Meeting the Challenges of Water Sustainability by Expanding the Boundaries of PSE

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THE OHIO STATE UNIVERSITY

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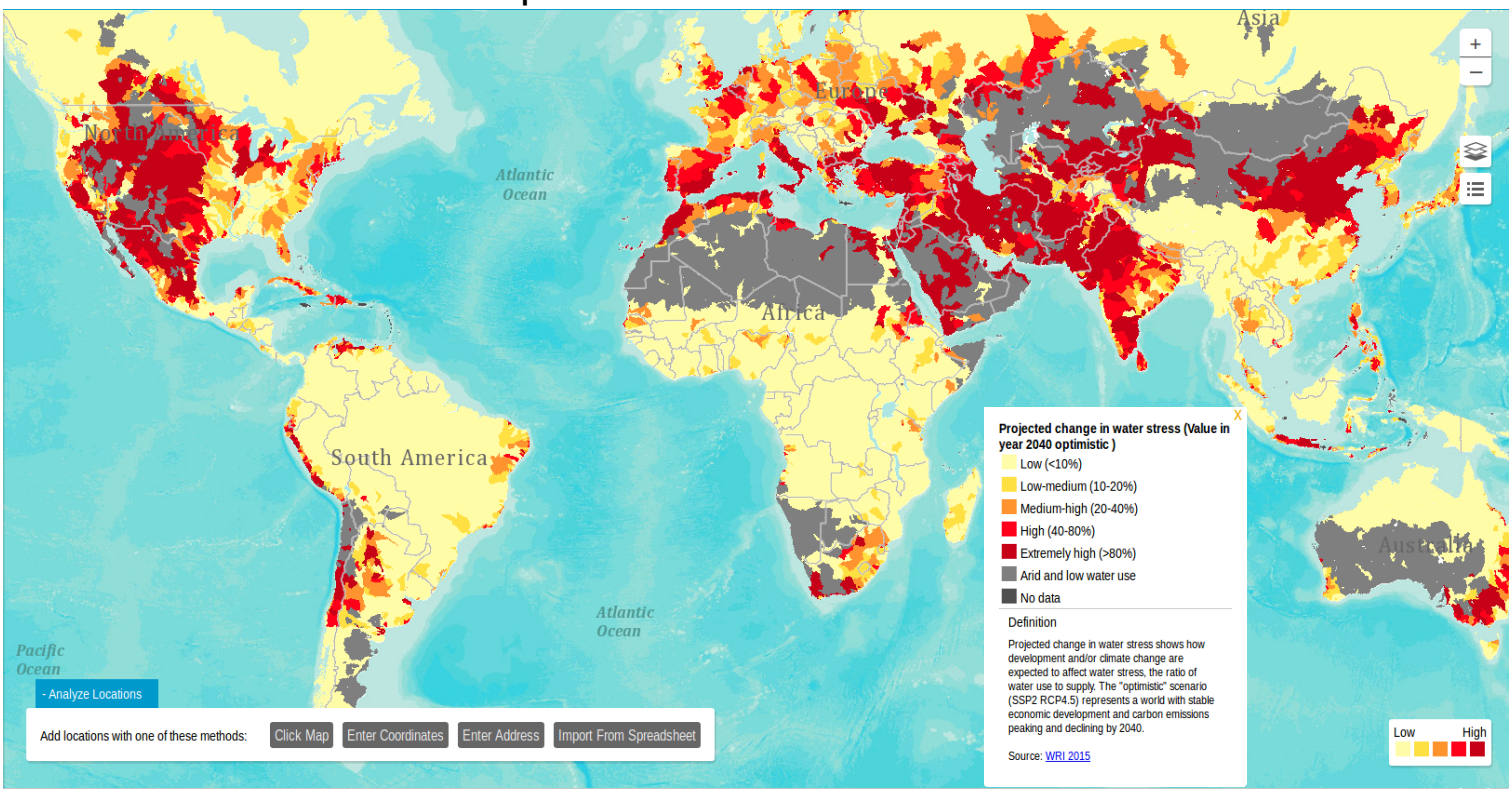
Water Challenges - Quantity

Water Stress in 2040 - Optimistic Scenario

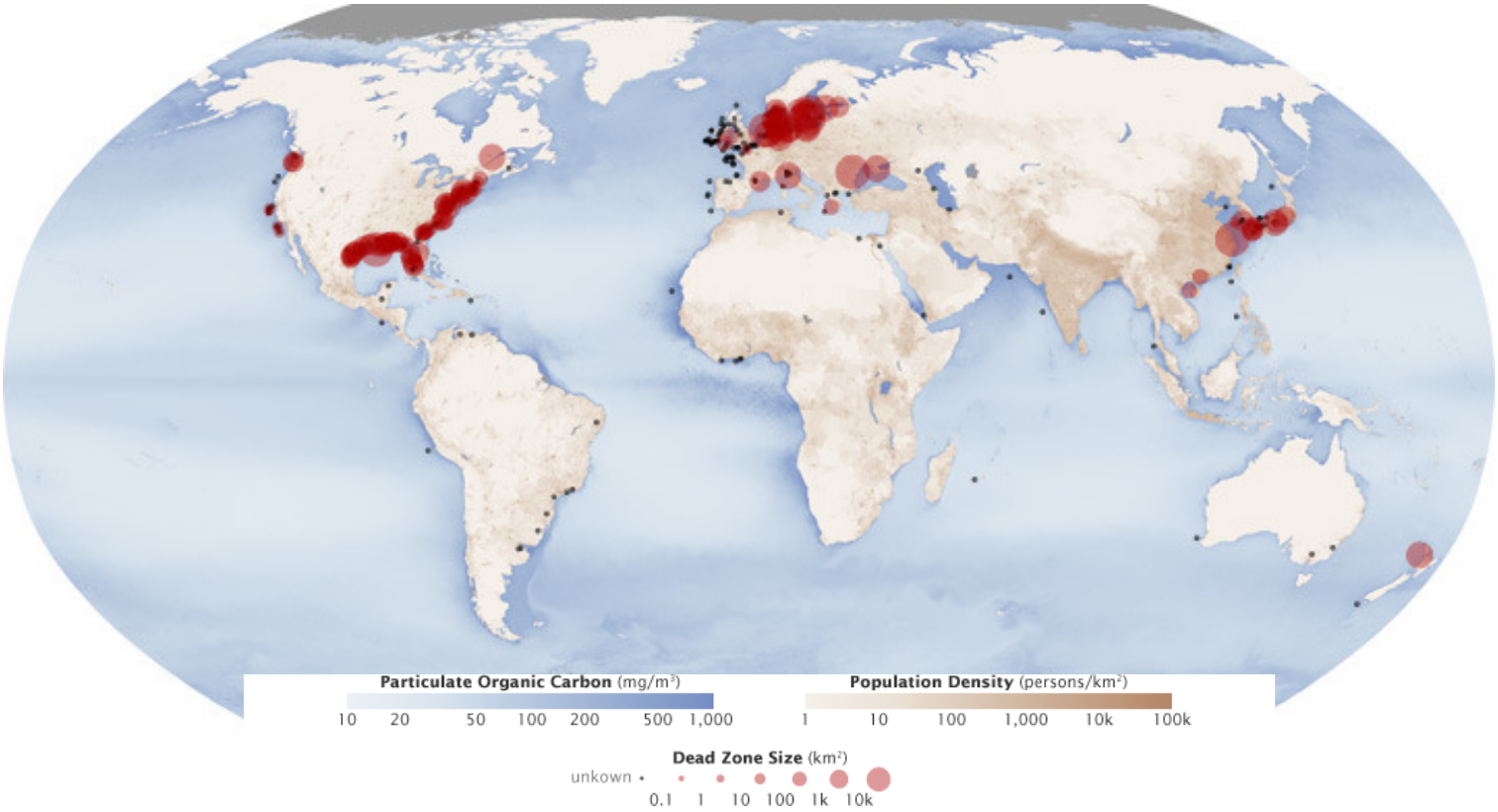


Even the optimistic scenario indicates formidable challenges

http://www.wri.org/applications/maps/aqueduct-atlas/

Water Challenges - Quality

Aquatic dead zones across the world due to excess nutrients



https://earthobservatory.nasa.gov/IOTD/view.php?id=44677

Awareness about Water Use

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- Dow
  - "A Sustainable Watershed for All - As one of the largest manufacturing companies in the world, Dow depends on a steady supply of water to create the products that are essential for everyday life and human progress. We know there are other water users - companies, farmers, and governments - who share our vision and have their own sustainable water management stories. Our vision and our hope is that through this blueprint, we inspire watershed stakeholders around the world to forge collaborations to sustainably manage scarce freshwater that is so vital to life on this planet."

PSE Efforts Toward Water Sustainability

- Quality - Reduce water emissions, purify polluted water
- Quantity - Improve efficiency of water use

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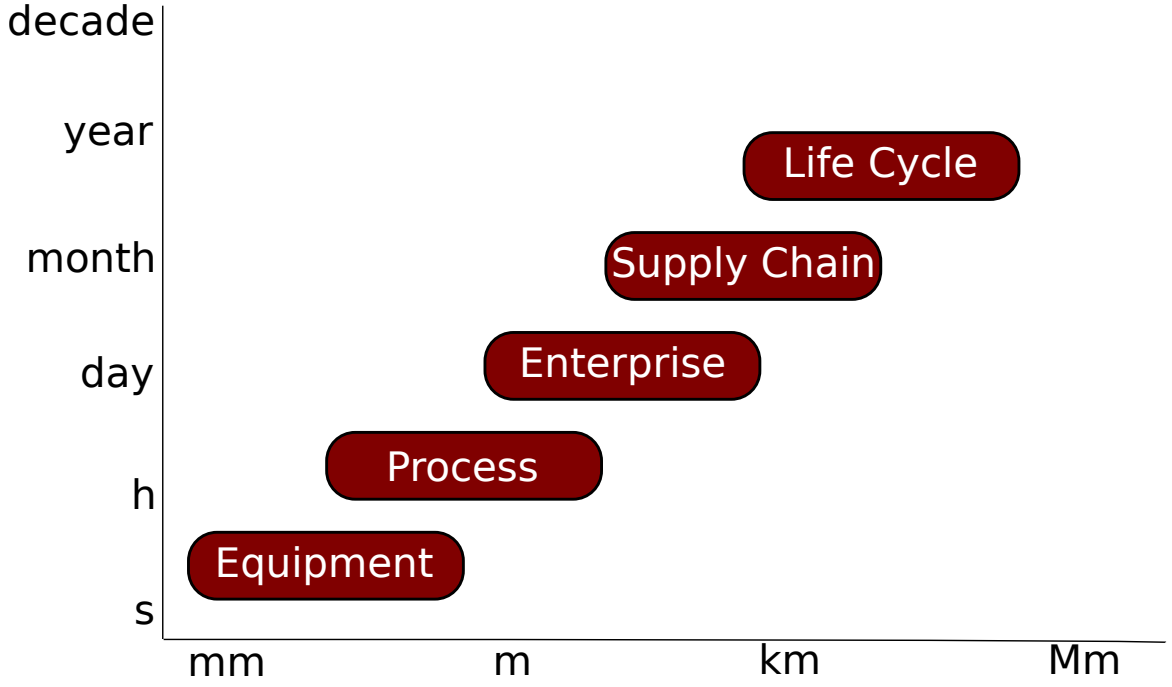

