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Water for Everything and the Transformative Technologies to Improve Water Sustainability

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Abstract

Worldwide, unsustainable consumption and production have resulted in "Gigaton Problems" associated with the use of non-renewable materials, fossil-based energy, and water, to name a few. Natural cycles (e.g., water, carbon, nutrients, and materials) have been altered by unsustainable consumption. For instance, unprecedented concentrations of carbon dioxide (CO_2) in the atmosphere are contributing to climate change, which impacts the sustainability and resiliency of water resources.

Water is essential to support sustainable human development and activities. It is used, essentially, for everything. But more water is used for energy, agriculture, industry, and transportation than for personal use. Consequently, the sustainability of our water resources is linked to the practices used to generate energy, produce food, provide transportation, and manage land. In effect, they should be viewed as one whole system.

In this Lecture, the focus is on how the engineering community can take the lead in developing integrated and efficient infrastructure systems that promote the sustainable use of water for personal consumption, energy generation, food production, transportation, and land development.

1. Challenges to Sustainable and Resilient Natural and Human Environments

Currently, 54 percent of the world's population lives in urban areas, with the global urban population increasing by 5.5-million people every month. By 2050, over 70 percent of the global population will be urban residents.[1] Worldwide, there are 560 cities with populations exceeding one million, and the number of mega-cities (i.e., cities with populations greater than 10 million) is steadily increasing.[2] In China alone, the scale and magnitude of urban infrastructure growth are immense. By 2025, the Chinese urban population is expected to increase by 350-million people, more than the current U.S. population.[3] To support this massive Chinese urban population, at least 5-billion square meters of road surfaces, 4-billion square feet of floor space, and between 700 to 900 gigawatts (GW) of new power generation capacity will need to be built over the next 20 years.

At present, cities account for 60 percent of global drinking water consumption, 75 percent of global energy consumption, and 80 percent of global greenhouse gas (GHG) emissions.[4] To keep pace with future trends in urbanization, global infrastructure will need to double in the next 30 years, requiring an investment of $57 trillion USD.[5] Addressing this unprecedented demand for urban infrastructure will be one of the greatest challenges of the twenty-first century.

Over the past 200 years, technological advances in manufacturing, health care, and food production have transformed the world; however, unsustainable consumption and production have resulted in numerous "global grand challenges," such as population growth, resource depletion, climate change, and biodiversity loss. Meanwhile, a significant number of people throughout the world live in extreme poverty, making them more vulnerable to the impacts of these challenges.[6] Pursuing the path of global sustainable development is imperative.

But what is "sustainable development?" The Brundtland Commission, whose mission is to unite countries to pursue sustainable development together, defines it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[7]

Environmental engineer Roy F. Weston, an early proponent of sustainable development, defined it as "a process of change in which the direction of investment, the orientation of technology, the allocation of resources, and the development and functioning of institutions transition toward longer-term sustainable activities. Longer-term sustainable development will meet present needs and aspirations without endangering the natural ecosystems and their capacity to absorb the effects of human activities, and without compromising the ability of future generations to meet their own needs and aspirations."

At the Brook Byers Institute for Sustainable Systems, our definition of sustainable development is "to recreate the anthroposphere – or, the part of the environment made or modified for human use – to exist within the means of nature." That is, humanity must use renewable resources provided by nature and generate waste that nature can assimilate without overwhelming natural cycles.

As we work towards meeting the growing demand for urban infrastructure, engineers will need to examine the interactions between natural, engineered, social, and economic systems and develop integrated and efficient infrastructure that promotes more sustainable and resilient natural and human environments.

1.1 Lack of Renewable Material Usage in Commerce: Gigaton Problems Resulting from Human Activity

The magnitude of challenges we face on a global scale is enormous (Figure 1). For example:

- The current global population is now 7.3 billion, with projections of over 9 billion by 2050.[8]
- The world Gross Domestic Product (GDP), which relies on tremendous inputs of nonrenewable resources,[9] was over $77 trillion USD in 2014.[10]
- In 2012, world energy consumption was 13.4 billion tons of oil equivalents (Gtoe), with 82 percent from nonrenewable fossil fuels. Furthermore, the combustion of these fossil fuels emitted 31.7 billion tons (Gton) of CO_2 [or 8.6 Gton of CO_2 as carbon (GtC)].

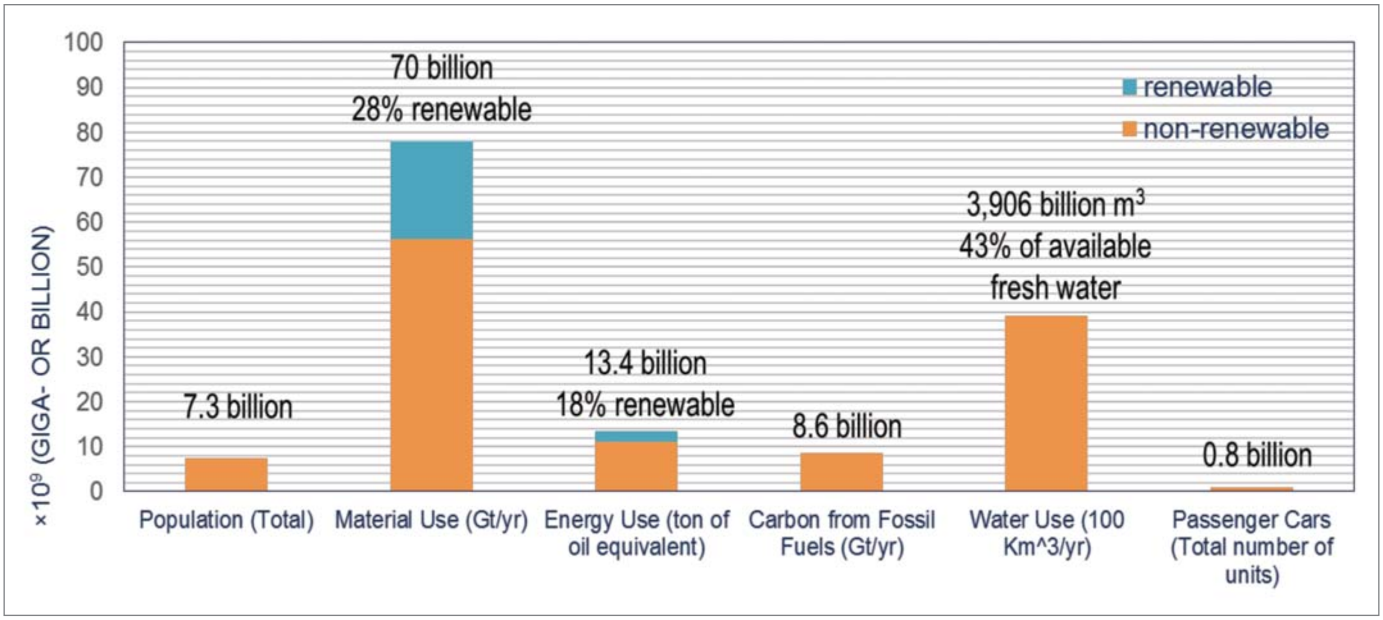


Figure 1: The gigaton scale of human activities.

- Global resource extraction as of 2011 was around 78 Gton, while the share of renewable resources was only 28 percent.[11]
- Annual global freshwater withdrawals in 2013 were around 3,906 billion cubic meters, which is about 43 percent of the world's readily available freshwater.[12] Around 70 percent of the water withdrawn is used for agricultural irrigation to produce food[13] (Figure 2).

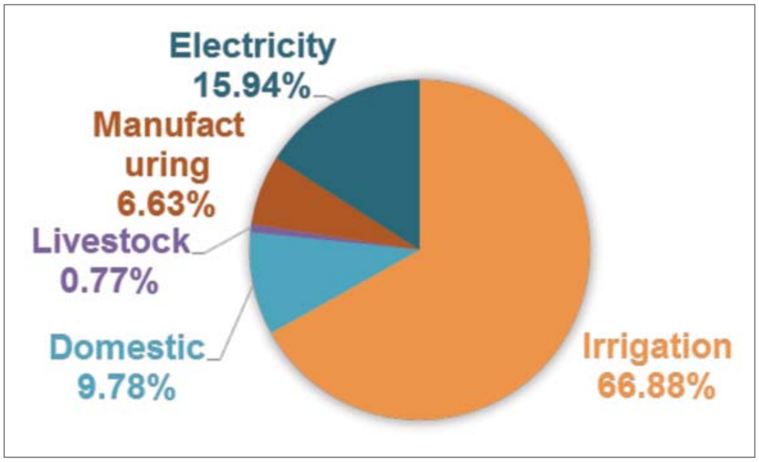


Figure 2: World water use by sector (note that livestock use significantly more water because irrigation water is embodied in livestock feed).

Notably, the demands shown in Figure 1 are attributable to about 1 billion people. From an egalitarian point-of-view, all citizens of the world should have the opportunity to live their lives in a similar way; therefore, the gigaton challenges shown in Figure 1 must be multiplied roughly by a factor of 10 for a global population of 10 billion. The massive consumption of energy, materials, and water on the giga ("billion") scale imposes significant stress on resource availability and impacts the environment.[14] It is referred to as the "Gigaton Problem."

1.2 Impacts of Water and Material Use Worldwide on Natural Cycles

Examining the anthropogenic (or, human-caused) impacts on natural cycles – in this case, the nitrogen, phosphorous, water, and carbon cycles – can help clarify the stresses caused by unsustainable consumption and production on the environment.

Anthropogenic interference in the nitrogen cycle is one of the largest geoengineering experiments conducted by humankind. The two greatest sources of anthropogenic nitrogen are (1) the burning of fossil fuels (which produces NOx) and (2) production of nitrogen fertilizer using the Haber-Bosch process.

