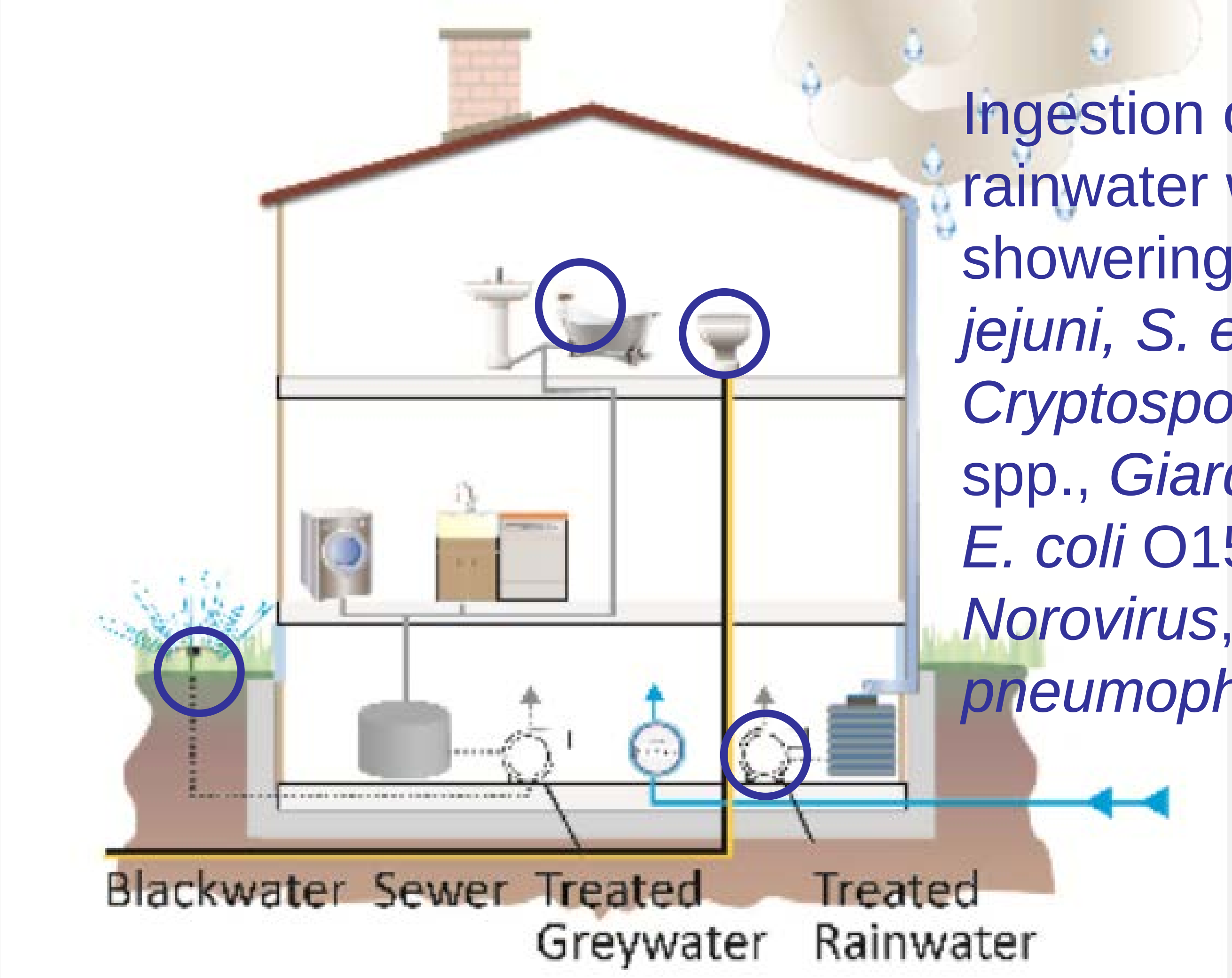
Energy recovery and greywater reuse

Salad crop consumption contaminated with non-potable water from treated greywater, *Campylobacter jejuni and Norovirus*



Ingestion of non-potable water from treated greywater; *Campylobacter jejuni* and *Norovirus*

Energy recovery and grey + rainwater reuse



Ingestion of treated rainwater while showering; *C. jejuni*, *S. enterica*, *Cryptosporidium* spp., *Giardia* spp., *E. coli* O157:H7, *Norovirus*, *L. pneumophila*