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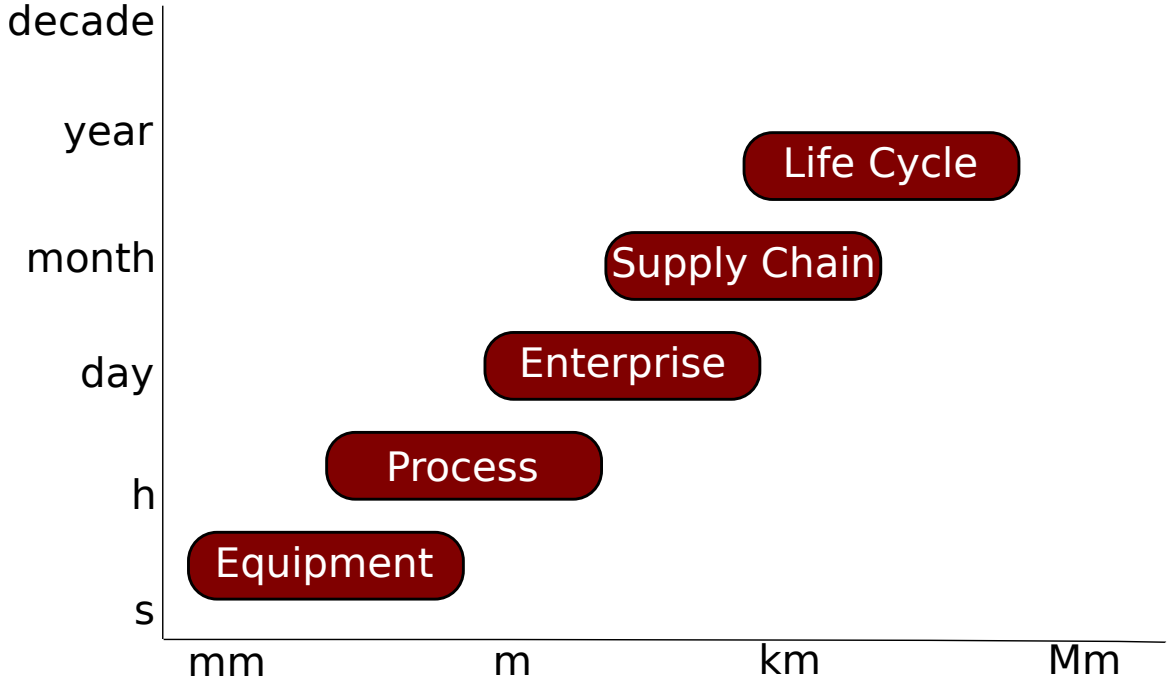
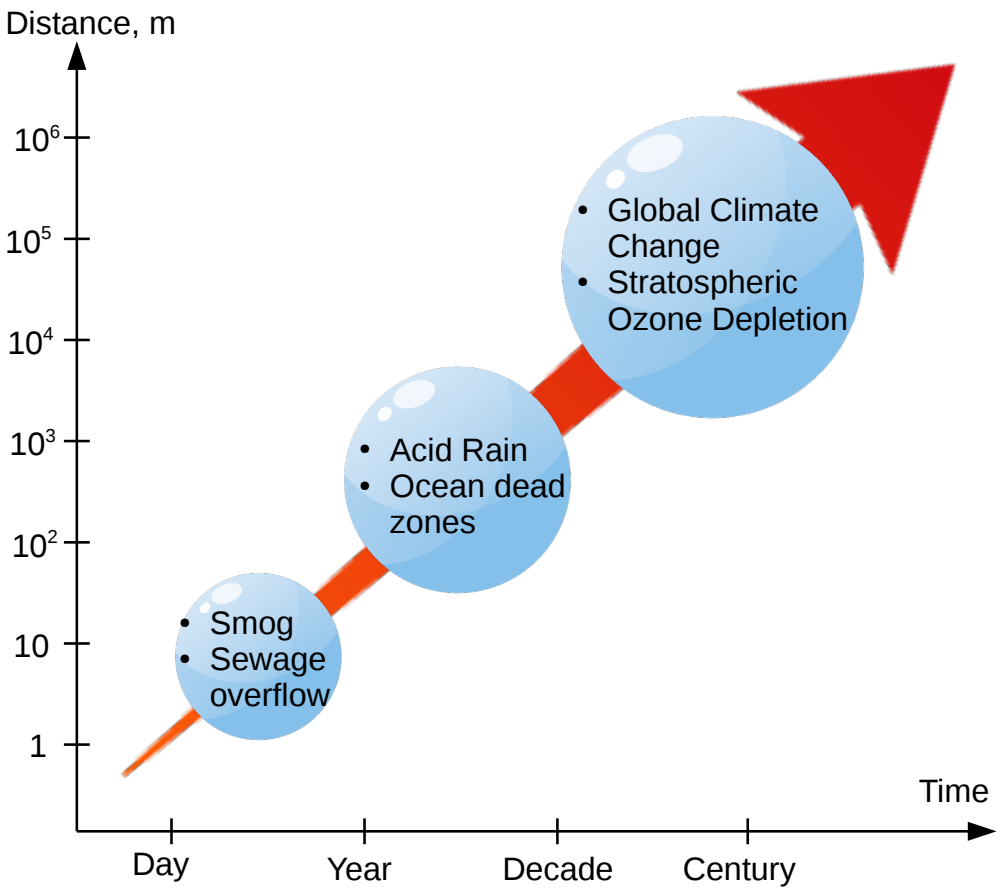


Will these efforts ensure sustainability?

Nature of Environmental Problems



Environmental problems shift

- In space
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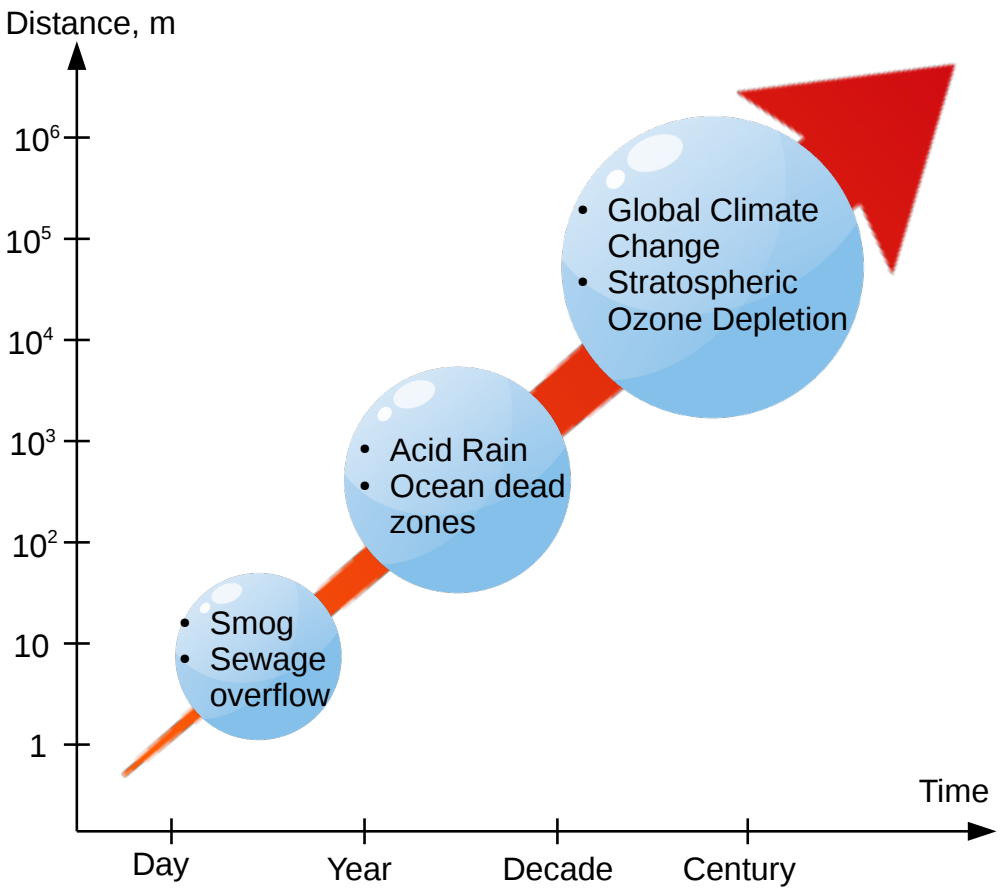

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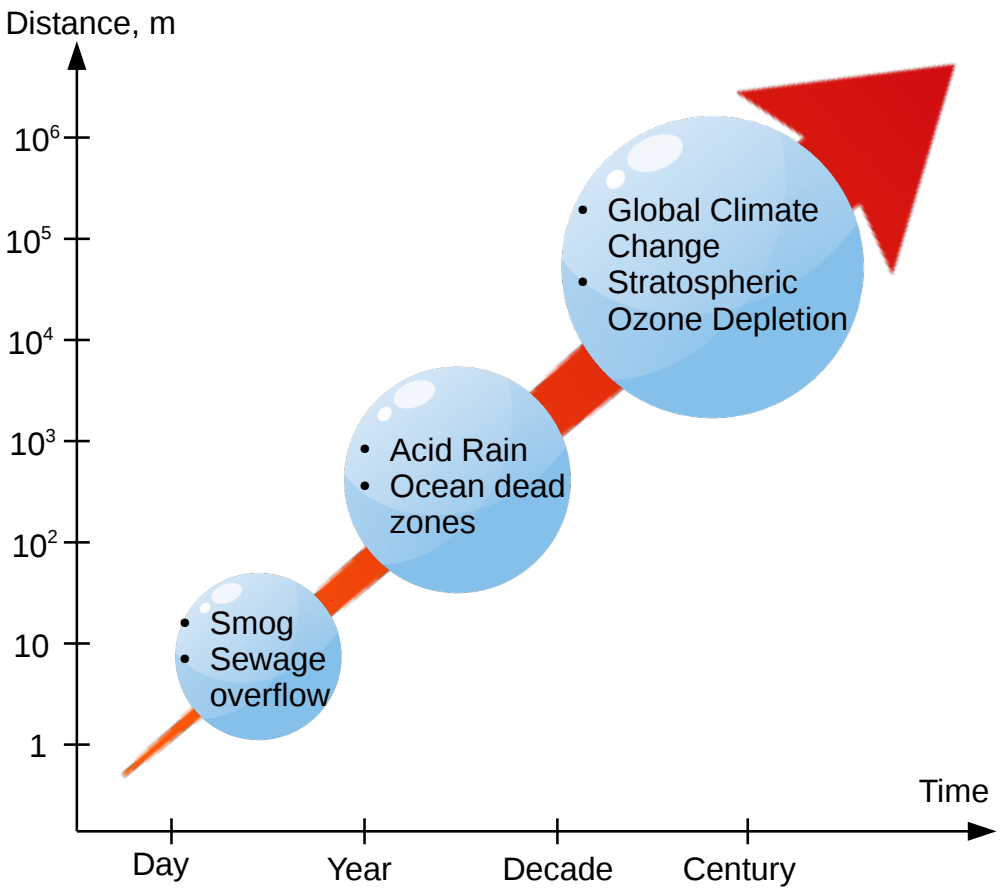

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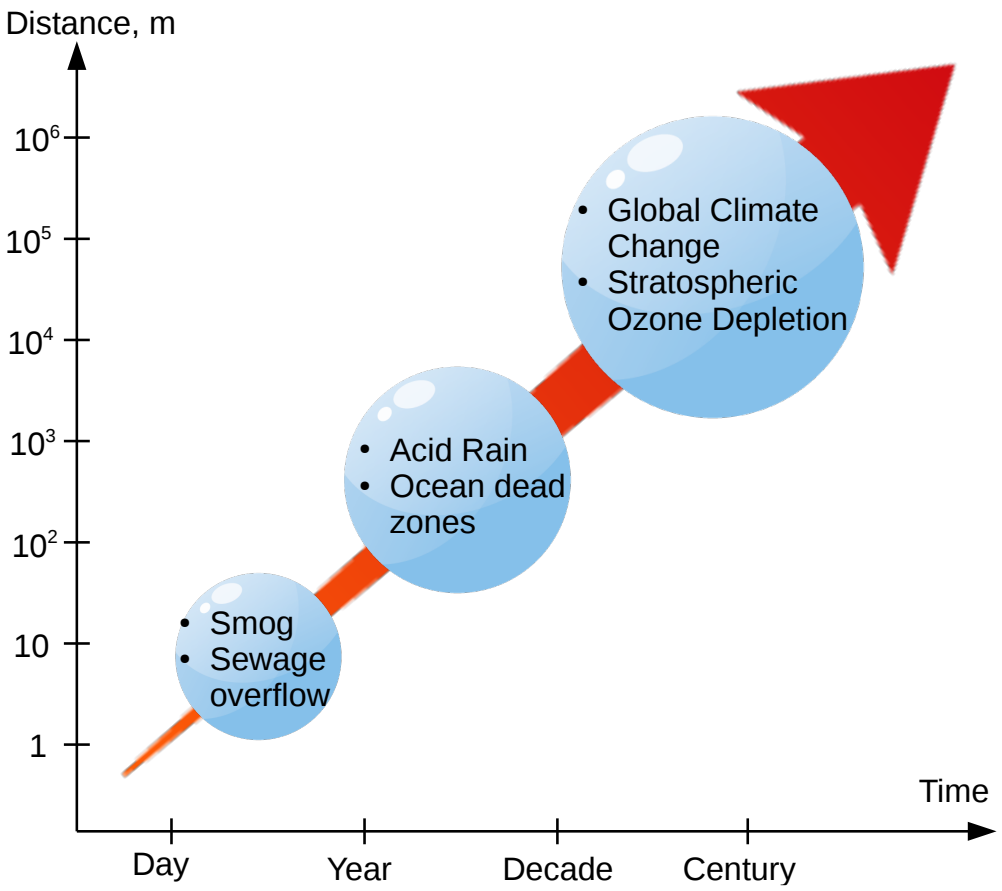

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Sustainable development belongs to the category of wicked problems

Water Sustainability

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– John Muir

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Therefore, we cannot isolate water sustainability from other systems and flows

Addressing Shifts in Space

Existing Work

- Approaches such as water footprint and life cycle assessment have been developed to prevent shifts in space along life cycle
- Incorporated in process design as constraints and objectives
- Footprint captured as fixed coefficients multiplied by process inputs

$$\max P(x,y) \quad \min(\Phi x + Q(y))$$
$$\text{s.t.} h(x,y) = 0; \quad g(x,y) \geq 0$$

Addressing Shifts in Space

Open Problems

- Design of "optimal" life cycle network by combining information at multiple scales - equipment, value chain, economy
- Elicit and utilize uncertainty information
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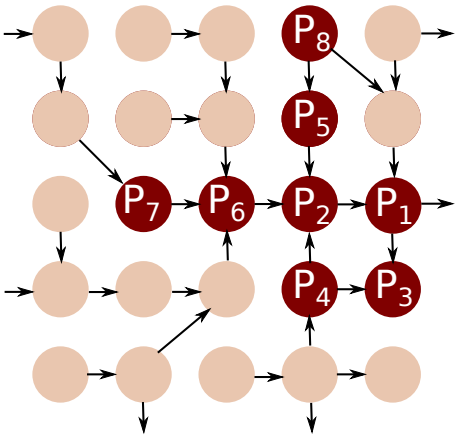