Fertilizer production is energy-intensive, requiring 32 megajoules (MJ) [9 kilowatt-hours (kWh)] per kilogram (kg) of ammonia-nitrogen (NH_3-N) to "fix" nitrogen from the air and create ammonia. Notably, about two-thirds of the nitrogen in the form of protein in the human body is from nitrogen fixed from the atmosphere through the use of the Haber-Bosch process. After food is consumed, nitrogen is passed by humans into wastewater. The energy required to remove nitrogen from wastewater is 18 MJ (5 kWh)/kg NH_3-N. The energy consumed for ammonia production in 2010 was 1.82 terawatt-hours (TWh) (or 1.2 percent of total global energy consumption).

The use of phosphate fertilizer ushered in the "green revolution" for agricultural production. A vital resource for farming, the global phosphate reserve is projected to last 125 years, provided that the current reserve estimate is accurate and current trend of increased mining continues (some estimates state it may last 300 years). In a sense, phosphorus is more critical a resource than nitrogen. Unlike nitrogen, it cannot be harvested at will from the atmosphere.

Technologies for wastewater treatment facilities and livestock farms should be designed to recover nitrogen and phosphorous and to reduce anthropogenic interference on the nitrogen and phosphorous cycles. Nitrogen and phosphorous should also be kept out of surface waters to prevent hypoxia and eutrophication.

As for GHG emissions, current trends indicate an increase in the emission rate from 10 Gigatons of CO_2-C equivalent per year in 2015 to 16 Gigatons of CO_2-C equivalent per year by 2050,[15] resulting in an average global temperature rise of 6°C. To restrict this rise in temperature to 2°C and 4°C, global emissions will need to be cut to 10.9 and 4.4 Gigatons of CO_2-C equivalent per year by 2050, respectively. The consequences for temperature rises of 2°C and 5°C to 6°C include:

- At less than a 2°C temperature rise, the Arctic sea icecap will disappear during the summer and droughts will spread throughout the sub-tropics, accompanied by heat waves and intense wildfires.
- At a 5°C to 6°C temperature rise, the earth will be hotter than it has been for 50-million years. The entire Arctic would be ice-free year-round. Most of the tropics, sub-tropics, and lower mid-latitudes would be too hot to be habitable. Sea level rise would be rapid enough that coastal cities across the world would have to be abandoned.

1.3 Near-Term Impacts in California

In Southern California, the average temperature has increased by 3ºF over the past century.[16] Since 2012, a record-breaking drought has depleted water supplies throughout the State. The decreased availability and increased cost of water not only affects local communities, but also threatens food production, which in turn affects the U.S. economy. Moreover, the combined impact of temperature increase and drought makes forests more vulnerable to wildfire. Anthropogenic warming accounted for 8 to 27 percent of the observed California drought anomaly in 2012-2014; it is expected to increase in the future.[17]

The situation could become much worse, however. An earthquake near the California coastline could trigger a tsunami, which could destroy the terrain and lead to flooding. Due to climate change, plentiful rainfall brought on by El Niño (which is occurring in 2015 and 2016) could resolve the drought in California, but could also create new problems like mudslides and debris flows. For example, on October 15, 2015, a wall of mud up to 20-feet deep was created from a 1,000-year rain event (i.e., 1.18 inches of rain in 30 minutes) in the High Desert (Antelope Valley) of Southern California. A greater abundance of water, however, could hinder long-term efforts in water conservation. Consequently, Californians will have to prepare simultaneously for droughts and floods.

1.4 Resilience

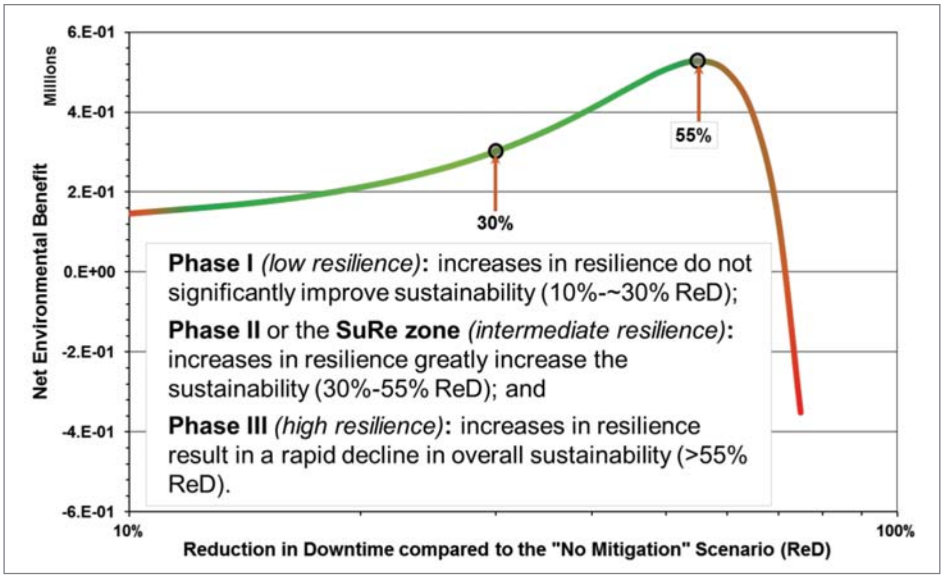
The resilience of human-nature coupled systems must be increased to survive both natural disasters and terrorist attacks. Resilient systems are able to maintain function in the face of exogenous (external) and endogenous (internal) stressors. They either bounce back after a shock or degrade gracefully and return to normal operation soon after repair.

As noted in Table 1, there are five components to resilience: robustness, redundancy, resourcefulness, rapidity, and renaissance.[18] Resiliency is a critical attribute of sustainability, as it enhances the flexibility and adaptability of the system and increases the long-term benefits of material and energy investments.

Table 1: Definitions of the Five Components of Resilience

Robustness	Ability of the system to withstand a given level of stress and/or demand.
Redundancy	Measure of inherent substitutability.
Resourcefulness	Measure of the capacity to mobilize resources for repair in the event of disruption.
Rapidity	Measure of the capacity to contain losses or prevent further degradation in a timely manner.
Renaissance	Measure of the ability to repurpose infrastructure or adaptive use capacity.

At the Brook Byers Institute for Sustainable Systems, we developed an approach to identify the sustainable and resilient (SuRe) zone of urban infrastructure development.[19, 20] A case study on the seismic retrofit of a potable water distribution system in California was used to verify the effectiveness of the approach (Figure 3). As part of this effort, it was estimated that an investment of close to a billion dollars (USD) would be needed to increase the resilience of 167 miles of distribution pipelines (which is the approximate length of the Hetch Hethcy pipelines) to reduce the downtime of the system by 8 days.[19] This investment is comparable to the $4.8-billion project recently undertaken by the San Francisco Public Utilities Commission to retrofit the entire water supply system for the San Francisco Bay region, including over 280 miles of pipeline and a water treatment plant for emergencies.[20]



Phase I *(low resilience)*: increases in resilience do not significantly improve sustainability (10%-~30% ReD);

Phase II or the **SuRe zone** *(intermediate resilience)*: increases in resilience greatly increase the sustainability (30%-55% ReD); and

Phase III *(high resilience)*: increases in resilience result in a rapid decline in overall sustainability (>55% ReD).

Figure 3: The sustainable and resilient (SuRe) zone (as shown by Phase II in the diagram) of urban water system planning and design. Note this curve is specific to the system, hazard, and location under consideration. The environmental benefit is measured in millions of person equivalents, and a positive value indicates a reduction in environmental impacts over the lifecycle of the project. Because the case study considered a population of 1 million, a value of 1 million in environmental benefits translates to reducing by half the environmental footprint of the case-study population over the lifetime of the project.

1.5 Traditional Versus Sustainable Engineering

To achieve greater sustainability and resilience, we need to move beyond traditional engineering approaches in which complex problems are broken apart into smaller pieces and solved individually. Moreover, merging individual optimal solutions may not necessarily lead to system-wide optimal outcomes. That is why sustainable engineering practices must be pursued that use "system thinking" to solve complex problems. Sustainable engineering tries to capture the impacts of human activities in three dimensions: environmental, economic, and social. It involves investigating how human needs can be met while ensuring anthropogenic impacts on the ecosystem are manageable.

Take, for example, New York City's watershed management program for drinking water supply. While investigating all supply and treatment options to provide clean, safe drinking water, the City discovered that protecting the watershed – rather than building a filtration plant – was the most economical, safe, and sustainable solution for creating a high-quality water supply. The key to successful watershed protection was creating partnerships between upstream landowners who can protect the watershed and downstream water users who benefit from the clean water.[21] These partnerships allowed the City to enjoy high-quality water at a lower cost than would have been the case if the filtration plant was constructed. In return for providing water quality services to the City, upstream landowners received additional income and funding to promote healthier streams and habitats. By developing a watershed protection program, the City avoided an estimated $8 to $10 billion in capital costs and $1 million in daily operational costs for filtration.[22]

2. System-View of Water: Where Water Goes

The flows of water in nature have been changed by the transformation of land, production of food and energy, and development of industry. Before we develop solutions for addressing water sustainability, it is worthwhile to look at where our water goes.

2.1 California's Water Balance

California's water balance is used as an example to illustrate the flows of water in a coupled human-nature system (Figure 4). In a normal year, about 200-million acre-feet (MAF) of water from precipitation and imports from neighboring states is available for water supply in California.[23] Almost 65 percent of this water is lost though evaporation, while the rest remains as runoff in the State's system (e.g., state and federal water projects, aqueducts from the mountains, State Water Project, and Colorado River). About 30 percent of this runoff flows directly into the ocean; the remainder (70 percent) is available for agriculture, energy production, and domestic water use.

In 2010, total water withdrawal for California was 42 MAF, of which 61 percent was used for agriculture and 17 percent for thermoelectric power production.[24] Among the 42 MAF of water withdrawn, 28 MAF was from surface water and 14 MAF from groundwater; however, only 7 MAF of water was used to recharge groundwater.