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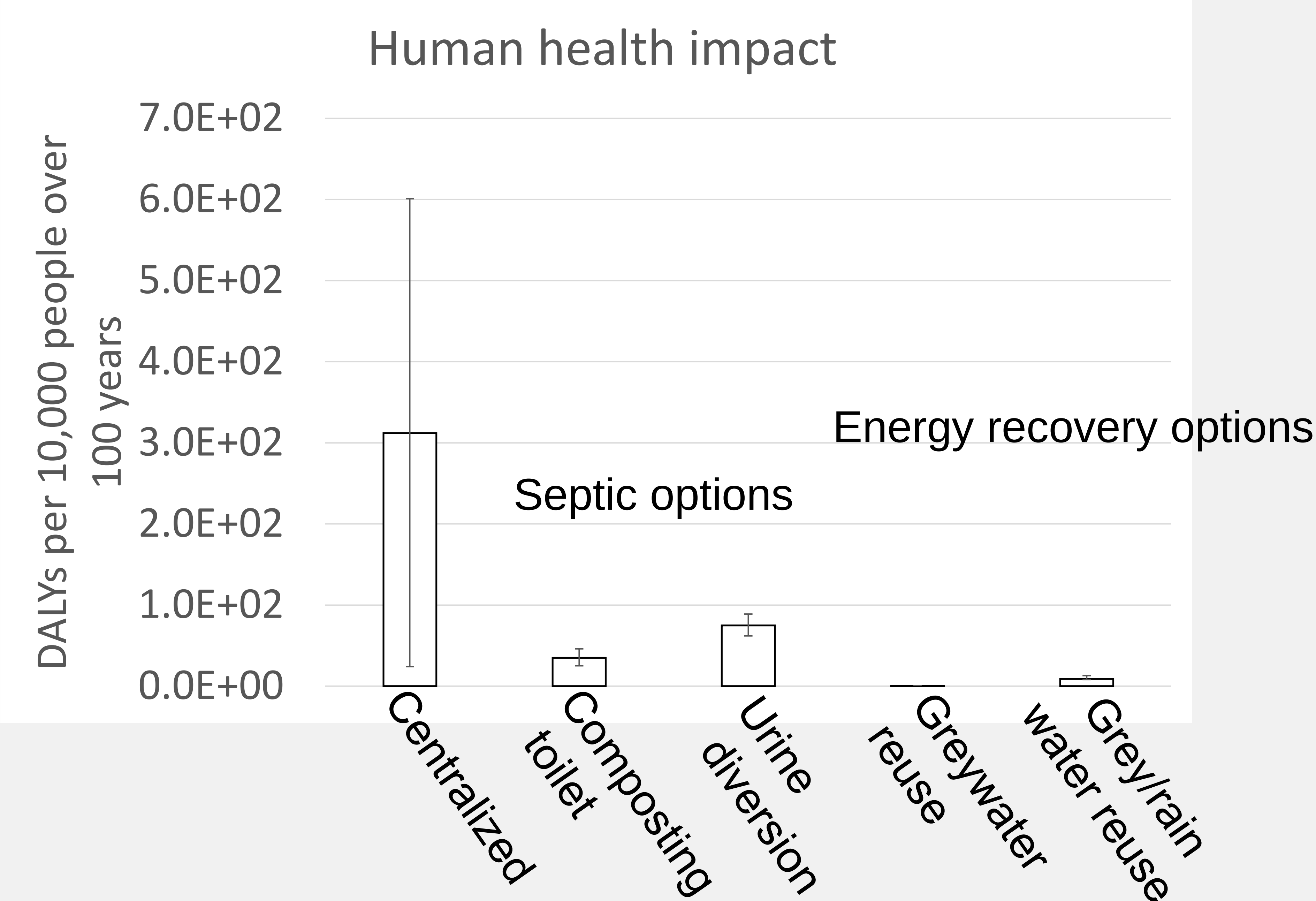

Human health impact
DALYs per 10,000 people over 100 years
7.0E+02
6.0E+02
5.0E+02
4.0E+02
3.0E+02
2.0E+02
1.0E+02
0.0E+00
Energy recovery options
Septic options
Centralized
Composting toilet
Urine diversion
Greywater reuse
Grey/rain water reuse

Environmental Metrics

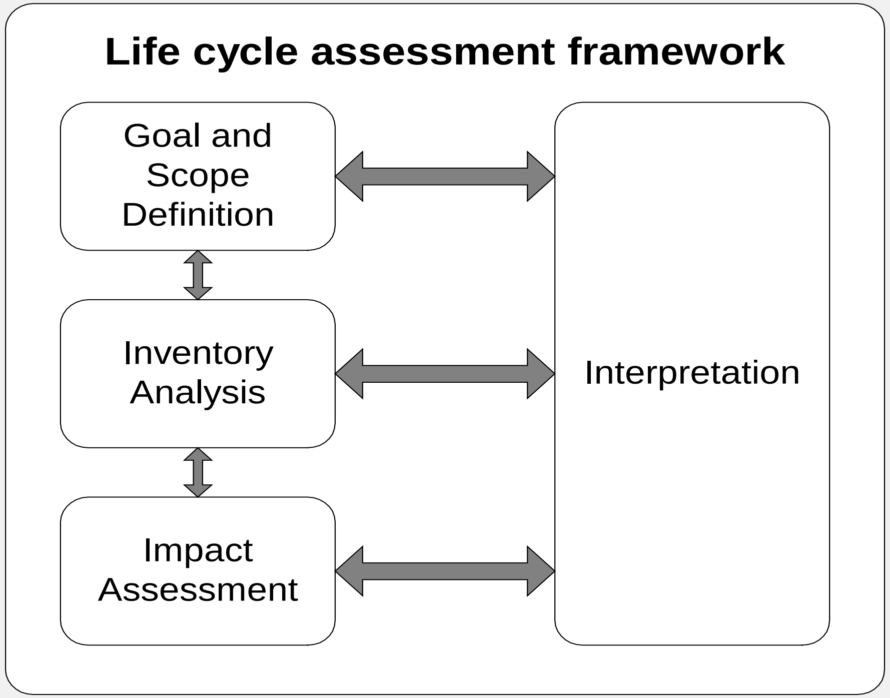
- Objective: Estimate the life cycle resource consumption and environmental impacts
  - *life cycle energy consumption*;
  - *life cycle global warming potential*, calculates the greenhouse gas emissions (i.e. CO_2, CH_4, and N_2O);
  - *life cycle eutrophication potential*, calculates both onsite and supply chain nutrient releases in air, water, and soil
- Tool: Life Cycle Assessment, Nutrient Fate and Impact Model
- Treatment of variability/uncertainty: Probabilistic with variability and uncertainty captured through Monte Carlo analysis
- Reference: Xue, X., Life Cycle Energy, Greenhouse Gas Emissions and Nutrient Releases of Several Water and Waste Service Options. TBD 2015.