Process Network

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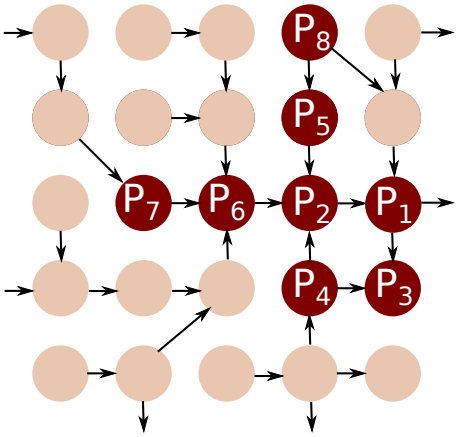

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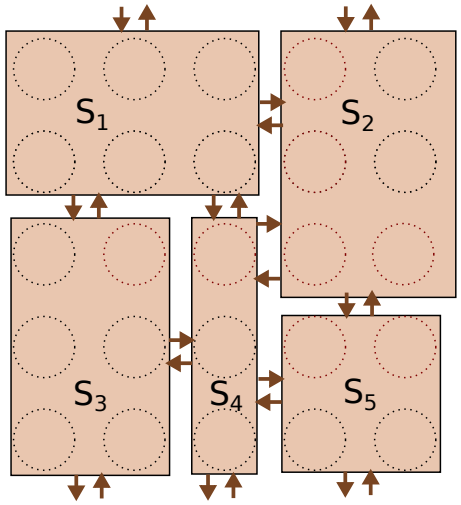

Input-Output

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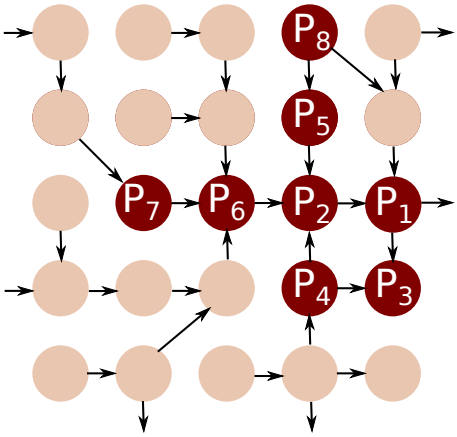

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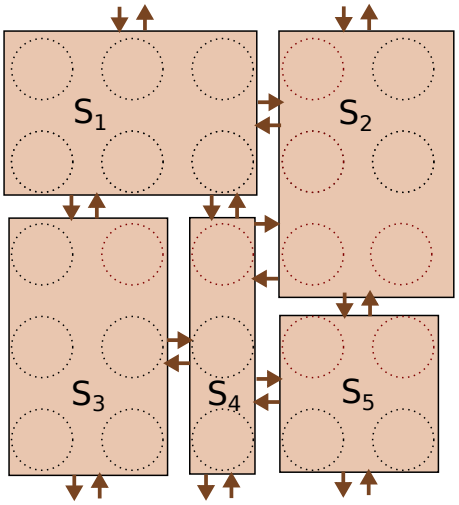

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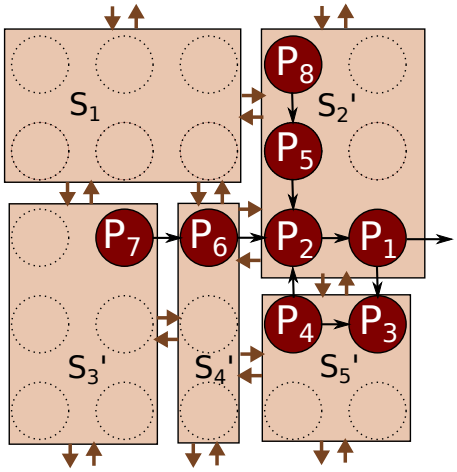

Hybrid

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  - Engineering is "the control of nature by man" (Rossiter, 1913)
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- The current paradigm of engineering will continue causing unintended harm and result in **Unsustainable Engineering**

Nature and Engineering

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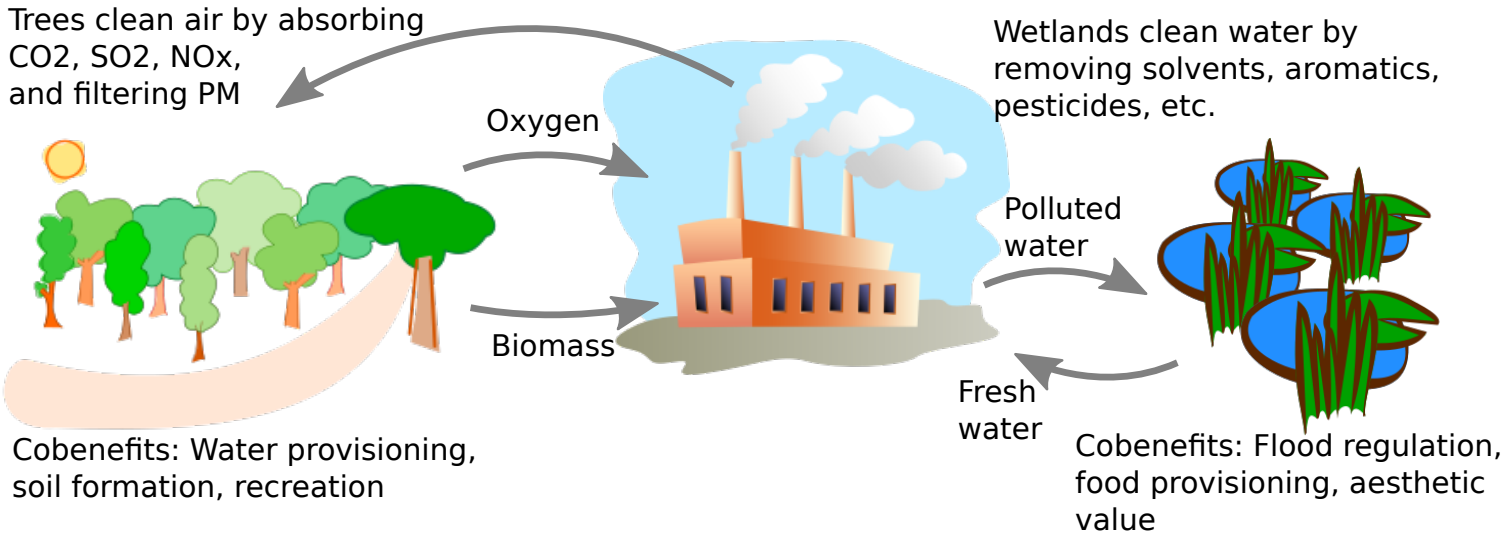

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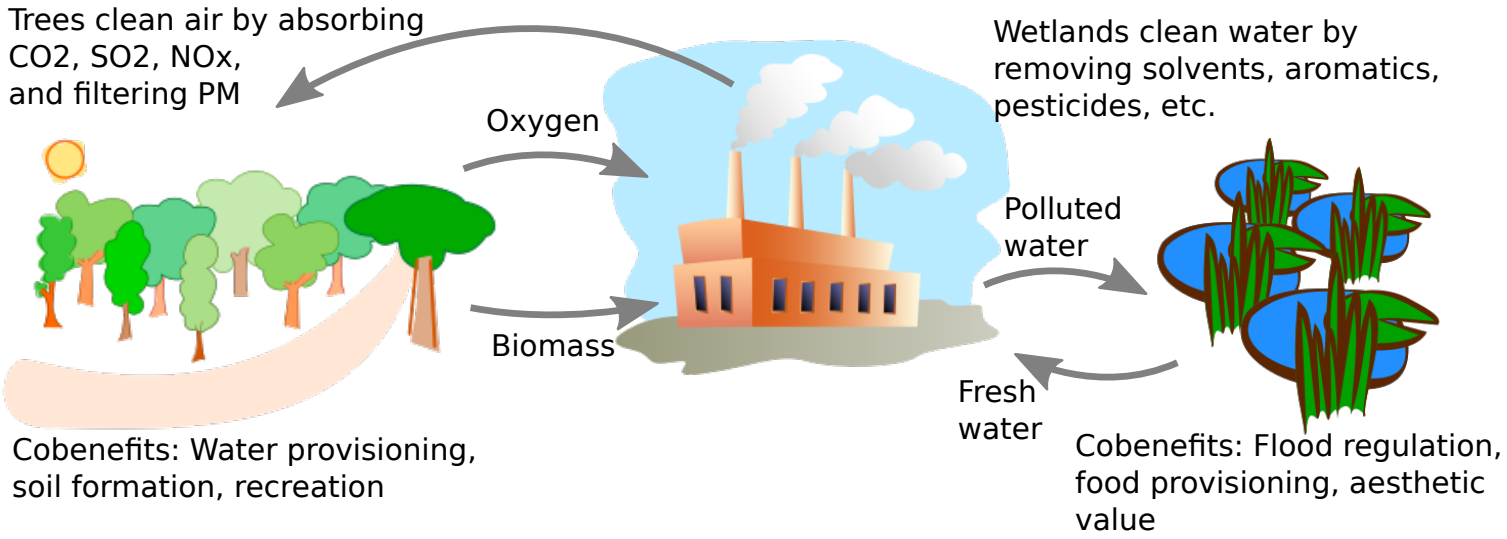
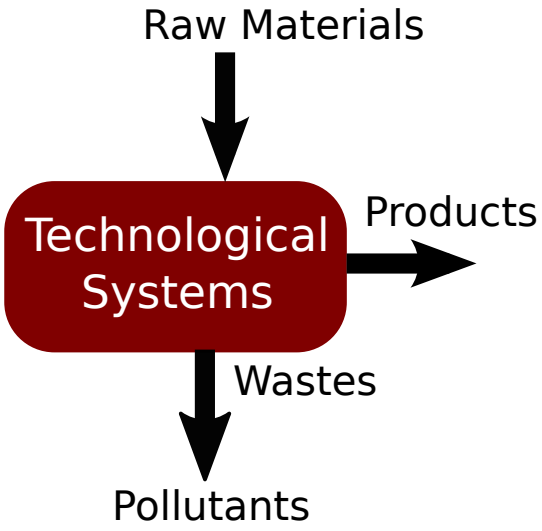


- However, engineering takes nature for granted
  - Focus is on minimizing impact of emissions and resource use
  - Capacity of nature to absorb impact or provide resources is ignored
- Shortcomings of ignoring nature
  - Unintended harm by exceeding nature's capacity
  - Lost opportunities for innovation and win-win solutions

Techno-Ecological Synergy



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Bakshi, Ziv, Lepech, *Env. Sci. Technol.*, 2015

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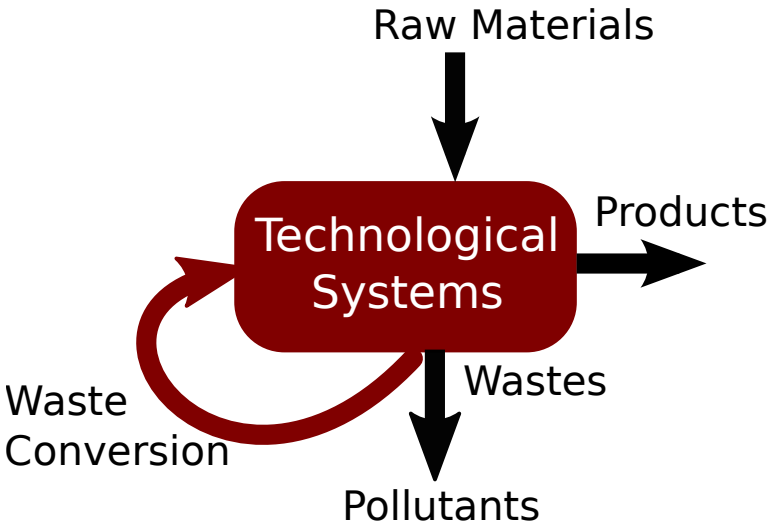

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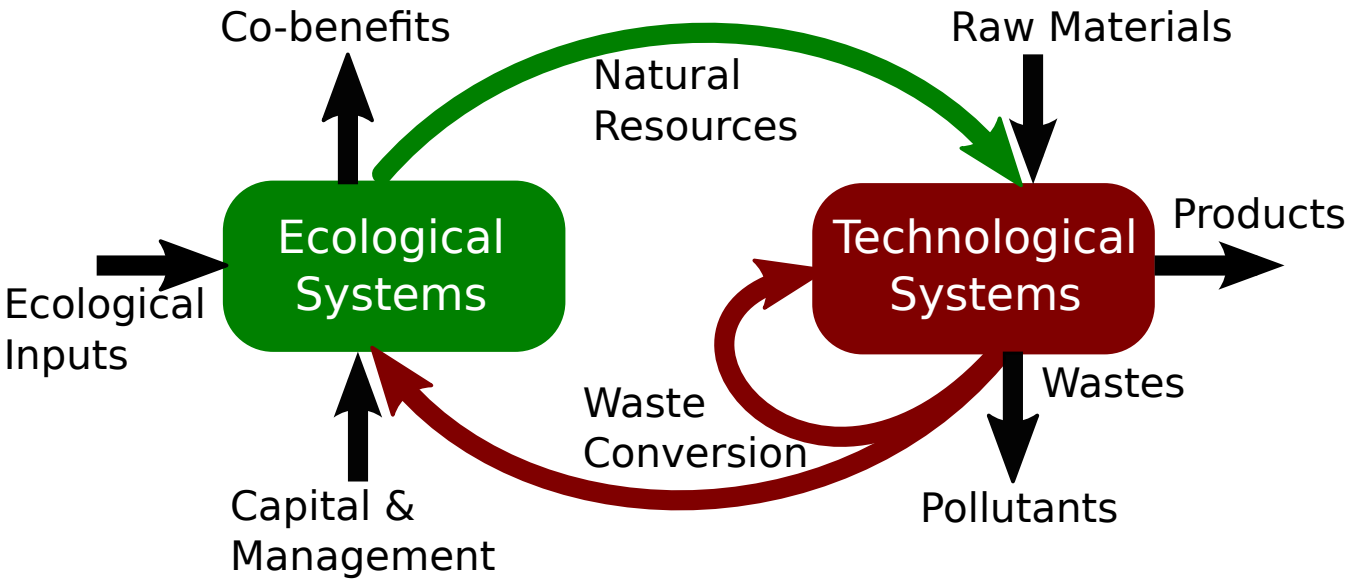