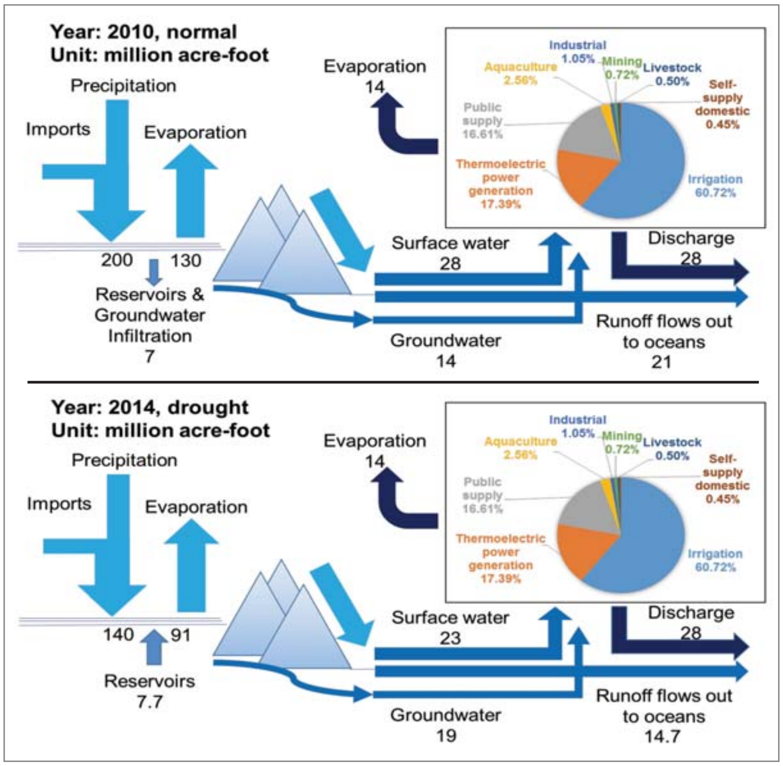


Figure 4: Water balance in California (2010 versus 2014).

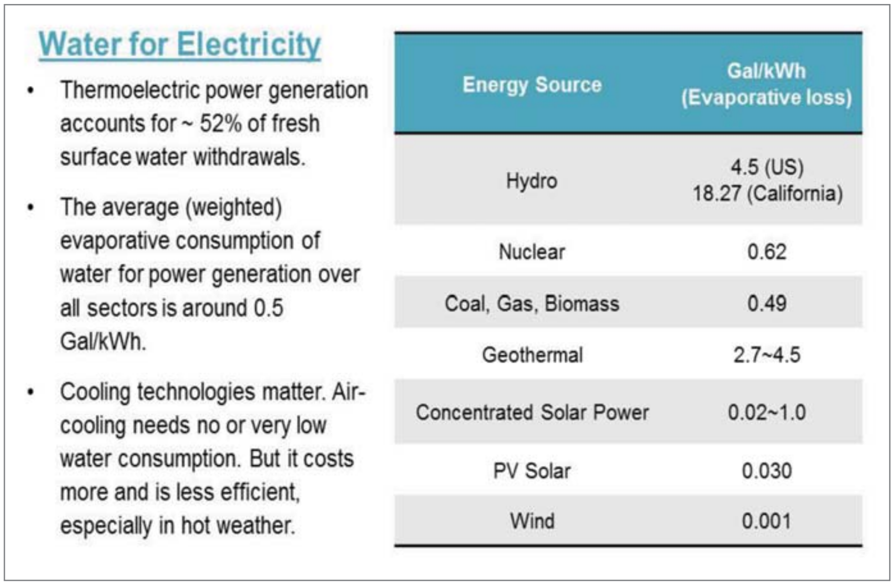
From a long-term perspective, the unsustainable use of aquifers in California could be a threat to the water cycle and ecosystem. Water scarcity is more severe in drought years when a shortage of precipitation reduces total available water. As a result, the State has to rely more on groundwater extraction. The drought and hot weather could also lead to an increase in water demand for showering, landscape irrigation, food production, and electricity generation. Considering the impacts of climate change, drought periods could be longer and more frequent than before. It is possible that water supplies will not keep pace with withdrawals in California.

2.2 Water-Energy Nexus

Water is needed to generate power (Figure 5). For example, total electricity usage throughout California in 2014 was 293 TWh.[25] Natural gas-fired electric generation accounted for 42 percent of total electricity used. Water withdrawal for electricity production totaled almost 7 MAF. Of this amount, about 27 percent was lost to evaporation, which represents about 1.86 MAF of consumptive water use. It should be noted that California's water footprint for energy is actually much higher because the State imports about 32 percent of its energy.

2.2.1 Thermoelectric Power Generation

On average, 52 percent of surface freshwater withdrawals in the U.S. are used for cooling purposes during thermoelectric power generation.[26] Thermoelectric power plants reject heat by evaporating water. There are several options for cooling: (1) once through; and (2) closed loop. While once-through cooling withdraws more water than a closed-looped cooling tower, the consumptive water use in the latter technology is higher. Air cooling can reduce water withdrawal and consumption; however, air cooling costs more and is less efficient, especially in hot weather.



Water for Electricity

- Thermoelectric power generation accounts for ~ 52% of fresh surface water withdrawals.
- The average (weighted) evaporative consumption of water for power generation over all sectors is around 0.5 Gal/kWh.
- Cooling technologies matter. Air-cooling needs no or very low water consumption. But it costs more and is less efficient, especially in hot weather.

Energy Source	Gal/kWh (Evaporative loss)
Hydro	4.5 (US) 18.27 (California)
Nuclear	0.62
Coal, Gas, Biomass	0.49
Geothermal	2.7~4.5
Concentrated Solar Power	0.02~1.0
PV Solar	0.030
Wind	0.001

Figure 5: Water use for various power production options.

2.2.2 Renewable Electricity

Some renewable electricity sources, such as wind and photovoltaic (PV) solar, consume less water because water is only needed to manufacture these renewable sources. One notable exception is hydroelectric power, which typically generates electricity from water stored in a reservoir. In the U.S., hydroelectric power has an average water consumption rate of 4.5 gallons/kWh due to evaporation from reservoirs.[27] The consumptive water use of hydroelectric power in California is 18.27 gallons/kWh, which is significantly higher than the U.S. average. Hydroelectric power contributes to 65 percent of total water consumption for energy production in California.

2.2.3 Biofuels

Water is used for primary energy generation, such as fuel extraction and processing (Figure 6). Although considered a sustainable energy source because of lower GHS emissions, biofuels consume much more water than conventional fuels like natural gas and oil.[28] The promotion of biofuels also accelerates deforestation and threatens food security. It is important to evaluate alternative renewable fuels (e.g., biodiesel recovery from wastes) and reduce the consumption of crude oil; however, we need to examine the water footprint to see whether water is available to use these alternative technologies at scale.

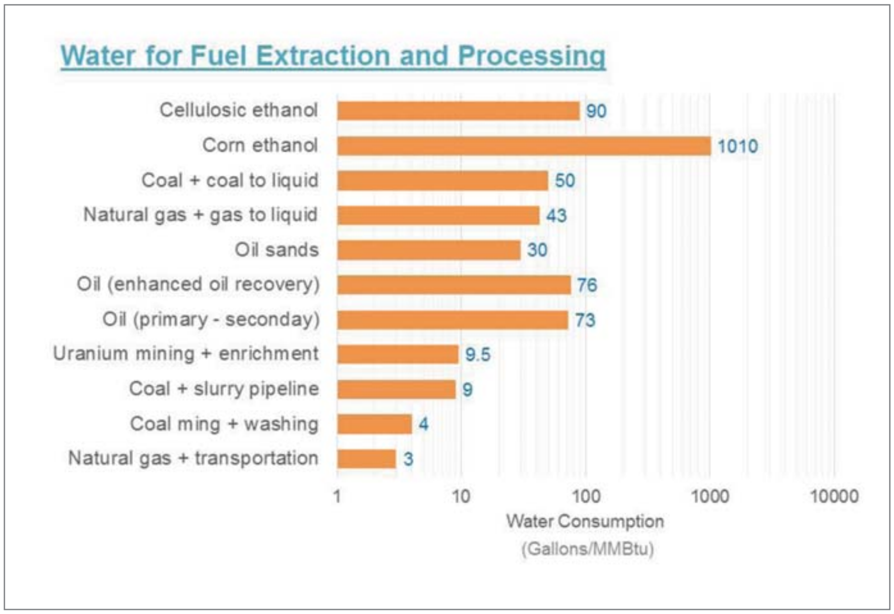


Figure 6: Water for primary energy production.

2.2.4 Energy for Water Supply and Use

Energy is needed to collect, treat, and distribute water. In 2010, the water system consumed over 600-billion kWh, or approximately 12.6 percent of the energy in the U.S.[29] In California, water-related electricity use is 48 TWh per year, accounting for nearly 20 percent of California's total electricity consumption.[30] Of that amount, about 28 percent is used in residential homes for activities like heating water and washing clothes, while about 22 percent is used for water pumping, extraction, transfer, and distribution (Figure 7).[31]

2.2.5 Sustainable Water-Energy Nexus

The interdependence between water and energy systems forms the “Water-Energy Nexus.” Recognizing this connection, or “nexus,” is the first step towards developing engineering solutions for sustainable water and energy supplies. For example, desalination is considered an important strategy to increase freshwater supply; however, it requires a large input of energy, which has significant environmental and human health impacts. To ensure a sustainable water-energy nexus, renewable energy sources (e.g., solar, wind, and tidal energy) should be integrated with desalination.

2.3 Water for Agriculture

Food production depends on the availability and reliability of water resources. Unfortunately, food and agriculture consume 100 times more water than used for personal needs like washing clothes and bathing. The sustainable management of water for agriculture is key to improving food productivity.

2.3.1 Water Use Efficiency

California is the largest producer of food in the U.S., providing over 400 commodities.[32] Agriculture uses approximately 61 percent of the State’s total water supply.[24] Water use and efficiency for various crops grown in California are shown in Figure 8. Water efficiency is defined as the percentage of the total amount of water applied by irrigation that is retained within the root zone and is available for crop evapotranspiration. Farmers have improved water use efficiency with solutions such as efficient irrigation technology (e.g., drip irrigation), improved irrigation scheduling, and regulated deficit irrigation (e.g., using less water for certain crops that have drought-tolerant life stages).[33] From a sustainable engineering perspective, however, these solutions may not be sufficient to address the growing demand for water.