Life Cycle Assessment

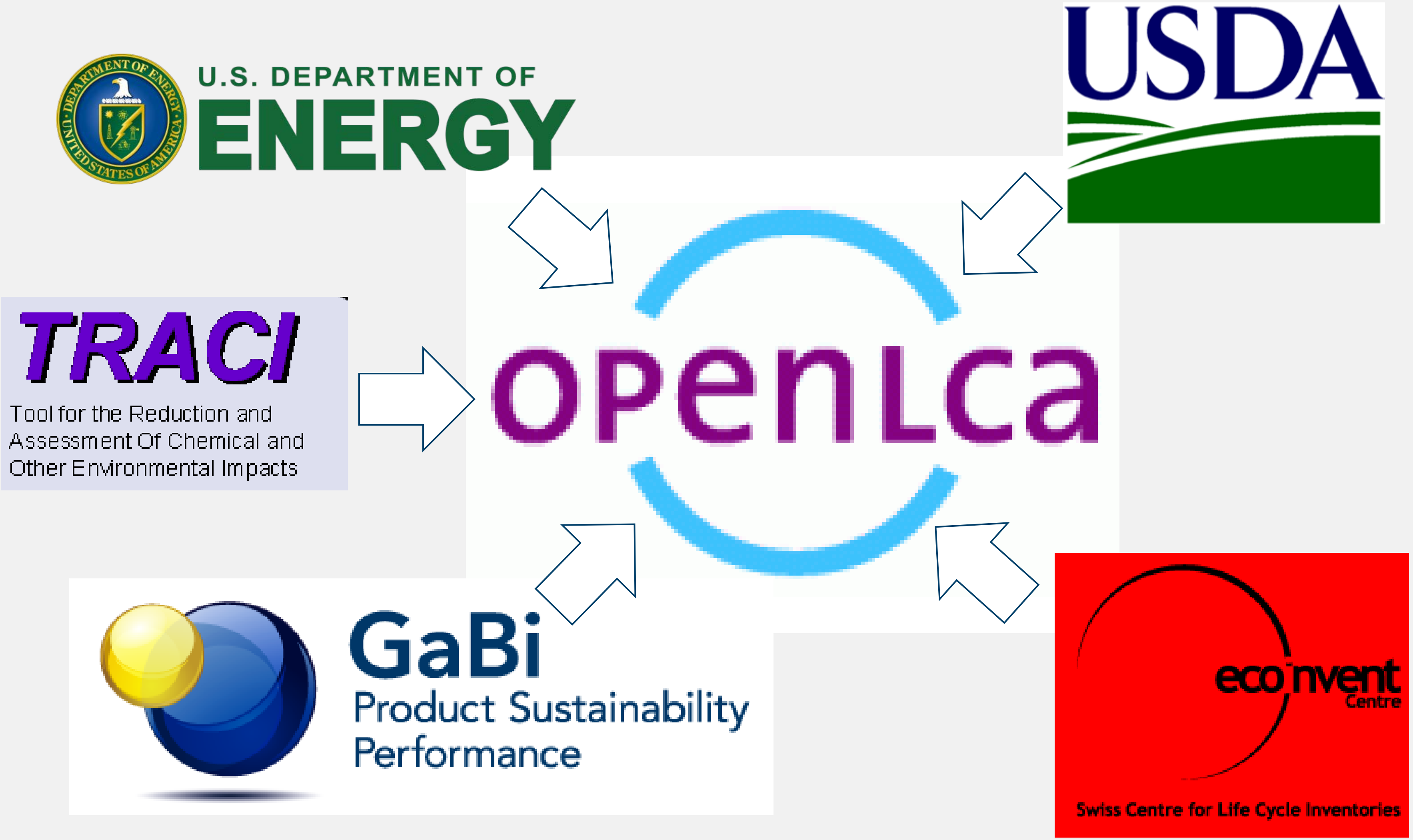
What can Life-Cycle Assessment (LCA) Offer?

- Draws a clear cause and effect chain from outcomes of interest to the built water services

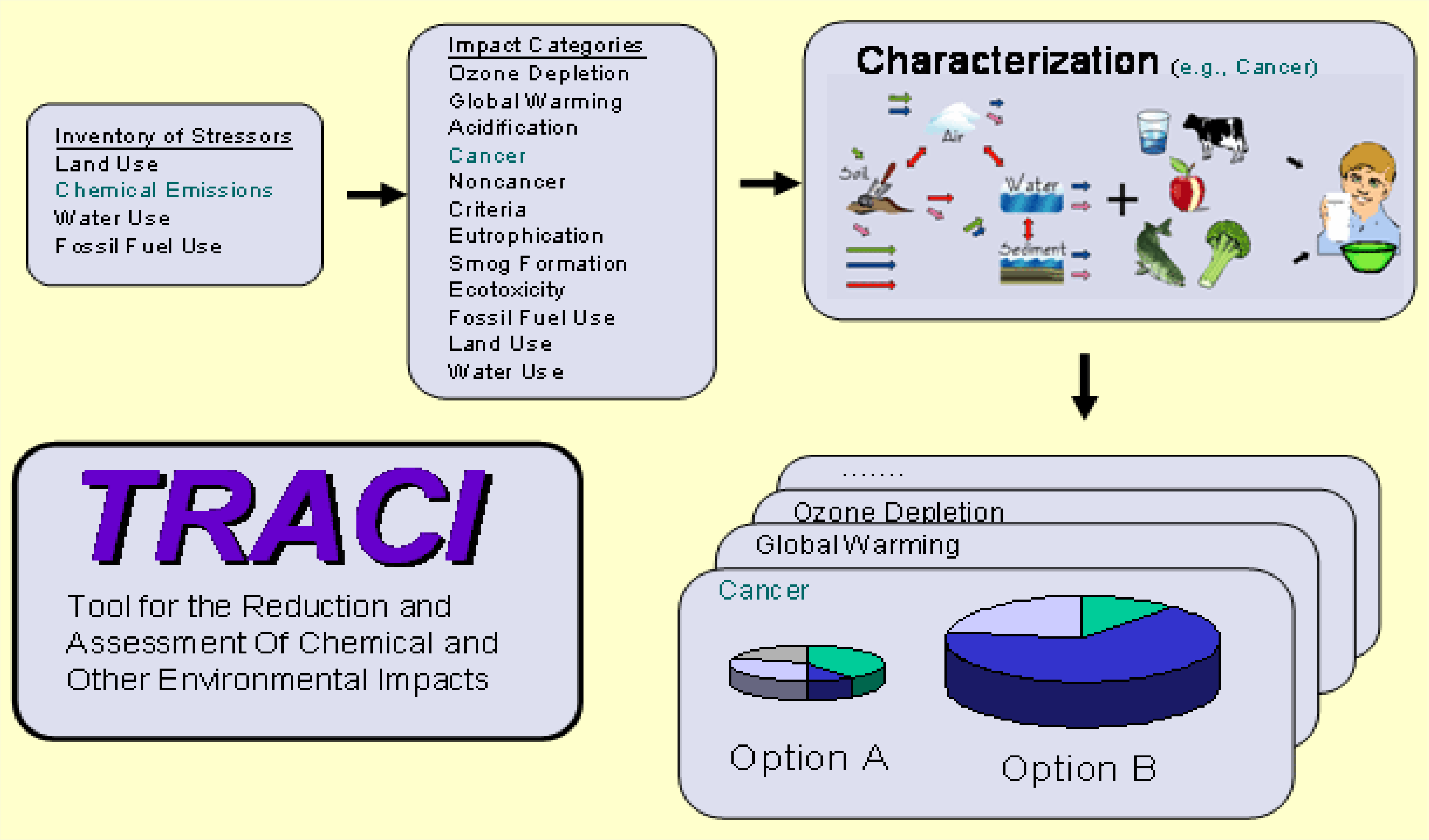
- ISO 14040
- "Flexible standard"
  - Life-cycle inventory (LCI)
  - Life-cycle impact assessment (LCIA)