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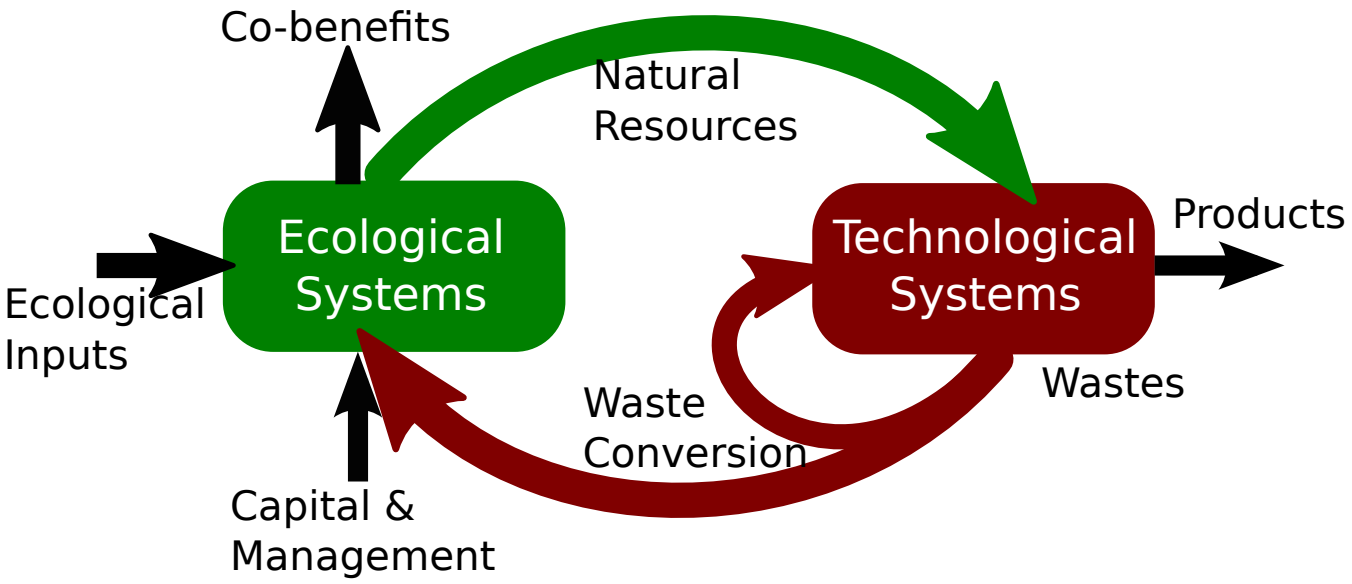

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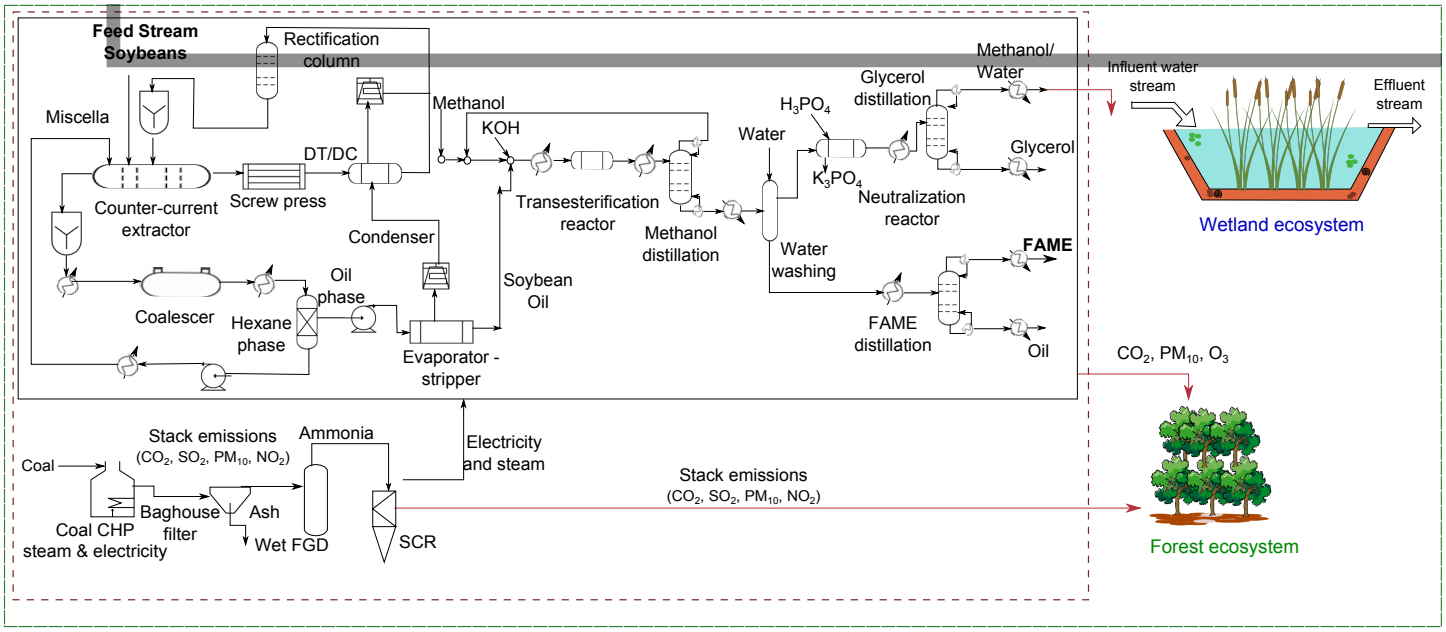
Ecosystems as Unit Operations



Do local ecosystems have enough capacity to supply goods and services to biodiesel manufacturing?

Gopalakrishnan, Bakshi, *AIChE Journal*, 2018

Biodiesel Manufacturing Site

Process Design with TES

Ecosystems for **end-of-pipe** treatment

- Process design by conventional approach

$$\begin{aligned} &\text{maximize } P(x, y) \\ &\text{subject to } h(x, y) = 0; \quad g(x, y) \geq 0 \end{aligned}$$

- Then add ecological system, $h_e(x, y) = 0$

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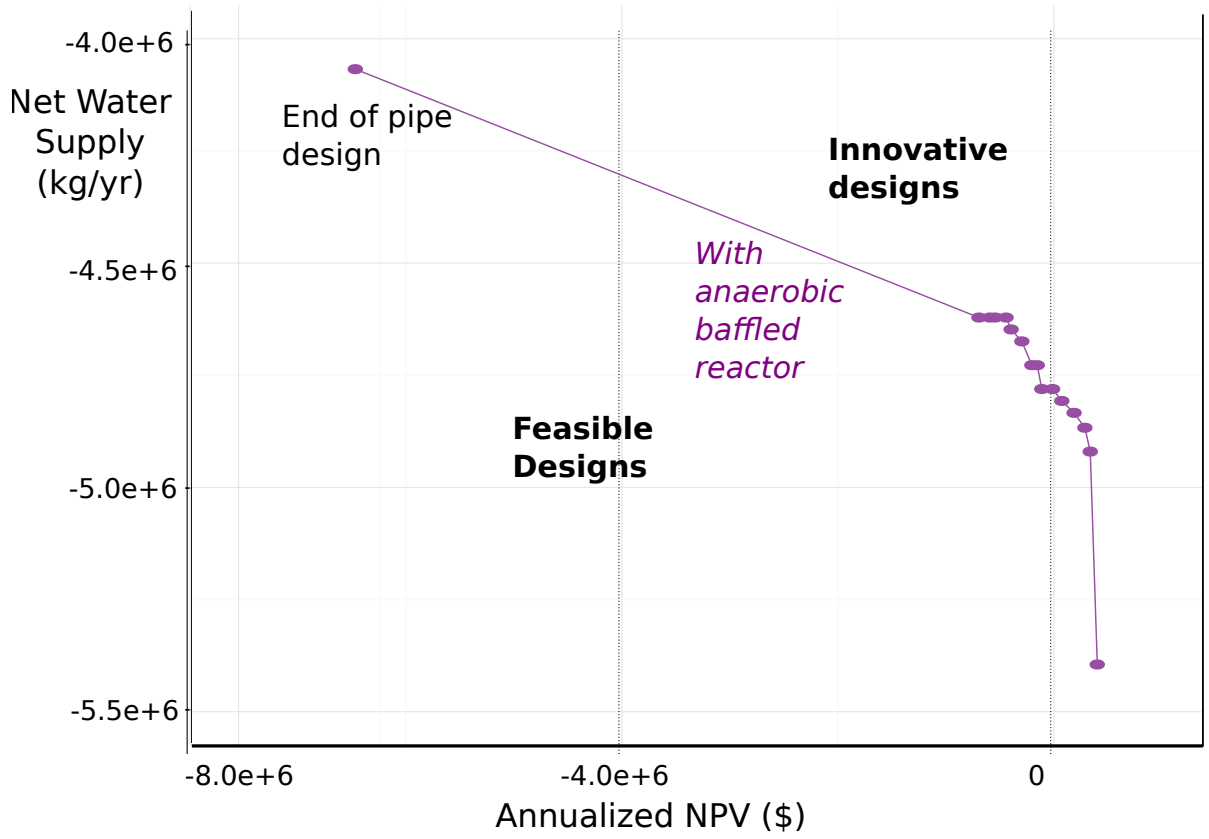
Ecosystems as **unit operations** for integrated design

$$\begin{aligned} &\max P(x,y) \quad \min Q(x,y) \\ &\text{s.t.} h(x,y)=0; \quad g(x,y)\geq 0 \\ &\quad h_e(x,y)=0 \quad \text{(ecosystem models)} \end{aligned}$$

TES Design of Biodiesel Process with Wetlands



Gopalakrishnan and Bakshi, 2017

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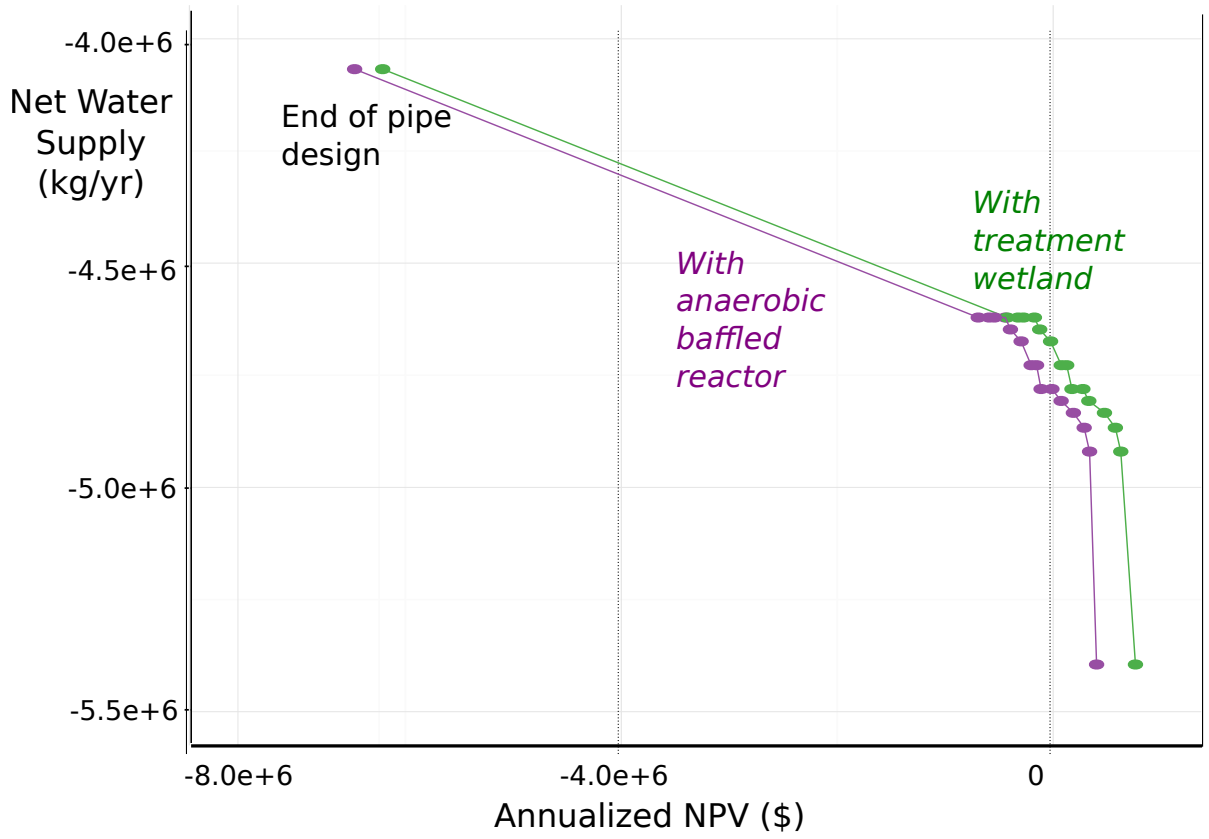