2.3.2 Livestock Production

Livestock production consumes the most water.[34] For example, 1 kilogram (kg) of chicken meat requires 1,000 gallons of water, 1 kg of pork requires 1,500 gallons of water, and 1 kg of beef requires 4,400 gallons of water.

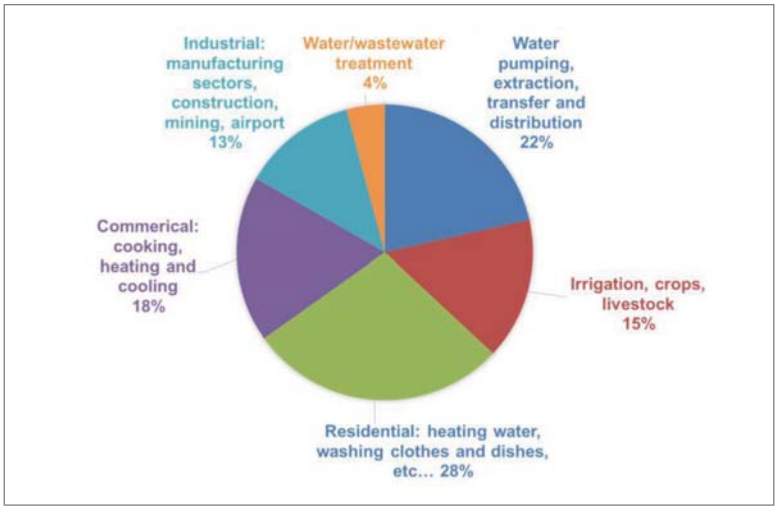


Figure 7: Energy for water provision in California.

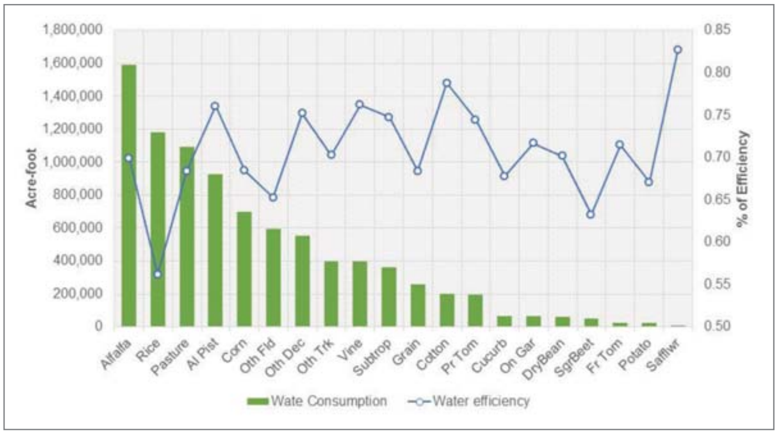


Figure 8: Water for agriculture in California. Grain: Wheat, barley, oats, miscellaneous grain and hay, and mixed grain and hay. Rice: Rice and wild rice. Cotton: Cotton. grBeet: Sugar beets. Corn: Corn (field and sweet). DryBean: Beans (dry). Safflwr: Safflower. Oth Fld: Flax, hops, grain sorghum, Sudan grass, castor beans, miscellaneous fields, sunflowers, hybrid sorghum/Sudan grass, millet, and sugar cane. Alfalfa: Alfalfa and alfalfa mixtures. Pasture: Clover, mixed pasture, native pastures, induced high water table native pasture, miscellaneous grasses, turf farms, Bermuda grass, rye grass, and Kleingrass. Pro Tom: Tomatoes for processing. Fr Tom: Tomatoes for market. Cucurb: Melons, squash, and cucumbers. On Gar: Onions and garlic. Potato: Potatoes. Oth Trk: Artichokes, asparagus, beans (green), carrots, celery, lettuce, peas, spinach, flower nurseries and tree farms, bush berries, strawberries, peppers, broccoli, cabbage, cauliflower, and Brussels sprouts. Al Pist: Almonds and pistachios. Oth Dec: Apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs, walnuts, and miscellaneous deciduous trees. Subtrop: Grapefruit, lemons, oranges, dates, avocados, olives, kiwis, jojoba, eucalyptus, and miscellaneous subtropical fruit. Vine: Table grapes, wine grapes, and raisin grapes.

In addition, about 30 percent of the world’s ice-free landmass is used to grow livestock feed, and 4.5 percent of all GHG emissions is produced by livestock.

Healthy, environmentally friendly eating habits should be encouraged to reduce the water, energy, and carbon footprints associated with livestock production. One potential meat substitute is “green” food from plants. An estimated 400,000 species of plants currently exist; each plant species has tens of thousands of proteins that could satisfy human needs. The challenge is to produce plant-based foods that are cost-competitive and mimic the flavor and texture of meat-based products. Some progress has been made in this area, such as:

- Plant-based chicken strips produced by Beyond Meat.
- Eggless mayonnaise produced by Hampton Creek.
- Plant-based “beef” burger patty produced by Impossible Foods.
- A beverage that serves a complete substitute for food called Soylent.

2.3.3 Food Waste

To save water for agriculture, the amount of food wasted per day must also be reduced. In North America and Oceania, the amount of food wasted per day is about 40 percent of the amount of food consumed for personal daily needs on a caloric basis [1,500 kilocalories per capita per day (Kcal/capita/day)]. Among the food waste, 61 percent of calories is lost during the consumption stage when purchased food is not eaten.[35] In California, food waste is 100-billion pounds per year, which equals 3,700 Kcal/capita/day.

2.3.4 Local Production

Food that is produced locally using more efficient cultivation practices could reduce the water, energy, and carbon footprints resulting from agricultural production. For example, Romaine lettuce sold in supermarkets in Georgia could originate from farms in California more than 2,000 miles away. A local practitioner in Georgia has developed a closed-environment fresh food crop plant using proven hydroponic cultivation and closed-loop carbon, energy, and nutrient structures. According to the practitioner’s report,[36] the carbon footprint of Romaine lettuce per head is reduced by 75 percent, water use is reduced by about 79 to ~95 percent, and land use is reduced by 95 percent as compared to lettuce grown in California and sold in Georgia.

2.4 Water for Industry

Industry is the engine of the U.S. economy, producing goods and services and creating jobs and wealth. A lack of sustainable water sources could threaten industrial production. Water is also required for the production of metals, plastics, cement, and other materials (Figure 9).

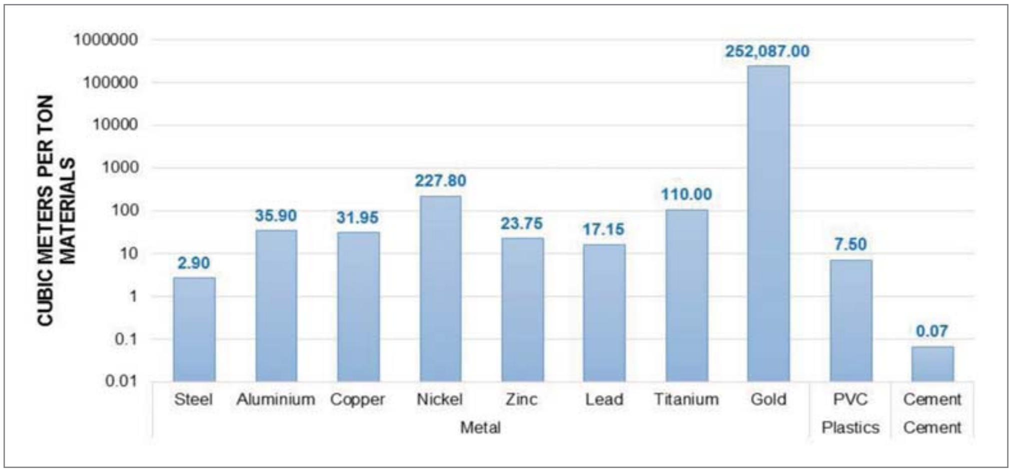


Figure 9: Water use for the production of various commodities. In 2013, gold production was 146,500 ounces. Gold dominated California’s metal production and comprised over 99 percent of the value of the State’s metal production. The water consumption of gold production was 848 AF.

In terms of water usage (in gallons) per U.S. dollar of output, water productivity varies depending on the industrial sector[37] (Figure 10). On average, the agriculture sector has the lowest water productivity, while the financial and insurance sectors have the highest. Improving water productivity is necessary to achieve sustainable water use for industries. Moreover, the degradation of water quality and ecosystem destruction due to industrial activities, especially in developing countries, should raise serious concern.

2.5 Water for Transportation

The transportation sector does not directly consume water; rather, water is consumed during vehicle and fuel production (Figure 11). The use of biofuels consumes more water than unleaded gasoline;[38] however, manufacturing electric vehicles has a higher water footprint than manufacturing conventional vehicles because of current electrical power generation practices. Introducing less water-intensive electrical power generation is critical to the long-term water sustainability of electric vehicles.

For example, if Metropolitan Atlanta had a 100-percent penetration rate of electric vehicles powered by existing electricity generation practices, the transportation sector would need to consume 90-million gallons per day of water, which is nearly as much water consumed for domestic use (105-million gallons per day). As a result, the State of Georgia could experience water shortages. Furthermore, communities outside of Georgia could also be affected due to water rights issues.

Public transportation is one possible solution that could systemically reduce the water, energy, carbon, and land use footprint of the transportation sector. To ensure the benefits of public transportation, ridership is the critical factor, relying on systematic land use planning and a full examination of the water-transportation nexus.