LCA database development



Life Cycle Impact Assessment



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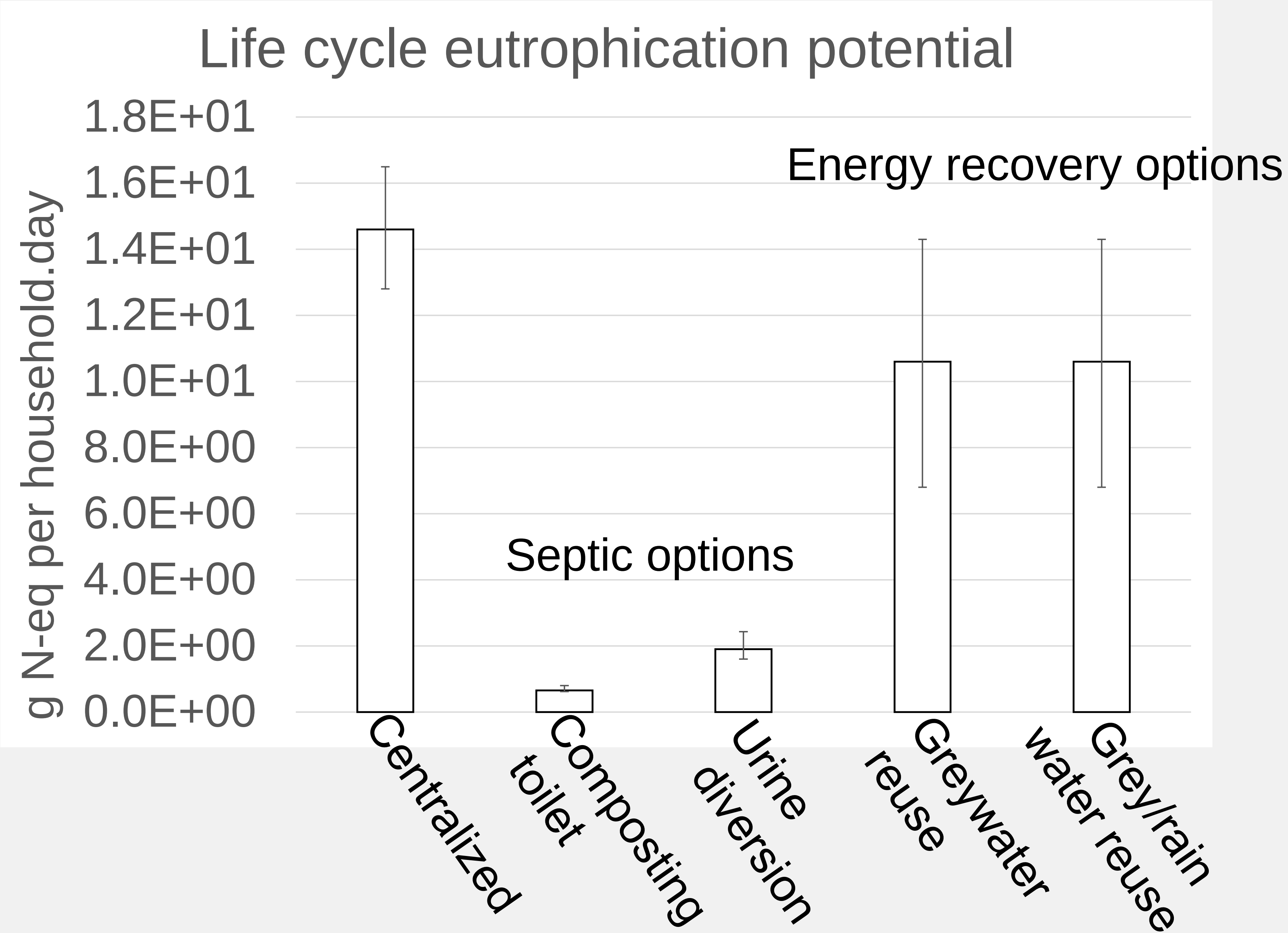
Life cycle eutrophication potential
g N-eq per household.day
1.8E+01
1.6E+01
1.4E+01
1.2E+01
1.0E+01
8.0E+00
6.0E+00
4.0E+00
2.0E+00
0.0E+00
Energy recovery options
Septic options
Centralized
Composting toilet
Urine diversion
Greywater reuse
Grey/rain water reuse