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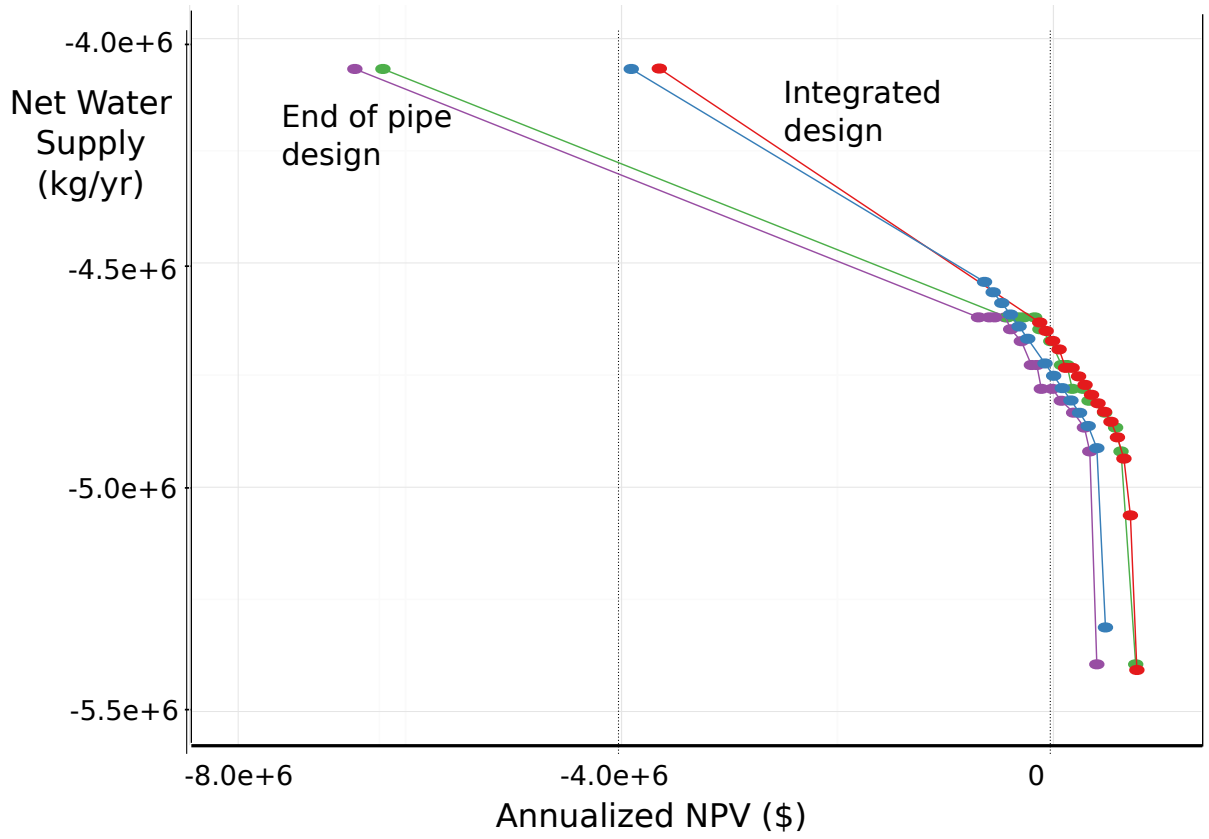

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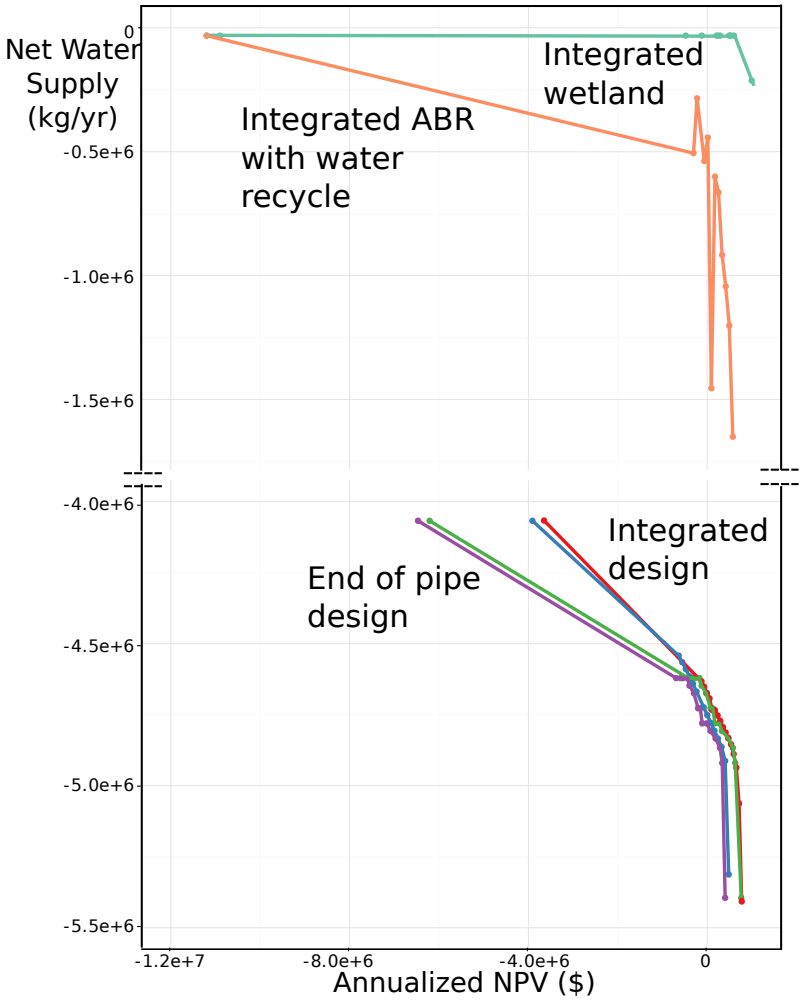
TES Design with Water Recycle



- Integrated design of biodiesel process with wetlands and feedback of water results in new "win-win" designs
- Including vegetation along with wetlands results in further improvement

Including Nature in Engineering: Benefits and Barriers

Diverse applications

- Biodiesel manufacturing
- Biosolids management in Central Ohio
- Single-family home and yard
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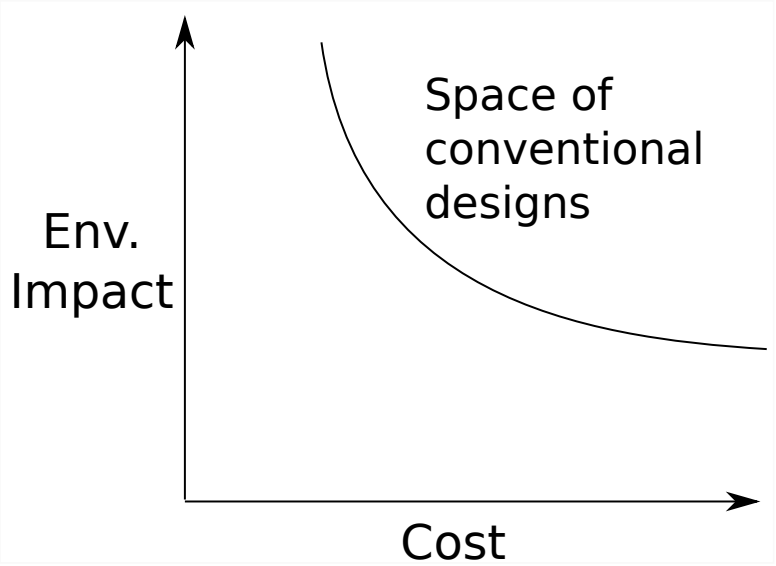

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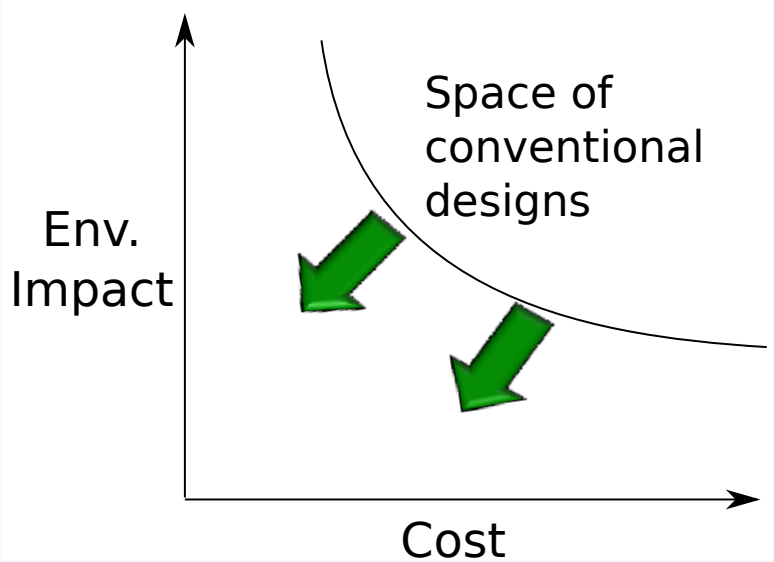

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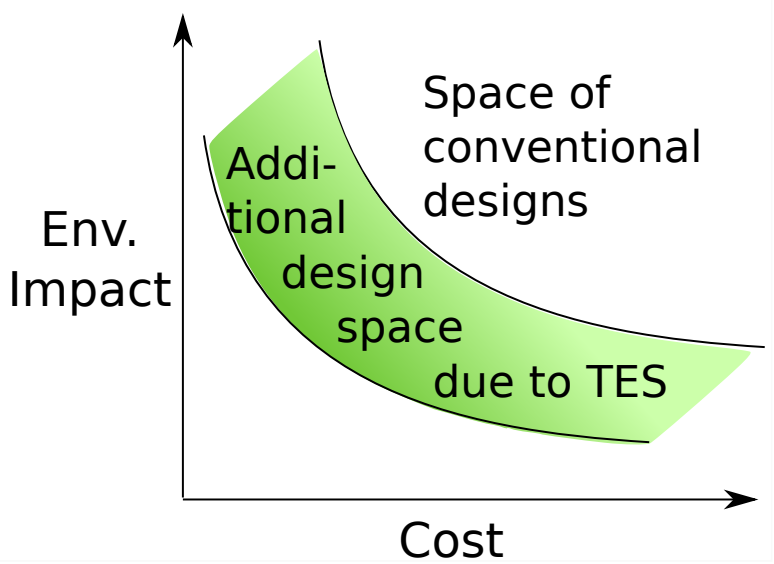

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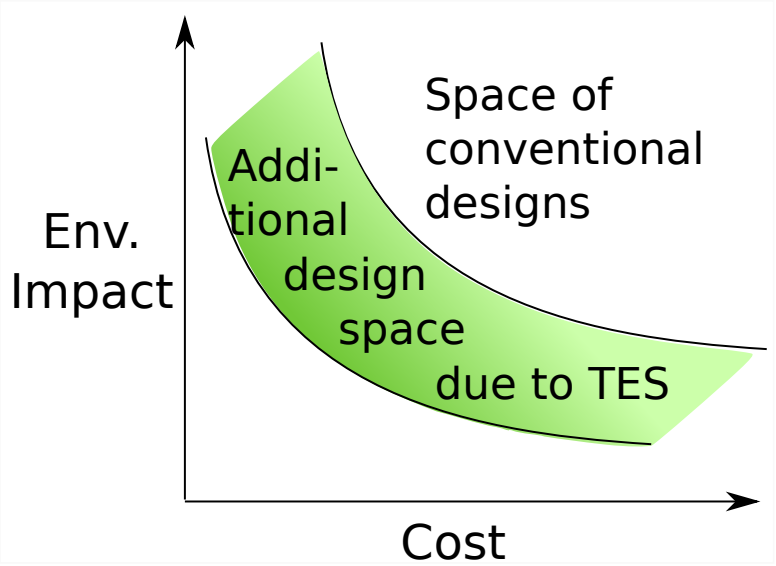

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- Innovative, win-win designs
- Cobenefits to society
- Restoration of ecosystems
- Respect ecological limits

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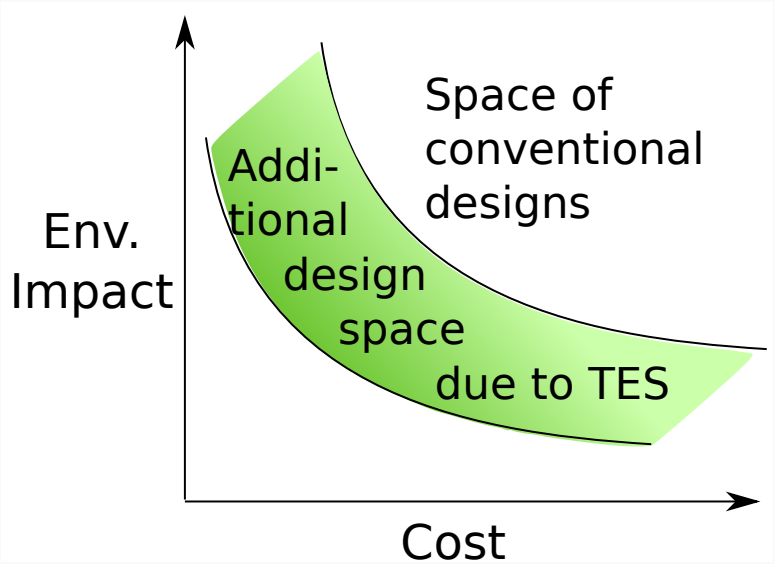

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Barriers

- Spatial and temporal variation
- Models and data
- Sustainability
- Applications

Application Opportunities

Industrial site design

- Integrated design of manufacturing processes with local and regional ecosystems

Urban Systems

- Urban design with gray and green infrastructure - from single house to neighborhoods

Watershed Management

- Manage land use for ecosystem services, and industrial, urban, agricultural activities

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Need to deal with fundamental differences in characteristics of technological and ecological systems

Opportunities for TES Design - Models and Data

- Need models and data to capture behavior of ecosystems
- Do we know enough about ecosystems?
  - Systems are complex and nonlinear, but many models are available
  - Measured data is available at multiple scales - local sensors to remote sensing
  - Significant spatial and temporal variability and uncertainty
- Effects of climate change
- Is TES design just a matter of extending current PSE methods to include ecosystems?