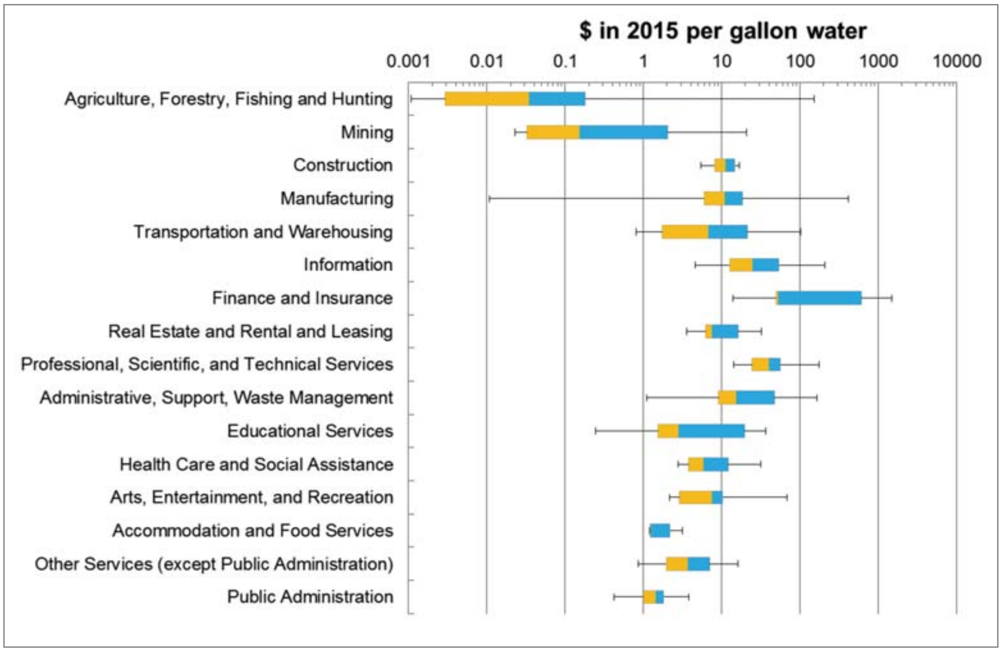


Figure 10: Productivity of water in various industrial sectors.

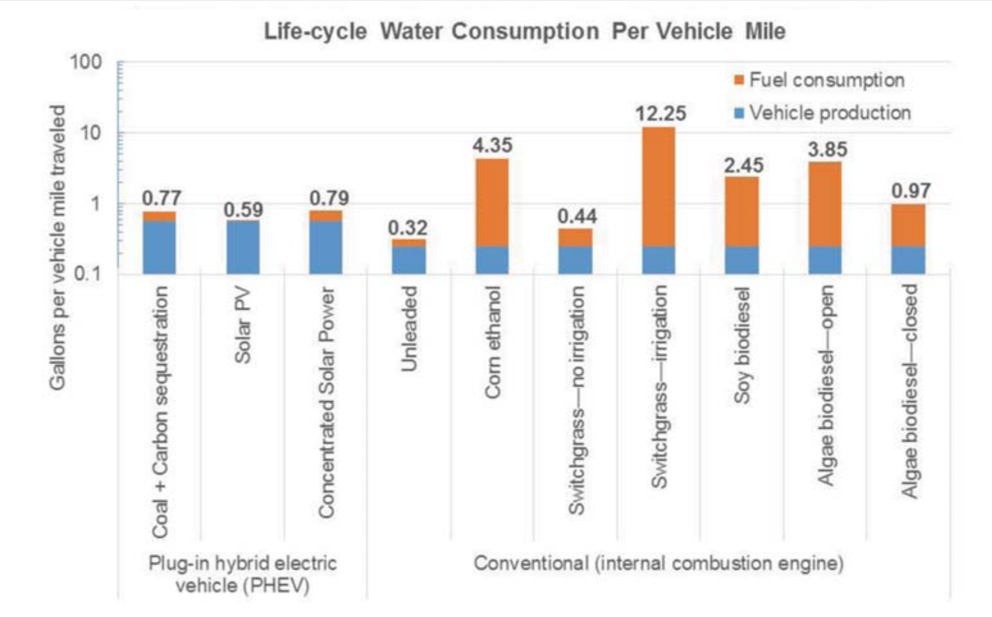


Figure 11: Water use for personal car transport (in gallons per vehicle mile traveled).

3. Systems-Based Thinking and Infrastructure Ecology: How to Build Infrastructure in a More Sustainable and Resilient Way

Achieving water sustainability is not about building more pipelines, pumping stations, and treatment plants for the collection, treatment, and distribution of water, wastewater, and stormwater; rather, it is about designing urban infrastructure systems (UISs) that are more integrated, sustainable, and resilient.

In the past, infrastructure was optimized in a "stovepipe" manner. For example, the provision of water and energy were designed as separate systems that function independently without any connection to each other. This approach is viable only because of the availability of inexpensive carbon-based fuels and non-renewable resources. But failing to recognize the interdependencies between infrastructure components can result in sub-optimal systems.

A new science is needed that recognizes the interdependence between infrastructures and advocates systems-based approaches for the design of UISs.[39]

3.1 Infrastructure Ecology

Transportation, water supply, power, communications, and information systems are all parts of an IUS, which shares many commonalities with ecological systems[40] in that they both:

- Exchange information, material, and energy among themselves.
- Draw resources from and transfer waste to the environment.
- Are complex, dynamic, and adaptive.
- Are comprised of interconnected components exchanging flows of energy and matter.
- Share some general architectural dynamics across time and space.
- Create novelty.
- Cannot be evaluated or understood by looking at any component element, but instead must be examined as a system.

Inspired by ecological principles, the transdisciplinary science of "Infrastructure Ecology" was created to characterize the complex interdependence of UISs and, ultimately, help improve the sustainability of urban infrastructure. Infrastructure Ecology views urban systems as complex adaptive systems, the sustainability and resilience of which emerge from the interactions and co-evolution of a city's interdependent engineering, ecological, and socio-economic infrastructures through time and space. Socioeconomics is a crucial element, acting as the "decision driver" behind the design, operation, and use of UISs.

The "12 Principles of Infrastructure Ecology" (Table 2), similar to the "12 Principles of Green Engineering" proposed by Anastas and Zimmerman,[41] provide a framework for urban planners, engineers, and other decision-makers to use when planning or designing new UISs or rehabilitating aged ones. Designing UISs using these principles can lead to:

- A better understanding of the dynamics of the interconnections between different UIS components.
- Adaptive design and holistic optimization to meet growing demands and reduce water, energy, and material usage.

Table 2. The 12 Principles of Infrastructure Ecology
1. Interconnected rather than segregated
2. Integrate materials, energy, and water flows
3. Manage inherent complexity
4. Consider system dynamics
5. Decentralize to increase response diversity, resilience, and modularity
6. Maximize the sustainability and resilience of material and energy investments
7. Synergize engineered and ecological systems
8. Design to meet stakeholder preferences
9. Maximize the creation of comfort and wealth
10. Socioeconomics is the decision driver
11. Adaptive management is a requisite policy strategy
12. Use "renewable flows" rather than "depleting stocks"

Building upon these principles, we have proposed a new set of conceptual designs that adopts transformative technologies to improve water sustainability, as discussed below.

3.1.1 System-Level Design of Decentralized Water Infrastructures

We examined the environmental impacts of implementing decentralized water infrastructures, such as low-impact development (LID) and greywater reclamation. LID techniques – which include bioretention basins, rain gardens, green roofs, cisterns for rainwater harvesting, and permeable pavement, among others – can be passive natural treatment strategies requiring negligible amounts of energy for stormwater detention and treatment. Not only is the quality of runoff improved, but LID techniques also regulate the quantity of runoff. They reduce the runoff volume, flatten and often reduce the runoff peak, and increase infiltration (depending on hydrologic conditions), thereby enhancing groundwater recharge.

At the neighborhood level, we examined the energy and water savings resulting from rainwater harvesting, greywater recycling, and combinations thereof for 10 different residential zoning districts in the City of Atlanta, Georgia (which has a population of 500,000 residents).

For a single-family housing community with a population density of 1.6 to 17.0 persons per acre, results indicated:

- One-hundred percent of the nonpotable water use (i.e., toilet flushing, irrigation, and laundry) could be met using rainwater harvesting, which is 60 percent of the total water demand. The nonpotable demand could be met using greywater reclamation.
- Lifecycle assessment scores for environmental sustainability were 72.5 and 40 percent lower, respectively, as compared to centralized water and wastewater facilities.

For apartment-dwelling multifamily communities with population densities of 15.0 to 290.0 per acre, 100 percent of nonpotable use could be satisfied with rainwater harvesting and greywater reclamation, which is 60 percent of the total water demand. Rainwater supplied less of the demand, however, as population density increased.

For all community designs, runoff from an 8-inch/24-hour storm (which has a 100-year return period) was controllable if rain gardens occupy 15 percent of the land surface.

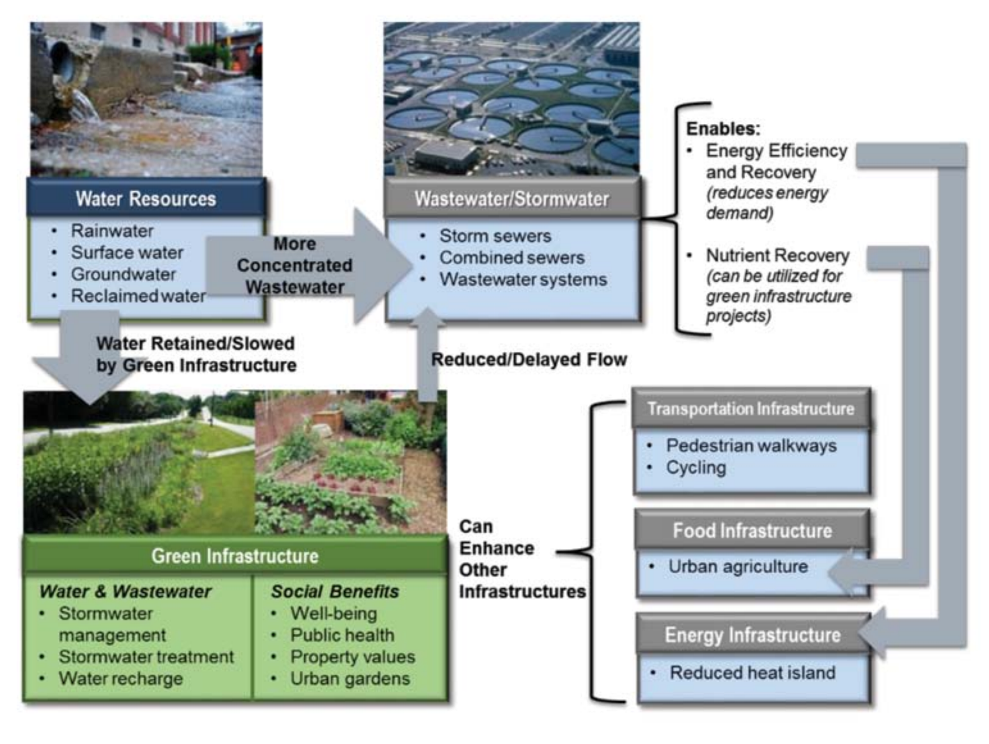


Figure 12: System-level benefits of LID best management practices (Credit: Greg Keolian).