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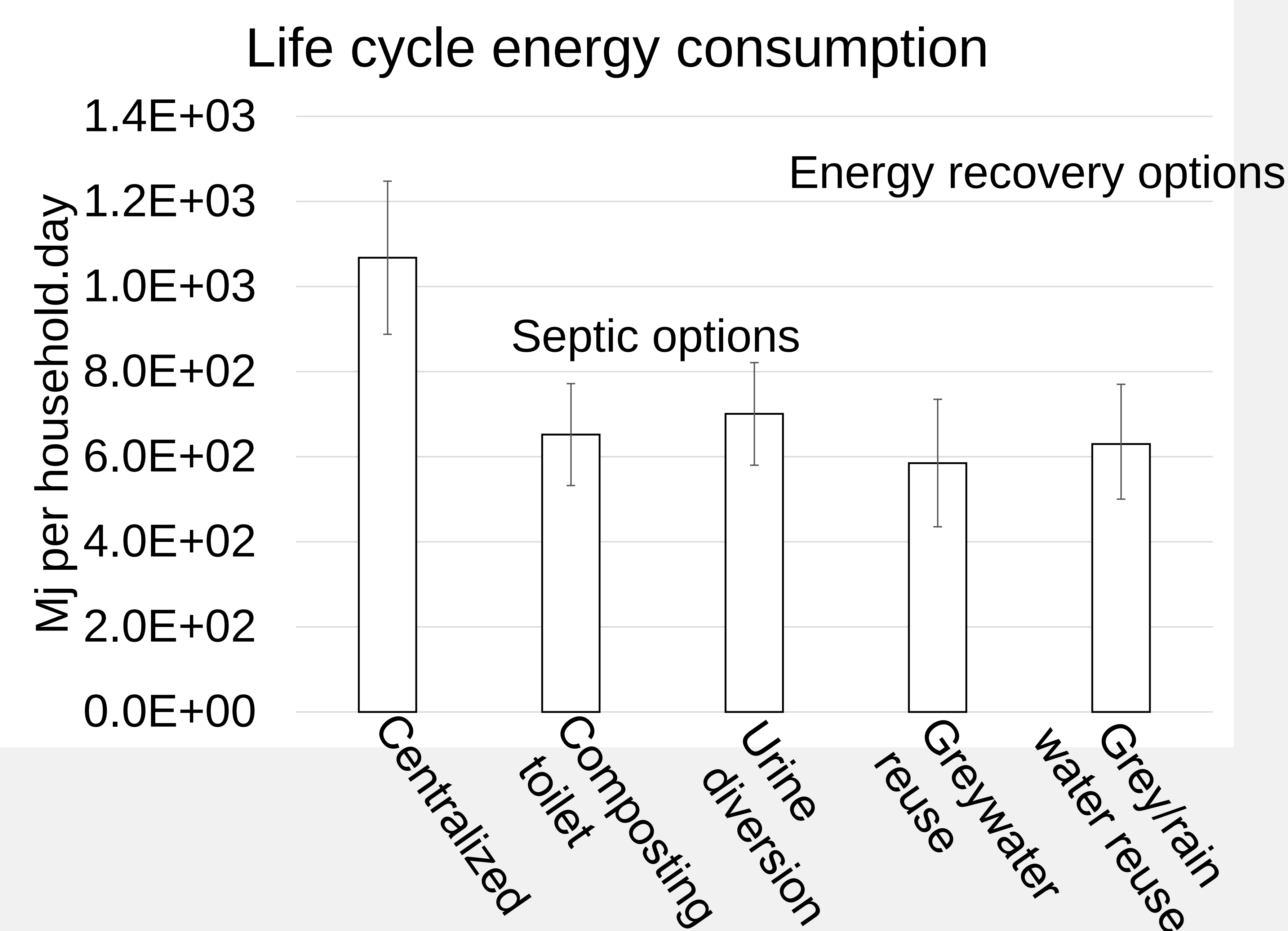
Life cycle energy consumption
Mj per household.day
1.4E+03
1.2E+03
1.0E+03
8.0E+02
6.0E+02
4.0E+02