Opportunities for TES Design - Methods

Extend optimization-based design to include and integrate technological and ecological systems

- Large-scale optimization
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Objective functions

- Large number of objectives ($\sim$23 ecosystem services)
- Aggregation of objectives
  - Monetary valuation (weak sustainability)
  - Loss of ecological holism (biodiversity)
  - Commodification of ecosystem services
  - Use information theoretic functions (resilience, entropy)?

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Does nature optimize?

- Individual activities in nature can be highly inefficient
- Nature emphasizes resilience, not just efficiency

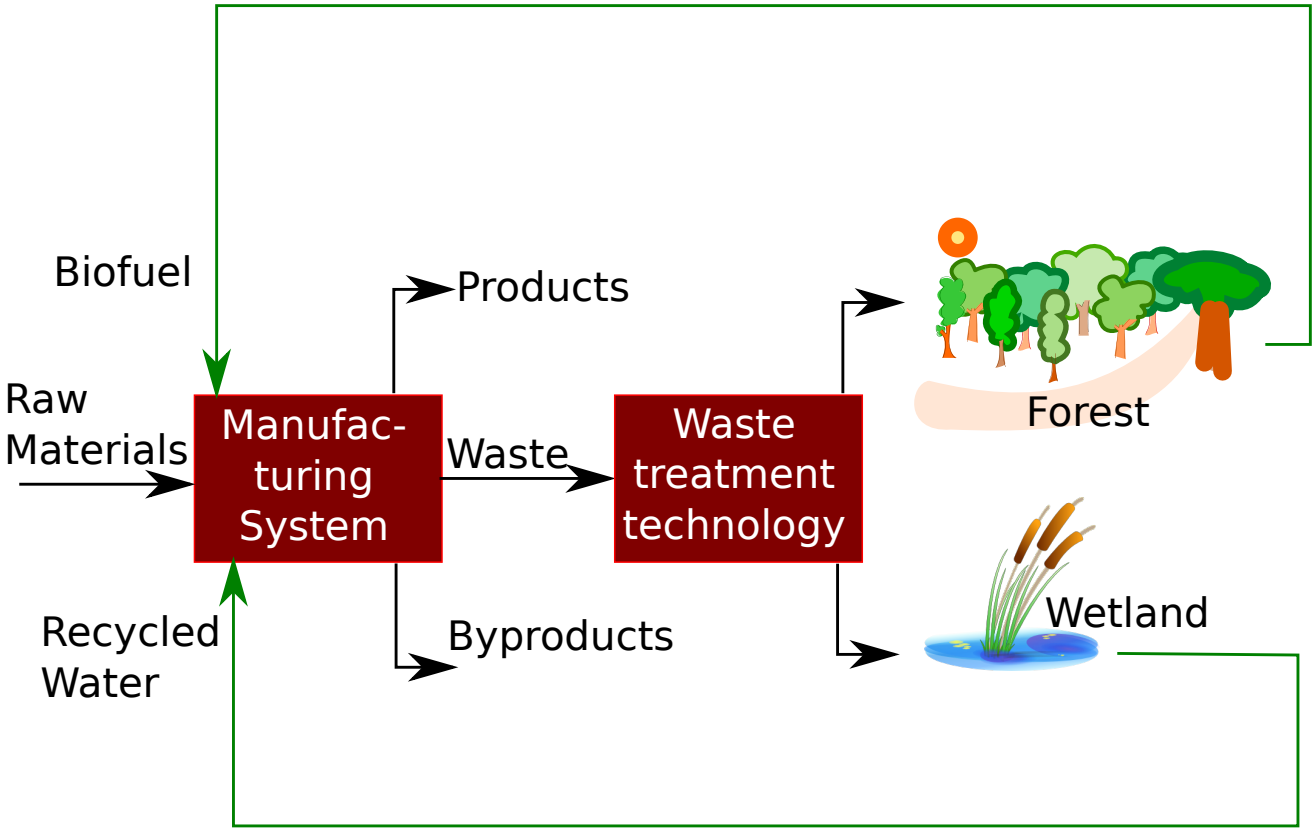
TES Design for Resilience

What is the effect of including ecosystems on TES and societal resilience?

- Less resilient - Greater networking can make systems vulnerable and fragile to disturbances
- More resilient - Networking provides more alternatives, and multiple pathways to reject disturbances

Utilize robust design?

Opportunities in Operation and Control of TES Systems



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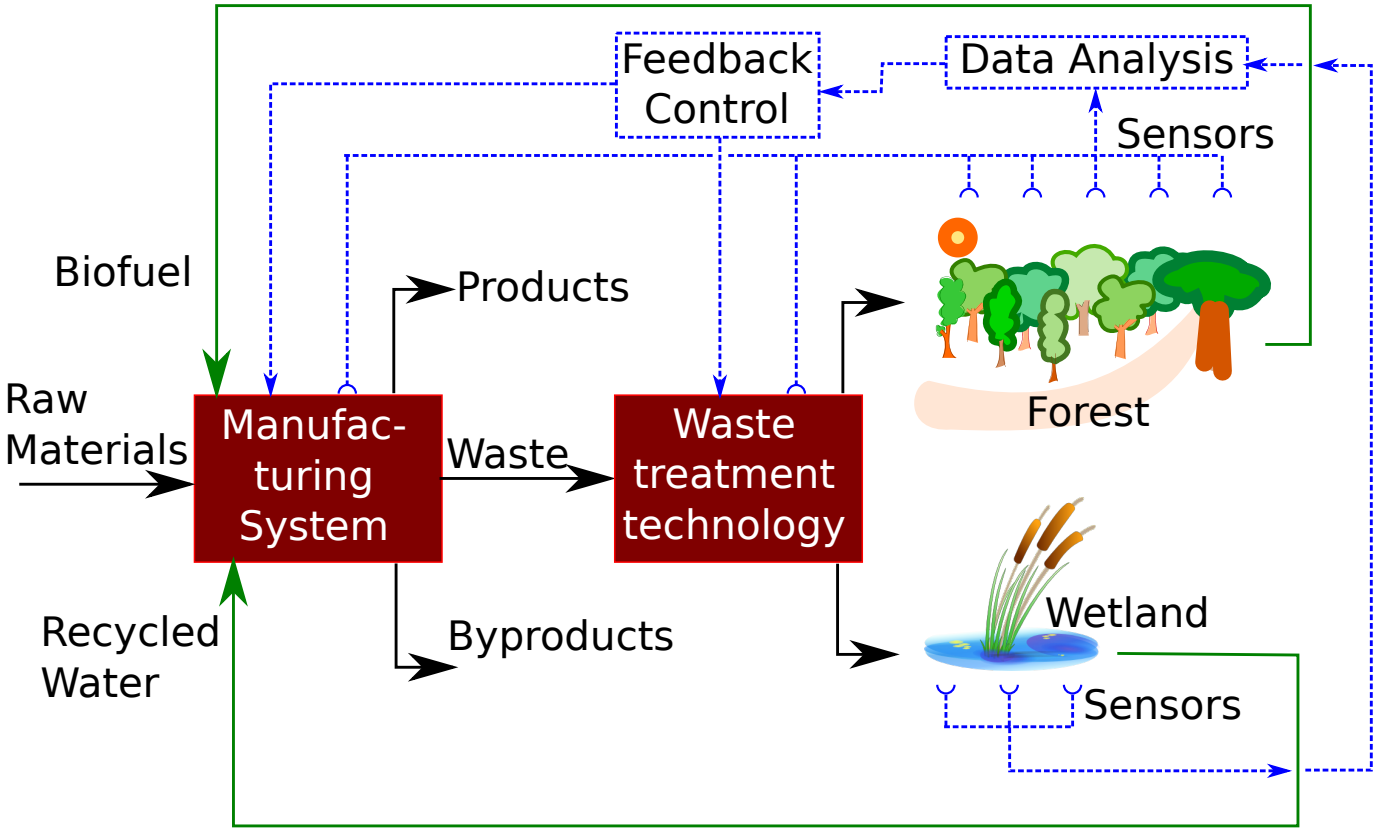

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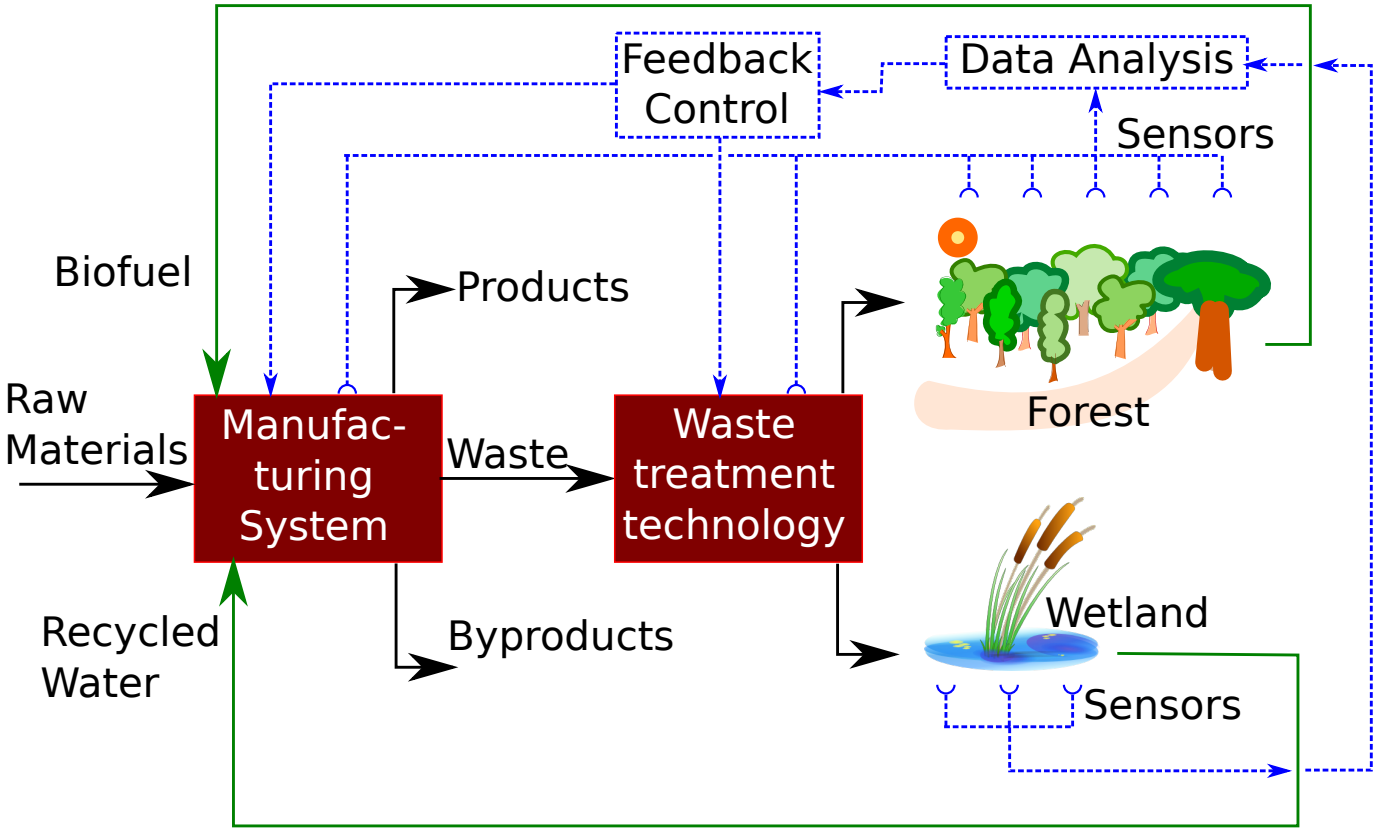

Also relevant to management of watersheds, urban water networks, etc.

Opportunities in Operation and Control of TES Systems

- Multiscale, multistage optimization
- Control theory
- Machine learning, statistics
- ...