From a system-level perspective, the large-scale implementation of decentralized water infrastructure can reduce dependency on centralized water infrastructure, as well as reduce the amount of energy used to operate water systems (Figure 12). The use of decentralized water infrastructure also eliminated runoff and pollutants from impervious surfaces, minimizing the risk of urban flooding and ecosystem damage.

Large-scale water reuse can increase the concentrations of biodegradable organic matter and nutrients in wastewater, making it easier to recover heat, energy, and nutrients. Recovered energy can be used to operate wastewater treatment systems, while recovered nutrients can maintain LID facilities or urban farms. LID can also help mitigate the “heat island” effect (i.e., built up areas that are hotter than nearby rural areas, which in turn impact energy demand, air pollution, GHG emissions, water quality, and others) and improve local walkability and livability. The creation of green alleyways for stormwater to flow to surface waters can be used for bicycling and can broaden the options available for transportation. In addition, property tax revenues could increase, allowing municipalities to properly maintain water infrastructure systems.

3.1.2 System-Level Design of Decentralized Energy Infrastructures

We have proposed an alternative off-grid electricity production system that consumes less water (Figure 13). The core of the centralized system is combined cooling, heat, and power (CCHP) using air-cooled microturbines and an absorption chiller. The CCHP at the Atlanta office of Perkins + Will meets the entire heating and cooling loads, supplying 40 percent of total electricity. The system reduces water demand by more than 50 percent (avoiding water used for grid electricity production), reduces carbon emissions by 15 to 40 percent, and reduces NOx emissions by 50 percent. The control of NOx emissions also could reduce surface ozone levels. By adding thermal storage to the CCHP system, it is possible to meet daytime electricity demand (when it is needed most), plus heat that is generated can be stored for nighttime use. The CCHP system also allows for more penetration of renewable energy sources, such as solar PV and wind (because it can make up for the variability of PV and wind output).

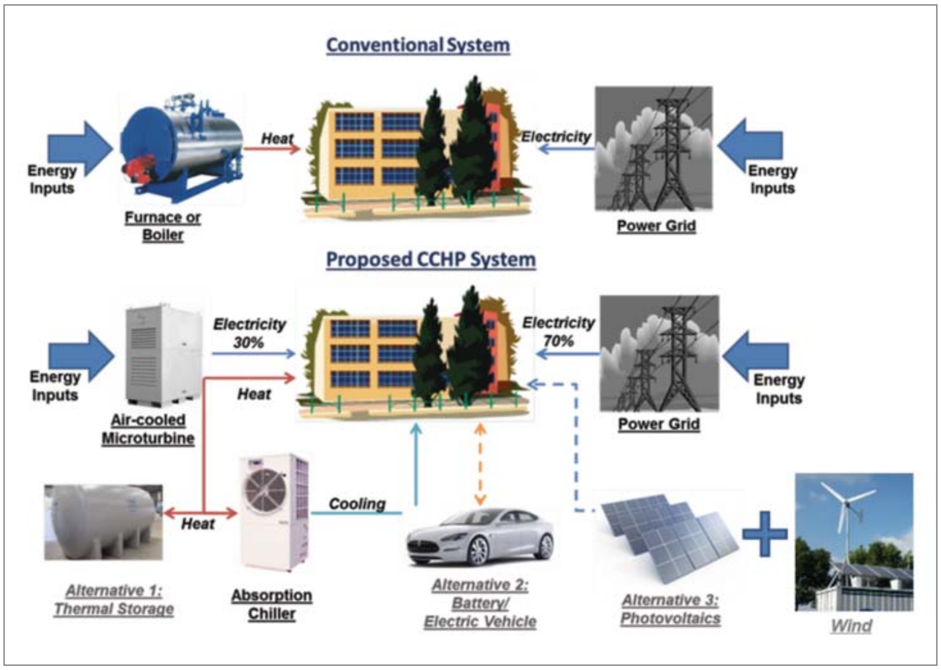


Figure 13: The off-grid energy system: Expanding the current CCHP system.

An off-grid system composed of CCHP, thermal storage, and renewable energy sources can be further integrated with an electric Vehicle-to-Grid (V2G) system to promote the electrification of transportation. V2G allows energy to be exchanged to and from a vehicle using the battery as an energy-storage device. During the day, the V2G system can charge batteries while cars are idle. Batteries could also be added for additional energy storage to make up for variations in renewable energy output. Such a system could potentially improve the sustainability and resilience of the energy infrastructure system and, more importantly, reduce water demand.

3.1.3 Integrated Urban Infrastructures for Food, Energy, and Water

Urban farming is perceived as a potential solution to reducing the environmental footprint of the agriculture sector in terms of water consumption, carbon emissions, and soil erosion (Table 3). The key to the success of urban farming relies on how the food, energy, and water infrastructure systems are built to operate urban farms. As shown in Figure 14, water can be collected from rainwater harvesting and stormwater treated by LID methods.

Diverting stormwater from the wastewater system creates a more concentrated wastewater, allowing for easier recovery of nutrients and energy. Nutrients can be recovered as Struvite, a slow-release fertilizer. The fertilizer can be used by urban farmers for vegetable production. Energy (i.e., methane) can be recovered from anaerobic digestion. Methane can be used in a CCHP system to heat and/or cool greenhouses and to provide electric power for lighting to grow plants onsite. Electricity could also be used to charge electric vehicles that deliver farm products to customers and markets. Assuming that pollutants can be removed, exhaust carbon from the

Table 3. Controlled Environment Agriculture (CEA) Hydroponic Indoor Farms Versus Traditional Field Growth

	CEA Fresh Farms Romaine (Local Grown, Georgia)	Field-Grown Romaine (California)
Land requirements	20 acres	620 acres
Leafy green production yields per year	33 million heads	33 million heads
Fossil fuel used during the growth cycle (not including crop transport)	200 gallons equiv. diesel	3,720 gallons diesel
Food miles	100 miles per truckload	2,577 miles per truckload
Fossil fuel used to transport 100 miles (or California to local markets)	22,200 gallons diesel	571,000 gallons diesel
Carbon footprint*	3,000 metric ton CO_2	12,000 metric ton CO_2
Freshwater used during the growth cycle	1.2 gallons per head	9 to 42 gallons per head
Freshwater used to wash lettuce per head for market	0.7 (one washing per head)	2.5 (three washings per head)
Total freshwater used annually	64 million gallons	0.3 to 1.5 billion gallons
Time from harvest to market	6 to 12 hours	4 to 7 days

**Note: CEA has not built farms at scale. The optimistic yield and cycle need verification.*

CCHP system can be captured and injected into the greenhouse environment for fostering greater photosynthesis and food production. NOx in the off-gas could possibly be used as a source of nutrients as well. The recovery of nutrients and energy has much potential; the next step is to build these systems and evaluate their performance for sustainability and resiliency.

3.1.4 Transforming the Transportation-Land Use Nexus: Transit-Oriented Development and Autonomous Vehicles

Land use is a critical factor that influences the demand for urban infrastructure. Sprawling, low-density development tends to consume more land, water (to produce transportation energy, including electricity; see Figure 11), materials, and energy than compact, high-density development with the same population.

One driving force that determines the land use pattern is the "transportation-land use nexus." The allocation of transportation facilities and buildings is interrelated. For instance, access to roads can affect investments in residential and commercial buildings, and the location of services, food, hospitals, and schools can influence the expansion of roads and public transportation.

The creation of a sustainable transportation-land use nexus is the key to the emergence of sustainable UISs. Transit-oriented development (TOD) is a promising design solution that could make land use more sustainable (by definition, TOD must produce housing that is within 10 minutes of walking distance to public transportation). It creates compact, walkable, mixed-use communities centered on high-quality public transit services. The large-scale implementation of TOD could provide affordable houses, walkable communities, and multiple modes of transportation (e.g., walking, bicycling, and mass transit). Moreover, the return on investment of transit systems improves when more people have easy access to mass transit.

Another alternative is shared autonomous vehicles, a promising technology combining short-term on-demand rentals with self-driving capabilities. It is estimated that an 80-percent penetration of shared autonomous vehicles could replace 72 percent of the cars in use today.[42] Consequently, we could reduce at least 72-percent parking spaces, which would be equivalent to an average 24.7-percent reduction in imperious area that can cause stormwater runoff. As a result, cities could gain up to 17-percent additional area for green space and stormwater management. In addition, rising land value and property tax revenues could provide for the maintenance of mass transit and autonomous vehicle services. Autonomous vehicles could also extend the range required for TOD, allowing the creation of more green space combined with high-density walkable communities.