2.0E+02
0.0E+00
Energy recovery options
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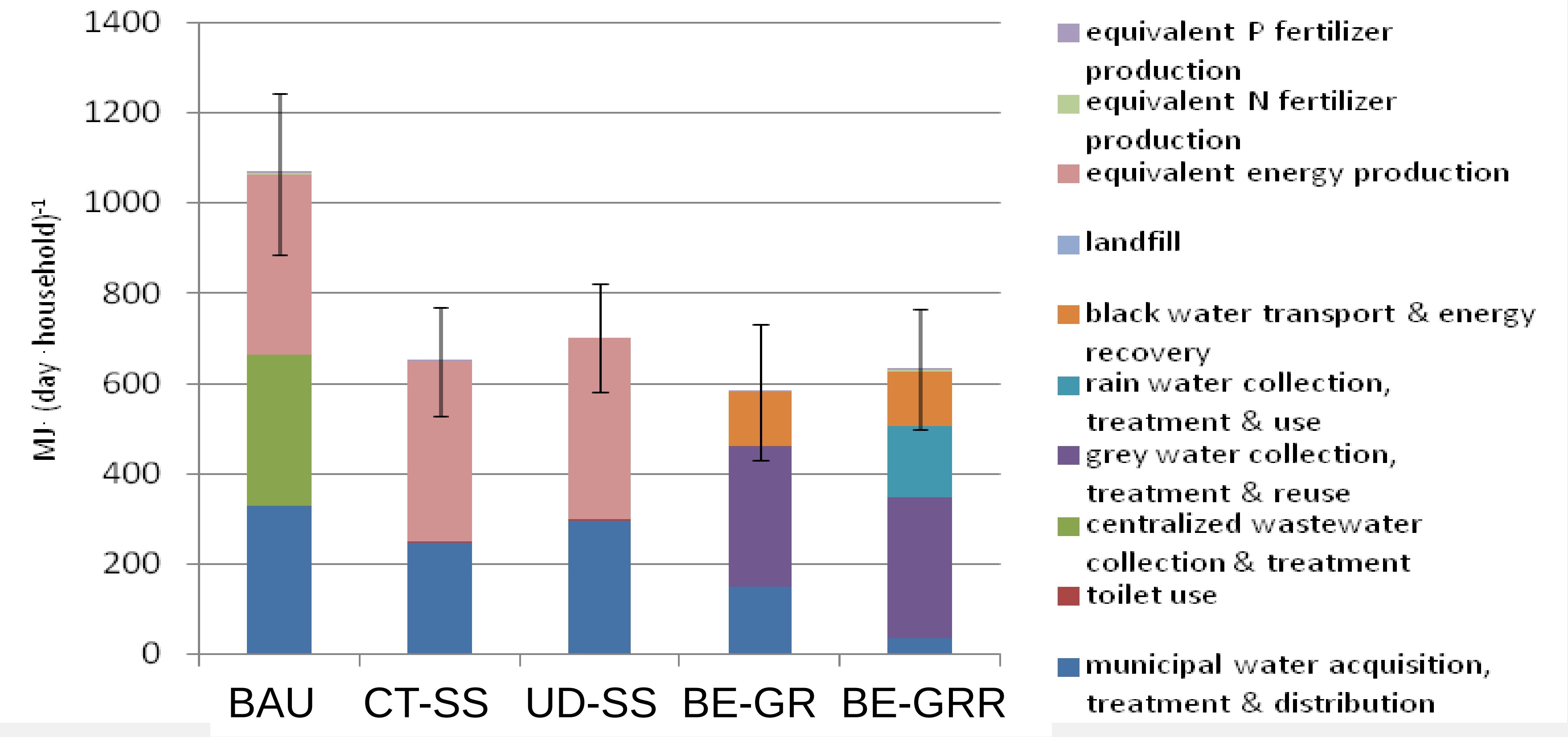
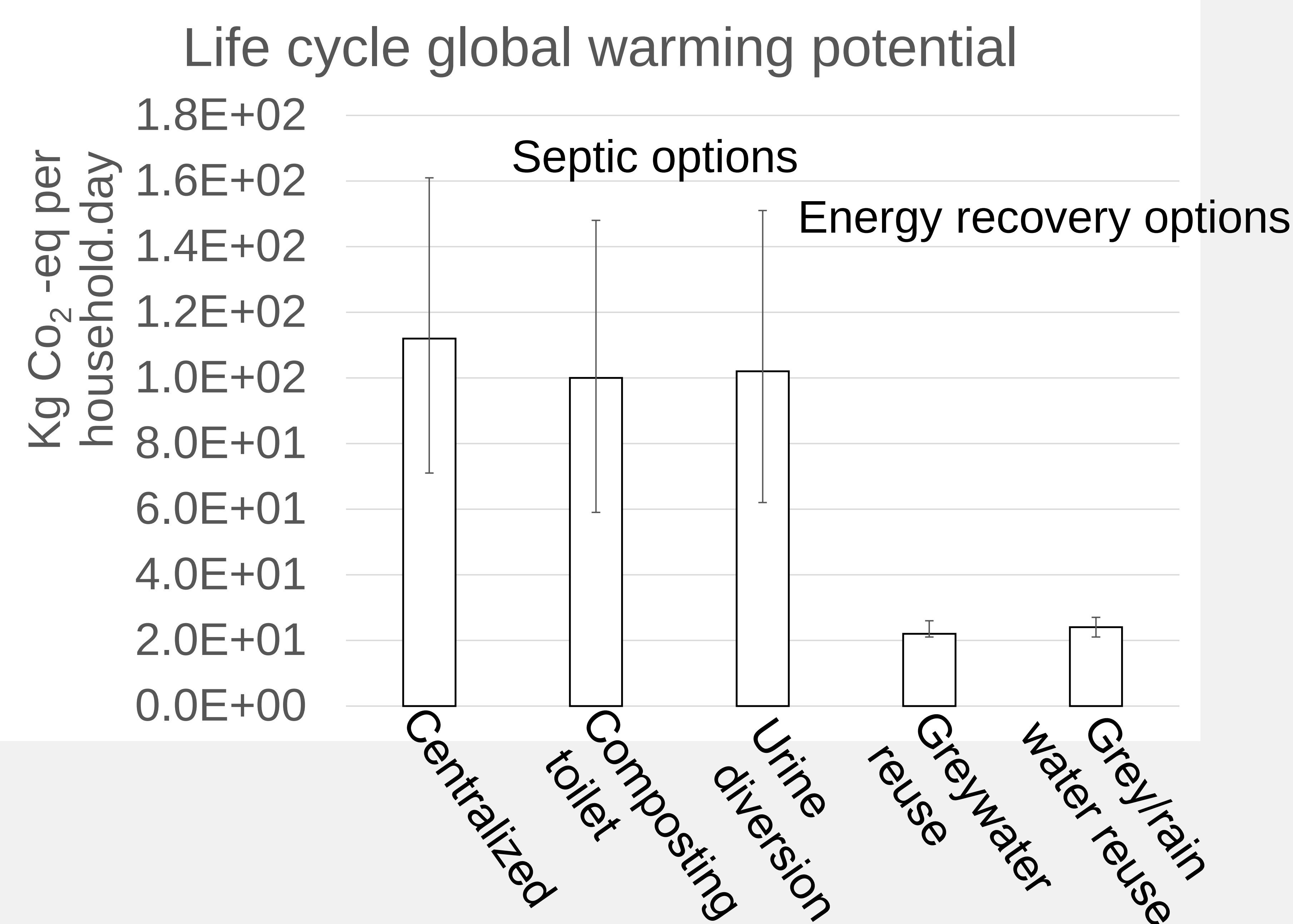
Cape Cod Case Study