Including nature in engineering presents opportunities and challenges to all aspects of PSE

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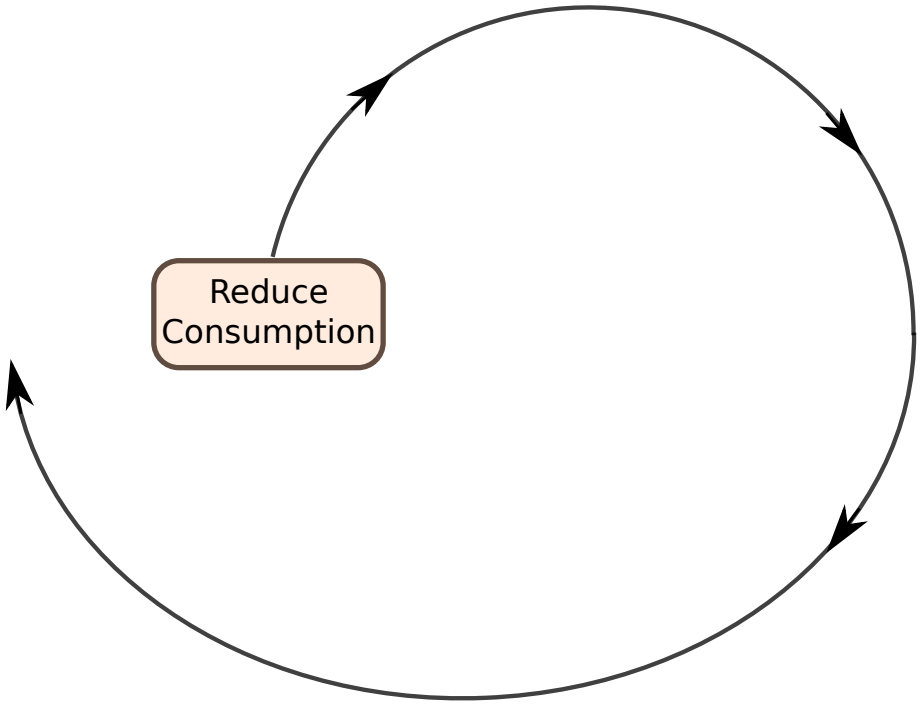
- The current paradigm of engineering will continue causing unintended harm and result in **Unsustainable Engineering**

Economics and Engineering

Engineering focuses on improving efficiency but ignores its effect in society



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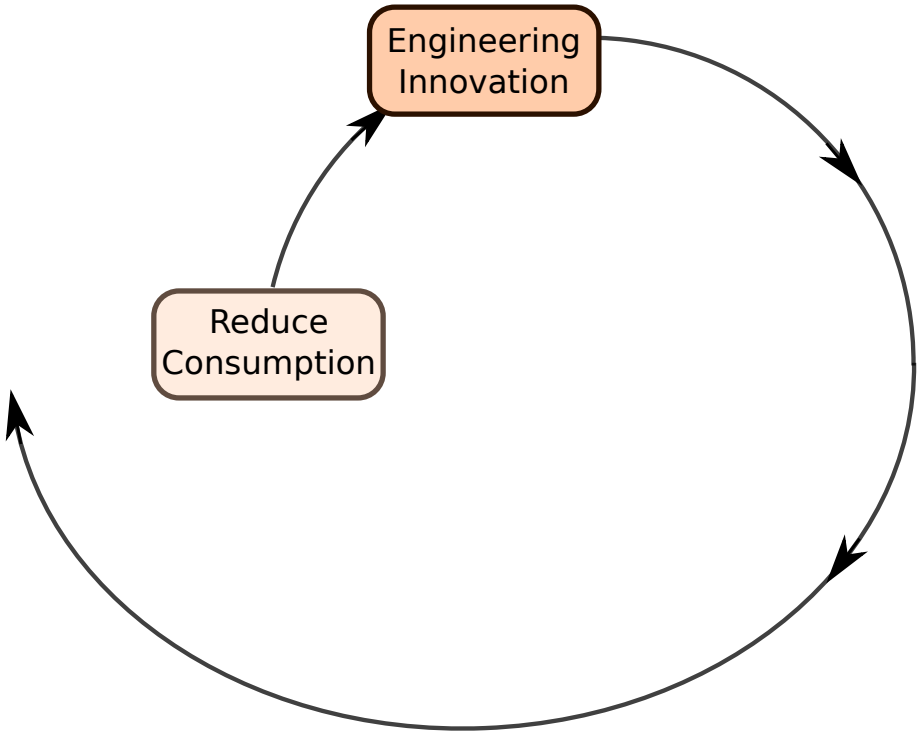

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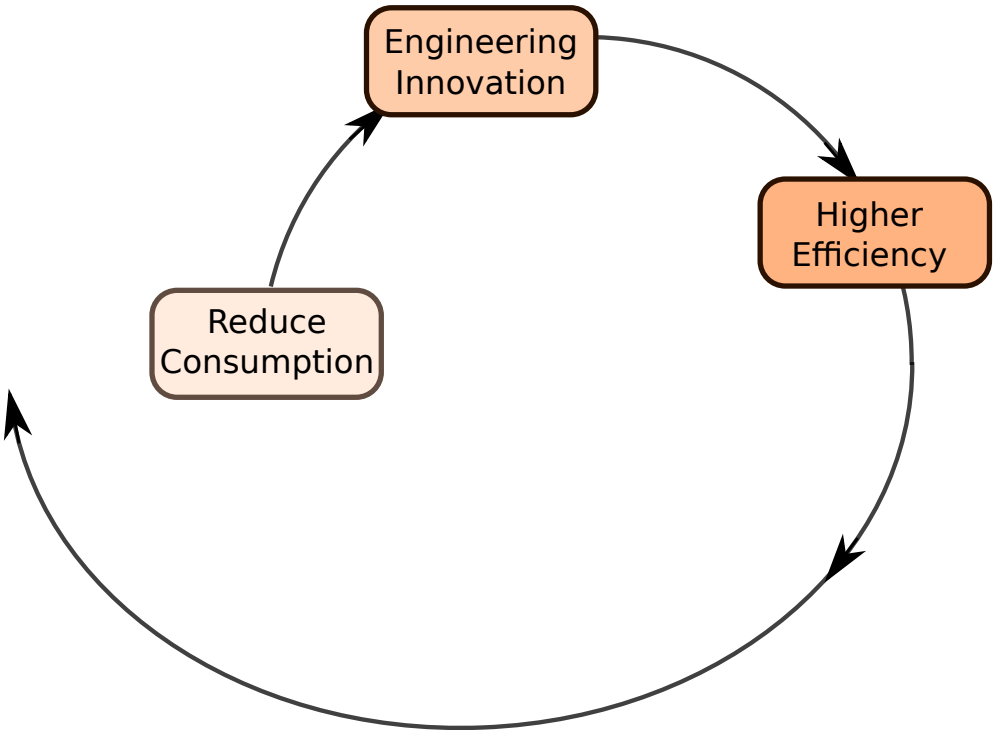

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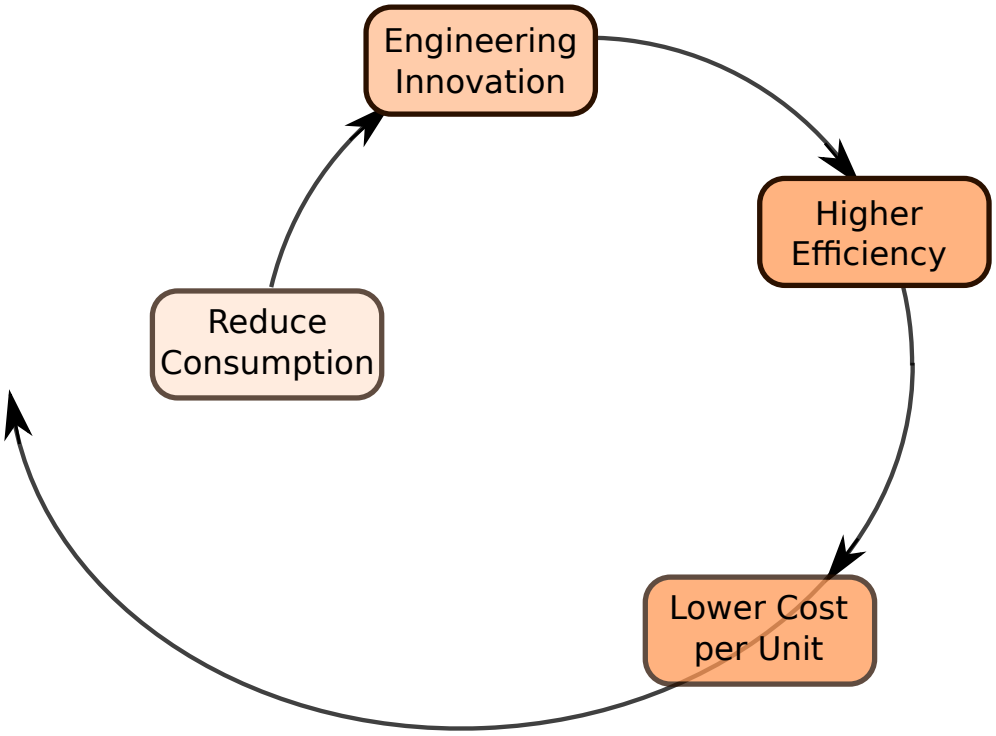

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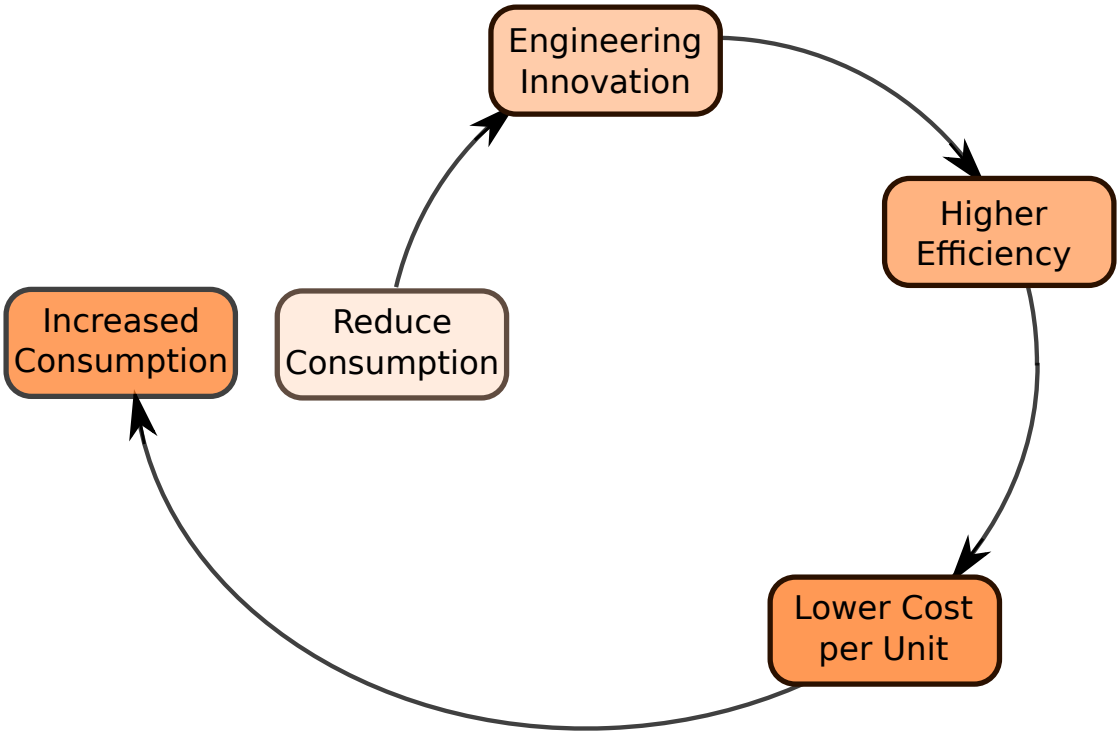

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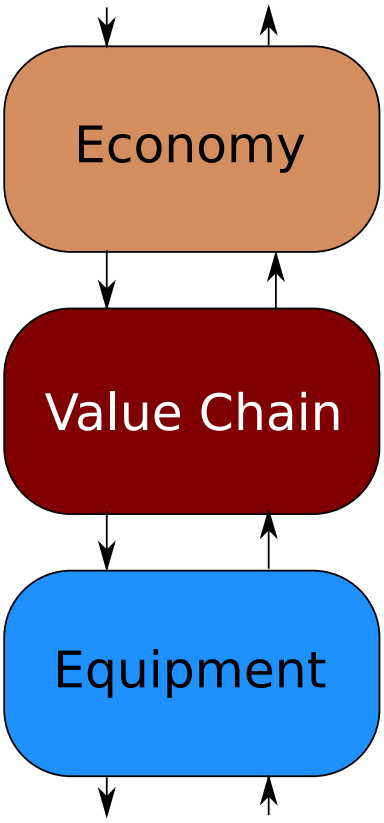
Integration of Economic and Engineering Models



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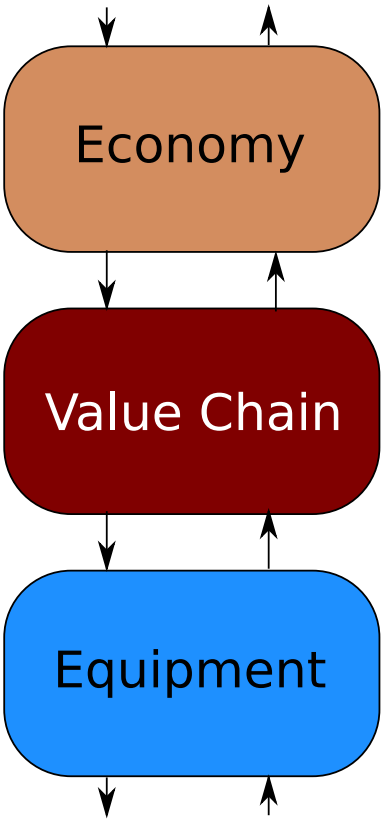