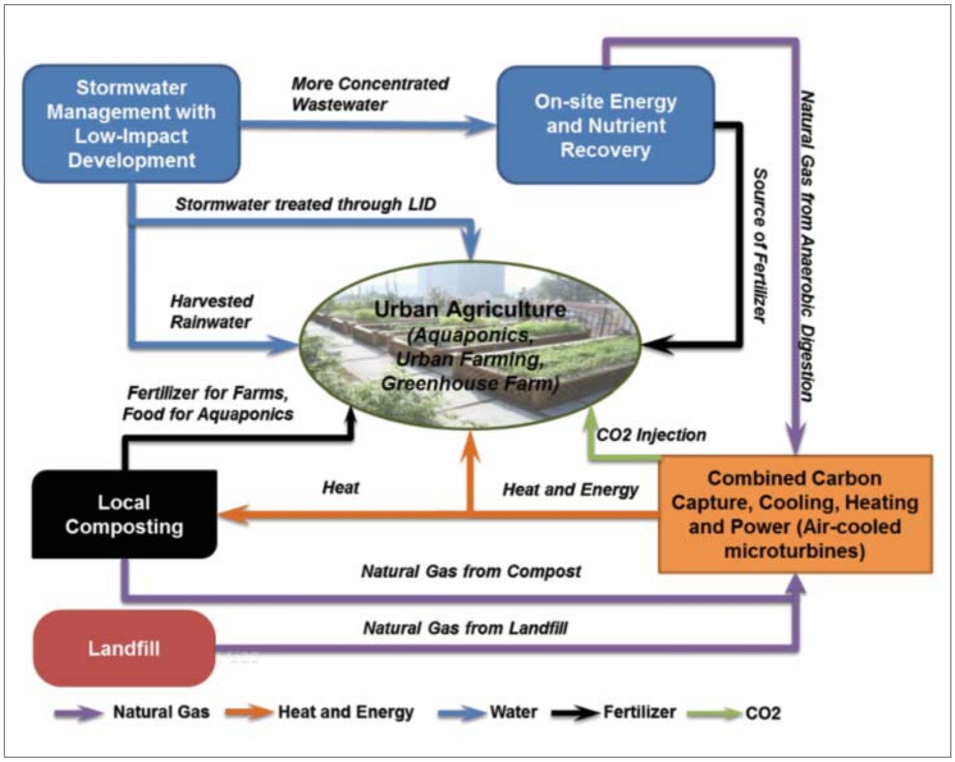


Figure 14: Urban farming: The opportunity to close the urban water, nutrients, energy, and carbon loops.

3.2 Synergistic Effects of Infrastructural Symbiosis

The Infrastructure Ecology approach makes it possible to consider the potential synergistic effects arising from "infrastructural symbiosis" by altering and reorganizing energy and resource flows. Infrastructural symbiosis can be defined as "the synergistic and symbiotic interrelations that exist in terms of flows between the different interconnected systems in a UIS." For instance, if decentralized water and energy infrastructures, TOD, and shared autonomous vehicles are combined in one feasible strategy, we might see the emergence of preferred neighborhoods that focus on compact growth (Figure 15). The accumulated synergistic effects would be significant, as these combinations could:

- Reduce water and energy consumption.
- Lower dependence on centralized systems.
- Increase the share of renewables in the electricity mix.
- Reduce vehicle-miles traveled.
- Increase tax revenue.
- Increase the resilience of infrastructures systems.

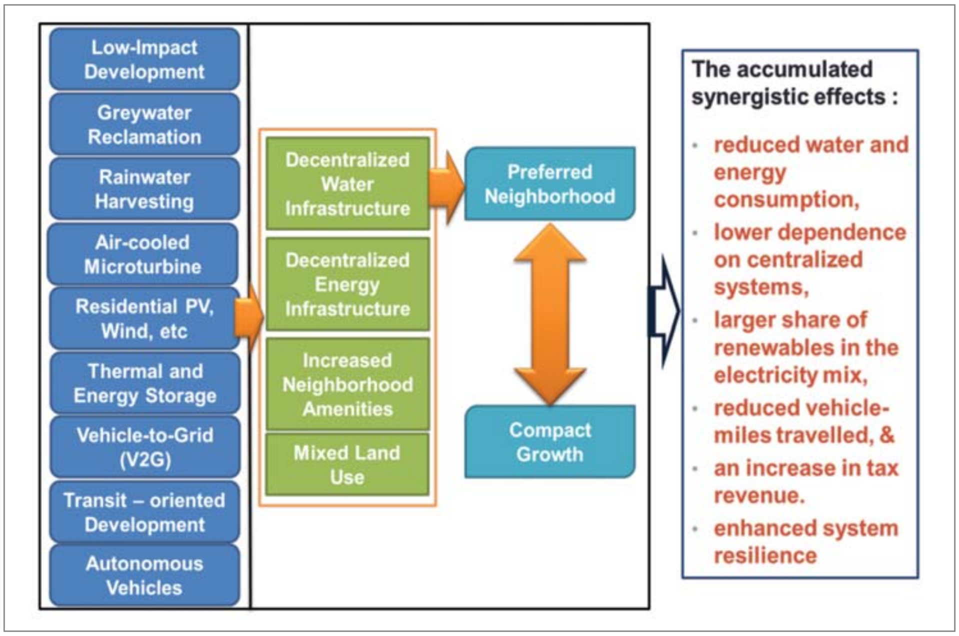


Figure 15: The synergistic effects of infrastructural symbiosis.

4. Managing the Complexity of Urban Infrastructures

UISs are complex adaptive systems interacting with the natural and socioeconomic environments. The development of sustainable UISs requires both an understanding and ability to manage this complexity.

4.1 Understanding the Complexity

Complexity results from the millions of decisions and interactions of diverse adaptive entities (i.e., citizens, firms, developers, and governments).[43] These decisions and interactions drive the dynamic and evolving interdependence between the urban physical infrastructure and socioeconomic environment through which it operates. Such interdependence leads to the emergence of specific land use patterns, quality of life issues, and carbon and water footprints, among others. By managing complexity, the right combination of features can be identified to develop and adopt more sustainable infrastructure.

4.2 Framework to Manage the Complexity

The fundamental question is how to manage complexity. We have been working to establish protocols and standards for interconnecting design, planning, and operations models of different infrastructure systems. The goal is to create a prototypical cyber-infrastructure system, or "meta-model," that can interconnect multiple models of grey and green infrastructure systems across different locations and time and space. Using the meta-model, one could:

- Develop scenarios of the demand and location for urban infrastructure due to development and redevelopment activities based on urban growth models (e.g., UrbanSim).
- Determine infrastructure system options (e.g., zero-energy buildings, construction methods, and material choices) available to meet this demand and (re)design the virtual city.
- Choose a transportation system design, including teleworking and autonomous vehicles, and determine traffic flows and travel times using micro-simulation models (e.g., TranSims).
- Determine the materials (including water) and energy needed to construct and maintain urban infrastructure.
- Assess the vulnerability of infrastructure to natural hazards (e.g., floods, earthquakes, and hurricanes) and manmade challenges (e.g., resource constraints or supply chain disruptions).
- Determine local, regional (e.g., water footprint), and global impacts (e.g., carbon footprint) of various scenarios using Life Cycle Impact Assessment (LCIA).
- Predict "heat island" effects using microclimate models and determine any resulting increases to water and energy demands.
- Visualize various sustainability and resiliency metrics (e.g., carbon and water footprints; material use and energy demands; and social and economic impacts).

We developed a version of the meta-model to describe the interactions between several decision-makers (i.e., local governments, developers, and home buyers) and fiscal drivers (e.g., property taxes and impact fees).[44] Using this model, we predicted:

- The adoption of apartment and single-family homes when impact fees are imposed for noncompliance with LID requirements to implement stormwater management.
- An increased adoption of apartment homes over single family homes (i.e., an increase of 24 percent in the impact-fee scenario over the no-impact-fee scenario) resulting from the lower cost of using LID and improved quality of life for apartment homes relative to single-family houses (i.e., LID landscaping, better public transportation services, and lower property tax).
- A 40-percent reduction in potable water demand from centralized plants and a 36-percent increase in net property tax revenue due to the impact-fee (versus the no-impact-fee scenario).

Another example of the meta-model application is the assessment of large-scale implementation of CCHP in Metropolitan Atlanta to reduce water consumption, CO_2, and NOx. An urban growth simulation tool was used to predict urban development for the Metro Atlanta region for growth scenarios, business-as-usual (BAU) scenarios, and more compact development (MCD) scenarios.[45] For example:

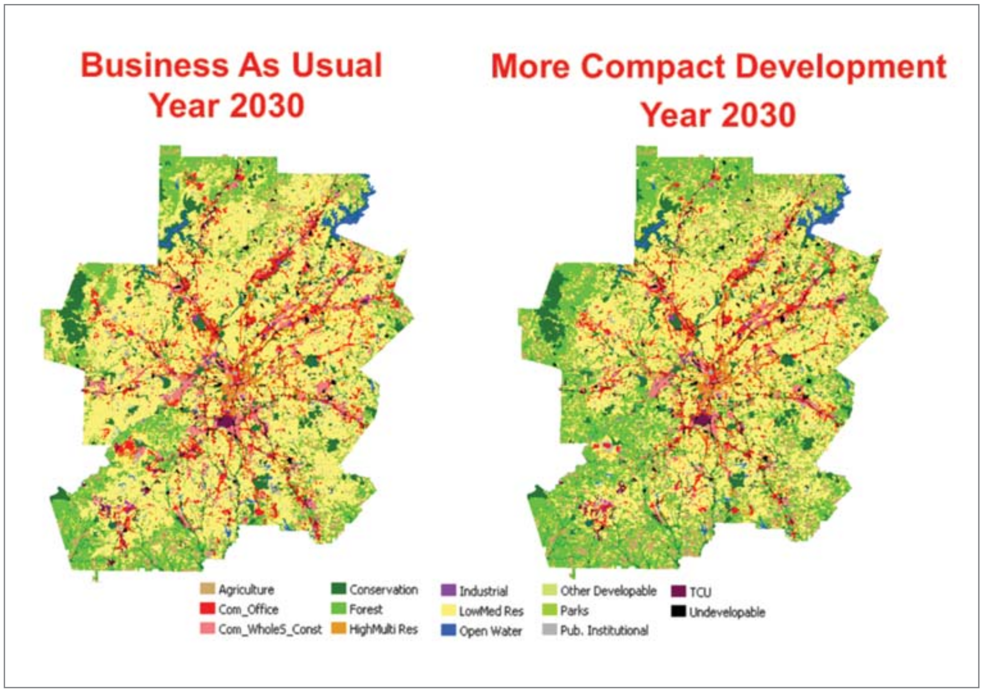


Figure 16: Projected growth scenarios for Atlanta, Georgia.