Results: LCA Energy consumption




Life cycle global warming potential
Kg Co2 -eq per household.day
1.8E+02
1.6E+02
1.4E+02
1.2E+02
1.0E+02
8.0E+01
6.0E+01
4.0E+01
2.0E+01
0.0E+00
Septic options
Energy recovery options
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Greywater reuse
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Technical Resilience Metric

- Objective: Characterize the community water and sanitary system's ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions
  - Events
  - Long-term changes
- Tool: Qualitative and quantitative assessment
- Reference: Schoen, M.; *et al*., Technologic resilience assessment of coastal community water and wastewater service options. Sustainability of Water Quality and Ecology 2015.

Resilience - characteristics

- *Robustness:* strength, or the ability of the system to withstand a given level of stress or demand without suffering degradation or loss of function;
- *Resourcefulness:* the capacity to mobilize resources when conditions exist that threaten to disrupt the system, i.e. monetary, physical, technological, and informational and human resources;

Ayyub, B.M. (2014) Systems resilience for multihazard environments: definition, metrics, and valuation for decision making. Risk Analysis 34(2), 340-355.
Bruneau, M. and Reinhorn, A. (2007) Exploring the concept of seismic resilience for acute care facilities. Earthquake Spectra 23(1), 41-62.

Resilience - characteristics

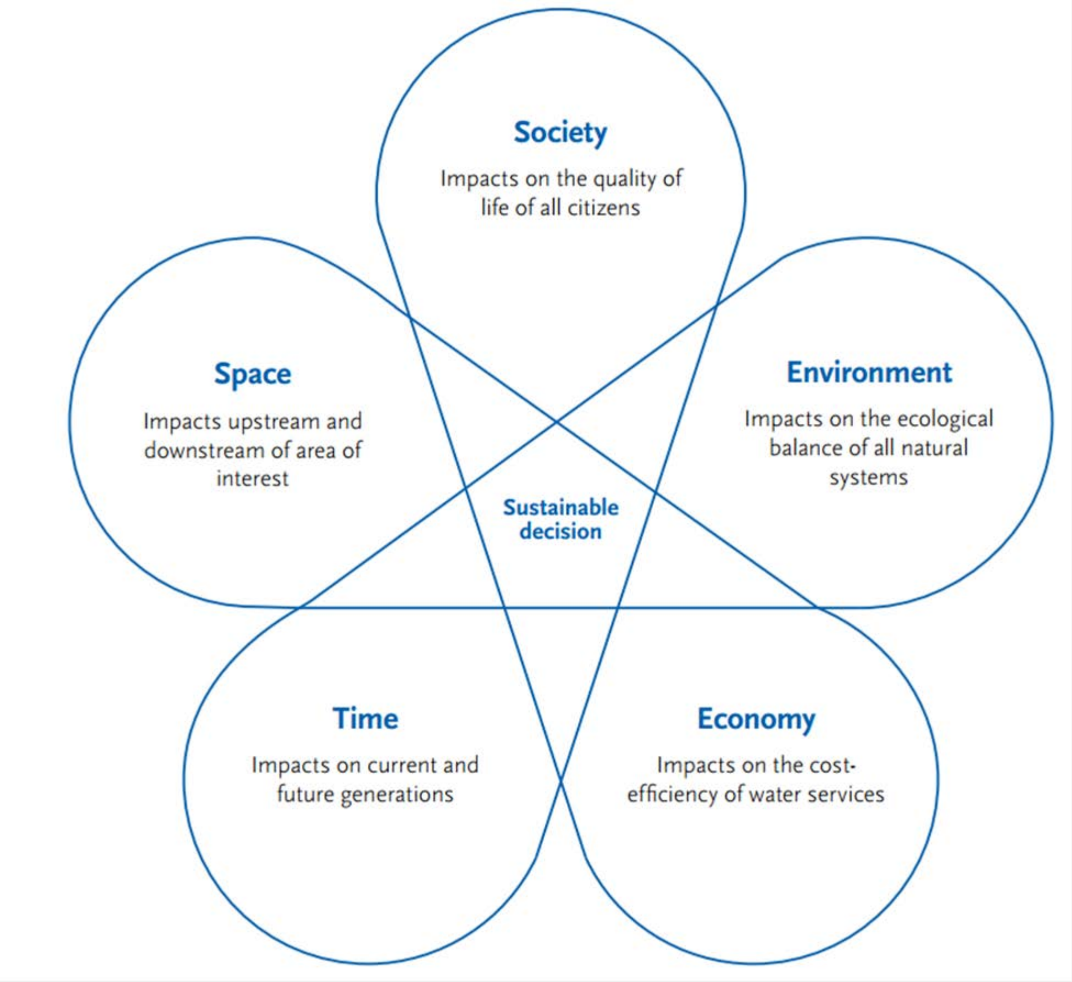
- *Rapidity:* the capacity to achieve goals in a timely manner in order to contain losses, recover functionality, and avoid future disruption;
- *Adaptive capacity:* ability to re-organize while undergoing change and we add to this definition, to prevent loss of function.

Overall Results

- Overall, no one community water and wastewater service system option was the most resilient, with the alternatives having potential water saving advantages, but unknown resourcefulness/rapidity.
- *Future*: Develop assessment to further differentiate the magnitude of impacts
  - Assess resourcefulness of alternative systems

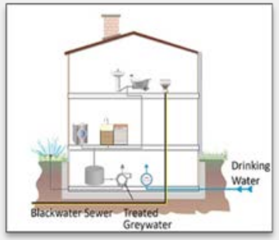
Take a guess…

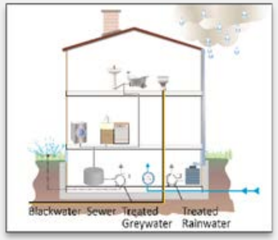
1. Which option is worst overall, based on these metrics?
2. Which option is best overall, based on these metrics?



Summary of best estimate scores

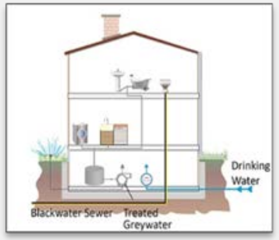


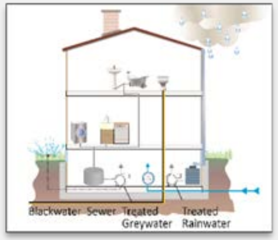




	Centralized	Composting toilet/septic	Urine diversion/ septic	Energy recovery/ greywater reuse	Energy recovery/ grey, rainwater reuse
Human Health	0.0017	0.015	0.0072	1.00	0.056
Eutrophication	0.045	1.00	0.34	0.061	0.061
Cost	0.38	0.81	1.00	1.00	0.52
Global Warming	0.20	0.22	0.22	1.00	0.92
Energy	0.55	0.90	0.83	1.00	0.93

Summary of best estimate scores





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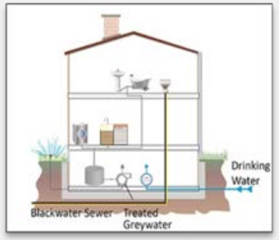
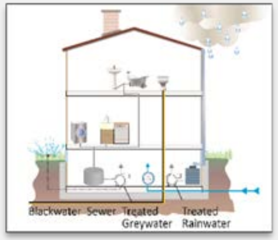
Summary of best estimate scores