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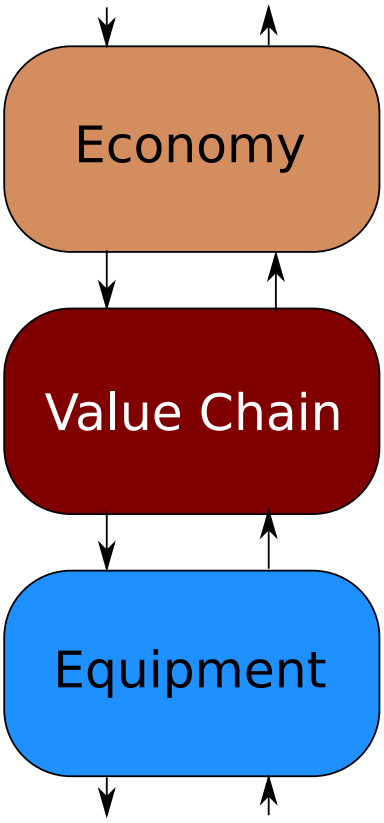

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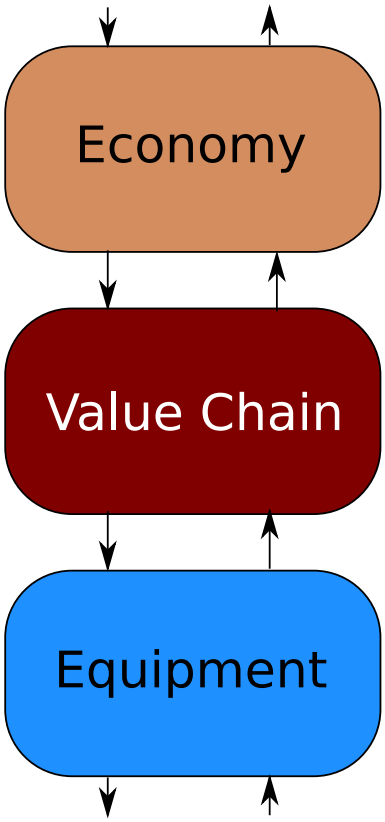

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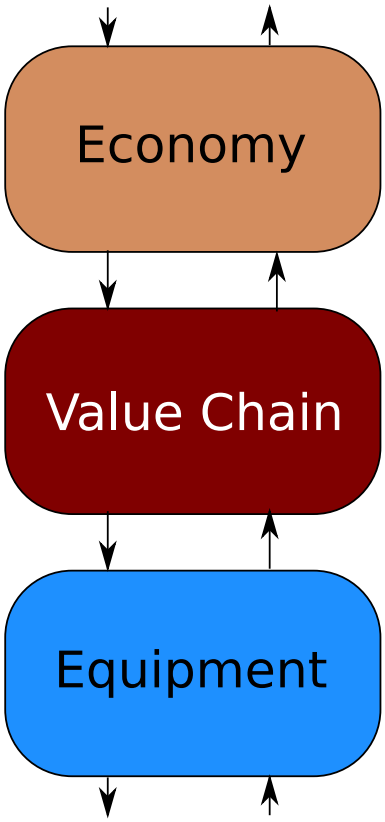

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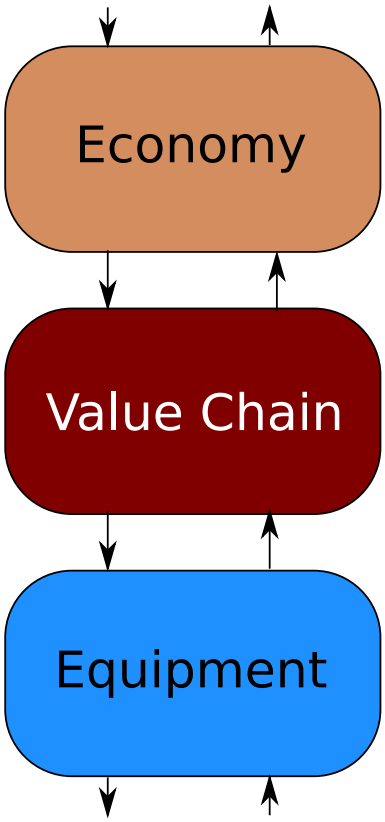

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Economics and Engineering - Opportunities for PSE

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Integrate economic models with physical models

- Multiscale modeling
- Economic models - input-output, choice of technology, partial equilibrium, dynamic computable general equilibrium

Requires strong collaboration with economists

Wicked Nature of Sustainability

- Most engineering problems, including those in PSE are “tame”
- Sustainability belongs to the category of “wicked” problems
  - No clear objective that everyone agrees with
  - Guaranteeing sustainability is possible only in hindsight
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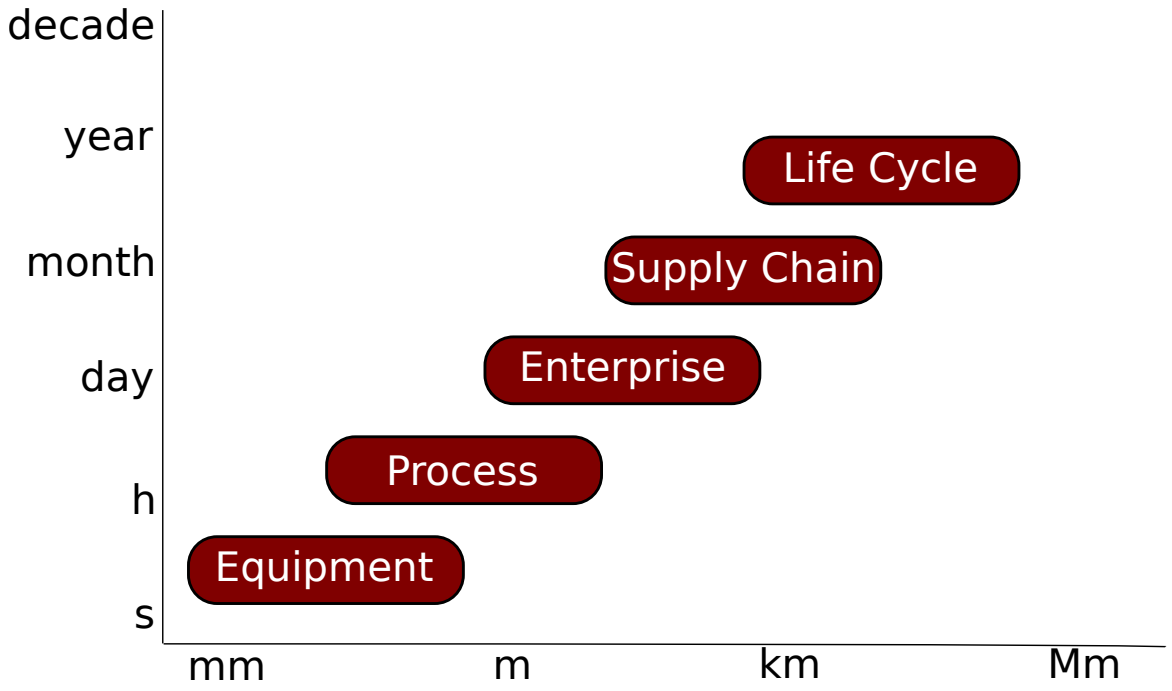
How do we solve such problems?

Mimic strategies that are successful for solving other wicked problems - Ecomimicry

ΦΨ for Water Sustainability

- Cannot consider water in isolation
- Address shifts in space, time, across disciplines, and between flows, while respecting nature's limits, and ensuring economic feasibility
- Opportunities for all of PSE



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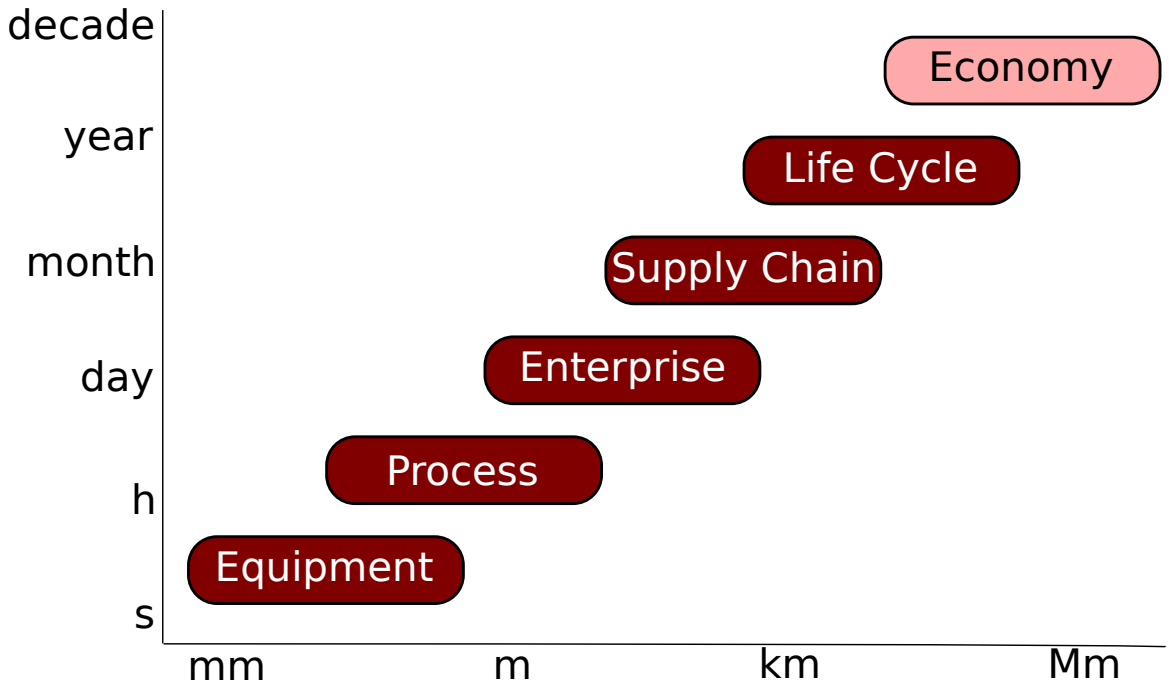

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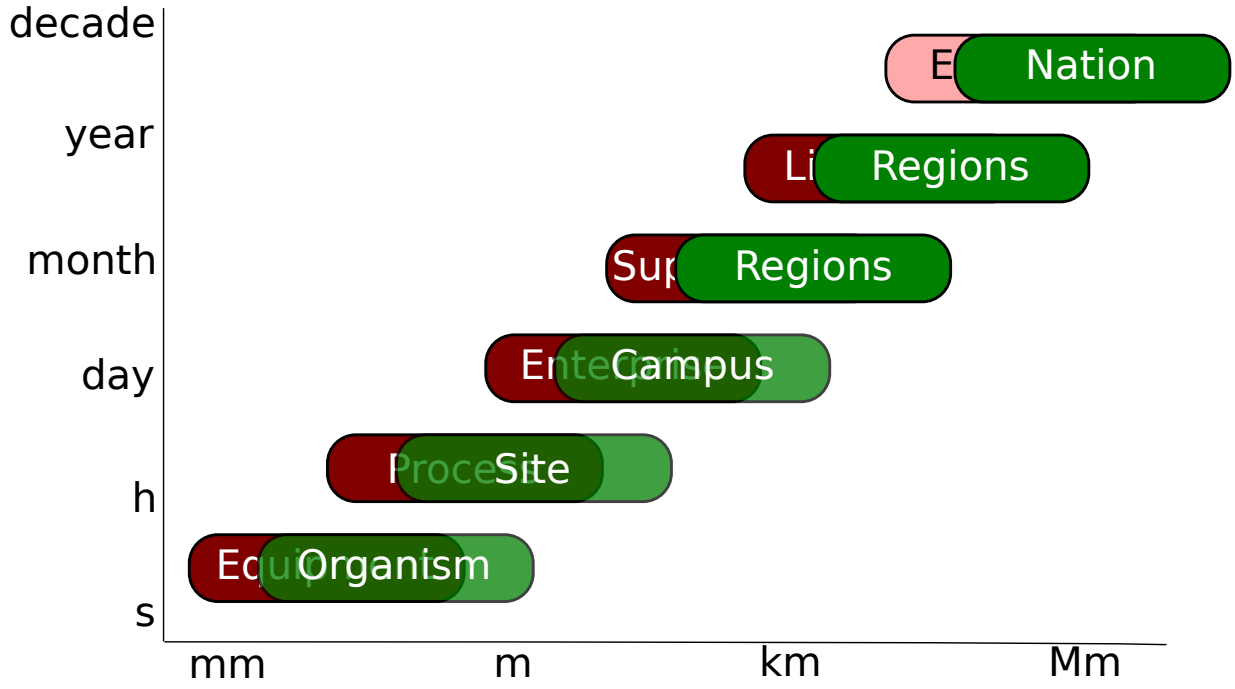

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Also, engineers are among the least ecologically literate

Collaborators

Engineering

- Tim Gutowski, MIT
- Dusan Sekulic, U. Kentucky

Ecology

- Satoshi Hirabayashi, USDA Forest Service
- Guy Ziv, U. Leeds
- Sami Khanal, OSU
- Brian Fath, Towson U.

Economics

- Brent Sohngen, OSU
- Alan Randall, OSU

Convergence of Engineering with Ecology and Economics