- For the MCD scenario, we predicted that 192,000 single family homes and 614,000 buildings containing multifamily homes (e.g., apartment homes or condos) would be added in Atlanta by 2030.
- For the BAU scenario, we predicted 305,000 single family homes and 501,000 buildings containing multifamily homes would be added in the Metro Atlanta region by 2030 (which can be seen as more sprawl in Figure 16, represented in yellow).
- As a comparison, in 2005, greater Atlanta had 458,000 single family homes and 1,200,000 buildings that contained multifamily homes.

A forecasted increase in energy production using MCD and air-cooled microturbines in a CCHP framework indicates that environmental impacts could be reduced significantly, as shown in Figure 17. If the CCHP system was designed to meet the cooling and heating demands of new residential and commercial buildings in Metro Atlanta from 2015 to 2030, the corresponding water withdrawal and consumption rates for energy production are reduced by 57 and 53 percent, respectively. The installation of CCHP saves 2.4 times the amount of water used for domestic consumption and \$680 million per year in energy costs. At the same time, CO_2 and NOx emissions are reduced by 23 and 65 percent, respectively. The next step is to examine the health benefits of CCHP by reducing NOx emissions and improving regional air quality.

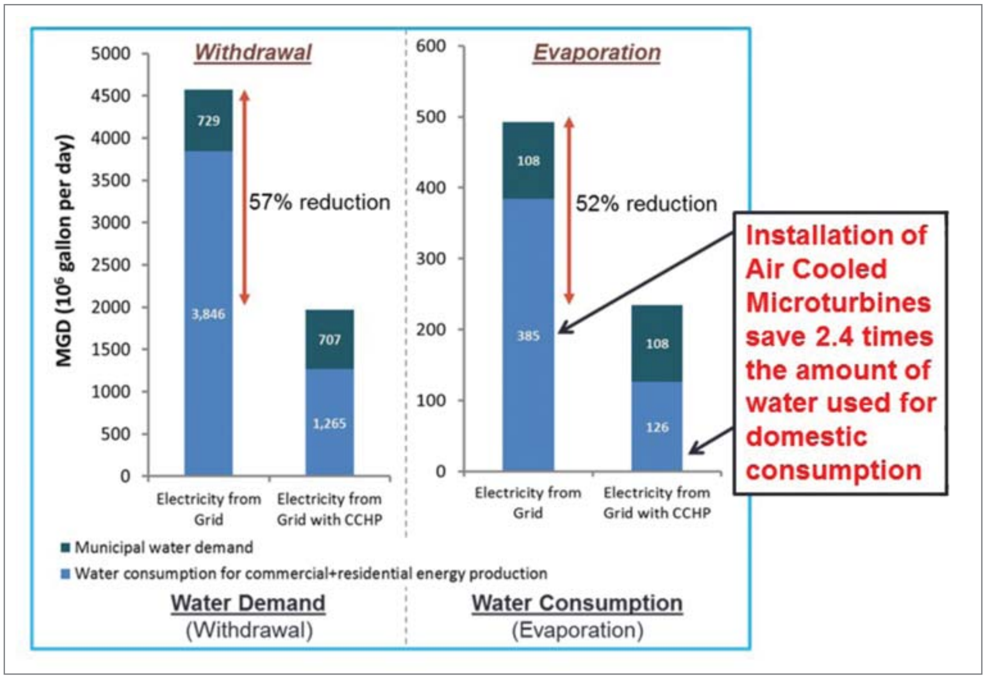


Figure 17: Water savings resulting from decentralized energy produced for new development in Atlanta, Georgia, using air-cooled microturbines.

5. Summary

Worldwide, unsustainable consumption and production have resulted in “Gigaton Problems” associated with the use of non-renewable materials, fossil-based energy, and water, to name a few. Natural cycles (e.g., water, carbon, nutrients, and materials) have been altered by unsustainable consumption. As the global population continues to grow, so too will these challenges.

Water is essential to support sustainable human development and activities. It is used, essentially, for everything. But more water is used for energy, agriculture, industry, and transportation than for personal use. Consequently, the sustainability of our water resources is linked to the practices used to generate energy, produce food, provide transportation, and manage land. In effect, they should be viewed as one whole system.

Accordingly, sustainable engineering approaches should be developed and used to solve these Gigaton Problems. System-based solutions that use the principles of Infrastructure Ecology and manage complexity will offer the greatest gains in resilience, sustainability, and adoption. The engineering community should take the lead in developing integrated and efficient infrastructure systems that promote the sustainable use of water for personal consumption, energy generation, food production, transportation, and land development.

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The 2015 Clarke Prize Honoree

JOHN C. CRITTENDEN, PH.D., P.E., NAE, CAE

Environmental engineer John C. Crittenden, Ph.D., P.E., N.A.E, C.A.E., Director of the Brook Byers Institute for Sustainable Systems at Georgia Institute of Technology, was selected as the twenty-second recipient of the NWRI Athalie Richardson Irvine Clarke Prize for excellence in water research because of his outstanding contributions to treating chemical contaminants in water and his leadership in addressing water demand for transportation, energy production, and domestic use in a holistic, sustainable manner.

Crittenden is the Hightower Chair and Georgia Research Alliance Eminent Scholar in Environmental Technologies and a professor in the School of Civil and Environmental Engineering at Georgia Tech in Atlanta, Georgia.

With a career spanning 37 years, Crittenden has been a pioneer in the research and development of water treatment technologies, particularly physical-chemical treatment processes. He first began examining the use of granular activated carbon (GAC) to absorb toxic organic compounds, such as industrial chemicals, from air and water while working with the American Water Works Association Research Foundation and U.S. Environmental Protection Agency in the early 1980s. At some treatment plants, air stripping is used to transfer organics out of the water and into air, and then GAC is used to adsorb these organics from the air. Crittenden found that if the relative humidity of the contaminated air stream is reduced through heating, then GAC becomes more effective in adsorbing organics. It is now common practice to heat air before it enters the GAC system. Crittenden's research has also paved the way for a greater practical understanding of advanced oxidation, which uses chemical treatment processes to destroy organic compounds present in groundwater and wastewater.

One of Crittenden's passions has been the development of mathematical models to predict the performance of physical-chemical treatment processes. This pursuit led him to develop a model called the Rapid Small Scale Column Test (RSSCT), which uses a simple set of experiments to simulate the operation of full-scale GAC treatment systems. Now an industry standard, RSSCT makes it possible for engineers to efficiently design GAC treatment systems more quickly and cost-effectively than traditional methods.

An intellectual leader in environmental engineering, Crittenden served as the senior author of the 2011 textbook, *Water Treatment: Principles and Design*, which has sold more than 10,000 copies. Another significant collaboration was the development of software to assess and implement effective treatment strategies. Together with his colleagues, he developed mathematical models called the Environmental Technologies Design Option Tools (ETDOTs), software routinely used for the preliminary design of GAC, air stripping, and advanced oxidation systems. These tools have also been used to optimize the water treatment system for the International Space Station. Crittenden and his colleagues worked with NASA to alleviate the costs of sending freshwater to space by helping to design a system on board the International Space Station to recycle impaired waters like wastewater, urine, and humidity condensation containing volatile organics from electronic equipment. NASA launched the system into space 3 years ago; it has since been used on the space station.

Crittenden is also distinguished among his peers for his vision and dedication to developing sustainable urban water resources. He takes a holistic approach that considers more than designing water treatment plants to remove contaminants – for him, it is essential to find alternative chemicals and approaches to keep harmful chemicals from being used in commerce. At Michigan Technical University, he directed a center for "green" chemistry and environmentally responsible engineering that focused on eliminating contaminants rather than just treating them. It involved engaging professionals from various disciplines to collaborate on research such as developing clean technologies for manufacturing and chemical production. Because of his leadership in this area, Crittenden was selected by the American Institute of Engineers as one of the 100 Eminent Chemical Engineers in Modern Times.

In 2008, Crittenden was recruited to Georgia Tech to direct the Brook Byers Institute for Sustainable Systems, established to create technological, management, and policy strategies to ensure a sustainable future (that is, "living within the means of nature"). To do so, researchers there, led by Crittenden, take a comprehensive approach in which systems are studied as a whole with all their complexities. Crittenden's particular interest is in developing sustainable water resources for people, agriculture, and the environment through a system-wide examination of water use in transportation, energy production, low-impact development (such as green roofs and permeable pavement), and land use. As an example, Crittenden's team estimated that the electrification of personal cars driven in the City of Atlanta would use more water than the amount of water consumed for irrigation and household use combined.

The Clarke Prize was presented to Crittenden on Friday, October 30, 2015, at the Twenty-Second Annual NWRI Clarke Prize Lecture and Award Ceremony, held at The Waterfront Beach Resort in Huntington Beach, California.

The

ATHALIE RICHARDSON IRVINE

Clarke Prize

for Outstanding Achievement
in Water Science and Technology

The 2015 Clarke Prize Lecture, *Water for Everything and the Transformative Technologies to Improve Water Sustainability* by John C. Crittenden, Ph.D., P.E., NAE, CAE of the Brook Byers Institute for Sustainable Systems, Georgia Institute of Technology, was presented on Friday, October 30, 2015, at the Twenty-Second Annual Clarke Prize Award Ceremony and Lecture, held at the Waterfront Beach Resort in Huntington Beach, California.

The National Water Research Institute (NWRI) of Fountain Valley, California, established the Clarke Prize in 1993 to recognize research accomplishments that solve real-world water problems and to highlight the importance of and need to continue funding this type of research. Dr. Crittenden was the twenty-second recipient of the prize, which includes a medallion and $50,000 award.

The Clarke Prize was named after NWRI's co-founder, the late Athalie Richardson Irvine Clarke, who was a dedicated advocate of the careful stewardship and development of our water resources. The Joan Irvine Smith & Athalie R. Clarke Foundation provide funding for this award.

More information about the Clarke Prize can be found at WWW.CLARKEPRIZE.COM.

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