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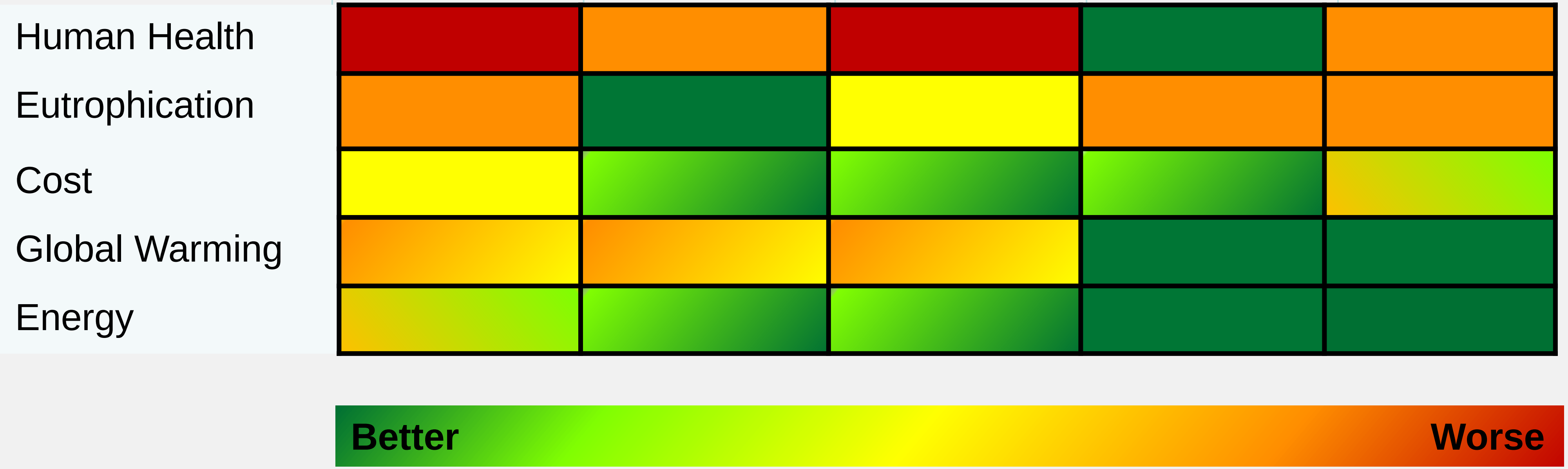
Summary of sustainability metrics

Centralized	Composting toilet/septic	Urine diversion/ septic	Energy recovery/ greywater reuse	Energy recovery/ grey, rainwater reuse



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Summary of sustainability metrics

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				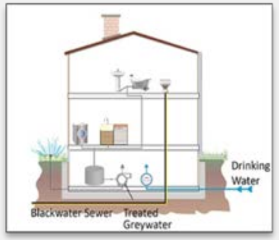	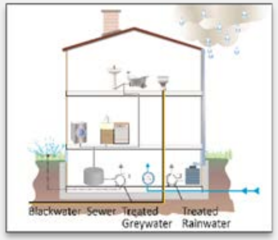
Human Health					
Eutrophication					
Cost					
Global Warming					
Energy					

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Overall results

- Alternative systems had lower environmental and human health impacts and costs than conventional, centralized systems
  - Results may be different for another locality (*e.g.*, centralized system costs and environmental impacts)

- Of the alternatives, the on-site water reuse/energy recovery approach had lowest human health impacts, but on-site water treatment costs “offset” energy production benefits
  - Need to explore health risks associated with less costly onsite treatment

- Need site-specific information on alternative options to differentiate resilience, cost and energy use/generation

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Future direction

- Improve the assessment
  - Better tools (e.g., more site relevant water and eutrophication impacts within LCA)
  - Refine risk estimates (particularly for non-potable water reuse)
  - Additional information on different “unit processes”
- Incorporate more directly into community decision making
  - Define scenarios and metrics of most interest to communities/selected stakeholders (e.g., scale and type of non-potable water reuse scenarios in San Francisco)
  - Create integrated assessments of selected scenarios
  - Translate the assessments into a relevant decision matrix (e.g., Multi Criterion Decision Analysis, or MCDA

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Robustness – ability to withstand stress

Challenge	System[a]	Centralized	Septic	Energy Recovery / Reuse
1. Extreme cold weather, snow, and ice	WW/RR	centralized treatment failure, collection failure from pumps[d]	on-site pipe damage to septic[f]	centralized treatment failure, collection failure from pumps[d]
2. Storm with increased surge	WW/RR	centralized treatment damage, collection damage, environmental contamination, sewage backup in homes[e]	on-site damage to septic system and other components, environmental contamination, sewage backup in homes[e]	**eliminates sewage backup in homes and leaks when collection system is submerged but undamaged,** centralized treatment damage, collection damage, environmental contamination[e,h]
3. Power outage	WW/RR	**continued services**		pressure sewer failure, on-site greywater and rainwater treatment failure[i]

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Robustness

Challenge	System[a]	Centralized	Septic	Energy Recovery / Reuse
4. Wildfire	WW/RR	centralized treatment damage, collection damage[g]	on-site damage to septic system and other components[g]	centralized treatment damage, collection damage[g]
5. Short term drought (3 months) with tourist influx	DW	shortage, saltwater ingress to groundwater, and ingress contamination in distribution[e]	**less water demand from WW/RR technologies preceding and during drought potentially reduces shortage, saltwater ingress to groundwater, and ingress contamination in distribution**[ei]	
	WW/RR	collection blockages and higher pollutant loads in downstream waterbodies[e]	higher pollutant loads in downstream waterbodies[e]	**continued operation with less water**[i]

World Health Organization Regional Office for Europe (2011) Guidance on Water Supply and Sanitation in Extreme Weather Events, World Health Organization, Copenhagen, Denmark.
Charles, K., Pond, K. and Pedley, S. (2010) Vision 2030. The resilience of water supply and sanitation in the face of climate change. Technology fact sheets, World Health Organization.

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Resourcefulness and rapidity

- Centralized system is already operated and managed by the town with trained staff.
- Centralized management improves resourcefulness. (WHO 2011)
- The septic systems are regulated under the Massachusetts sanitary code for on-site wastewater systems and are permitted by local boards of health.
- Generally, the lack of centralized management has resulted in improperly maintained septic systems. (WHO 2011, Crites and Tchobanoglous 1998)

Resourcefulness and rapidity

- The digester system includes both decentralized and centralized components.
- Overall, resourcefulness for the digester options will depend on the type of management implemented by the community.

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How can the results be used?

- Decision makers and/or researchers can gather additional information to further differentiate the alternative systems
  - Less challenging: site-specific greywater treatment system costs
  - Challenging: energy generation from digestion/co-digestion
  - Challenging: rapidity of alternative systems

How can the results be used?

- The raw data can be used in a stakeholder-preferred decision approach (e.g., Multi Criterion Decision Analysis (MCDA)) to explore tradeoffs among options.
  - Add relevant criteria (e.g. water withdrawal)
  - Specify the importance of different metrics relative to each other (i.e. the preferences).
- We recommend an approach that can account for uncertainty and variability
  - Especially *uncorrelated* variability among systems