Gigatechnology: Developing Sustainable Urban Infrastructure to Solve Gigaton Problems
Changjiang River Scientific Research Institute (CRSRI)
Wuhan, China, June 4, 2018

GIGA TECHNOLOGY

The largest systems in which humans manipulate mass and energy

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Brook Byers Institute for Sustainable Systems™

Georgia Institute of Technology®

Outline

- What is Sustainability and the Gigaton Problem?
- How to Create More Sustainable and Resilient Urban Infrastructure:
  - Infrastructure Ecology
  - Emergent Properties
- The Hyper Nexus of Water, Energy, Land Use, Transport, Buildings, Citizens, etc., and Technological Options
- Managing Complexity and Putting It All Together
- Summary

Sustainable Systems

- We need to recreate the anthroposphere to exist within the means of nature. That is, use renewable resources that nature provides and generate waste nature can assimilate without overwhelming natural cycles. We also need to generate knowledge and technology to improve the environment and the human condition.
- This will require us to examine the interactions between the natural, engineered, social and economic systems.

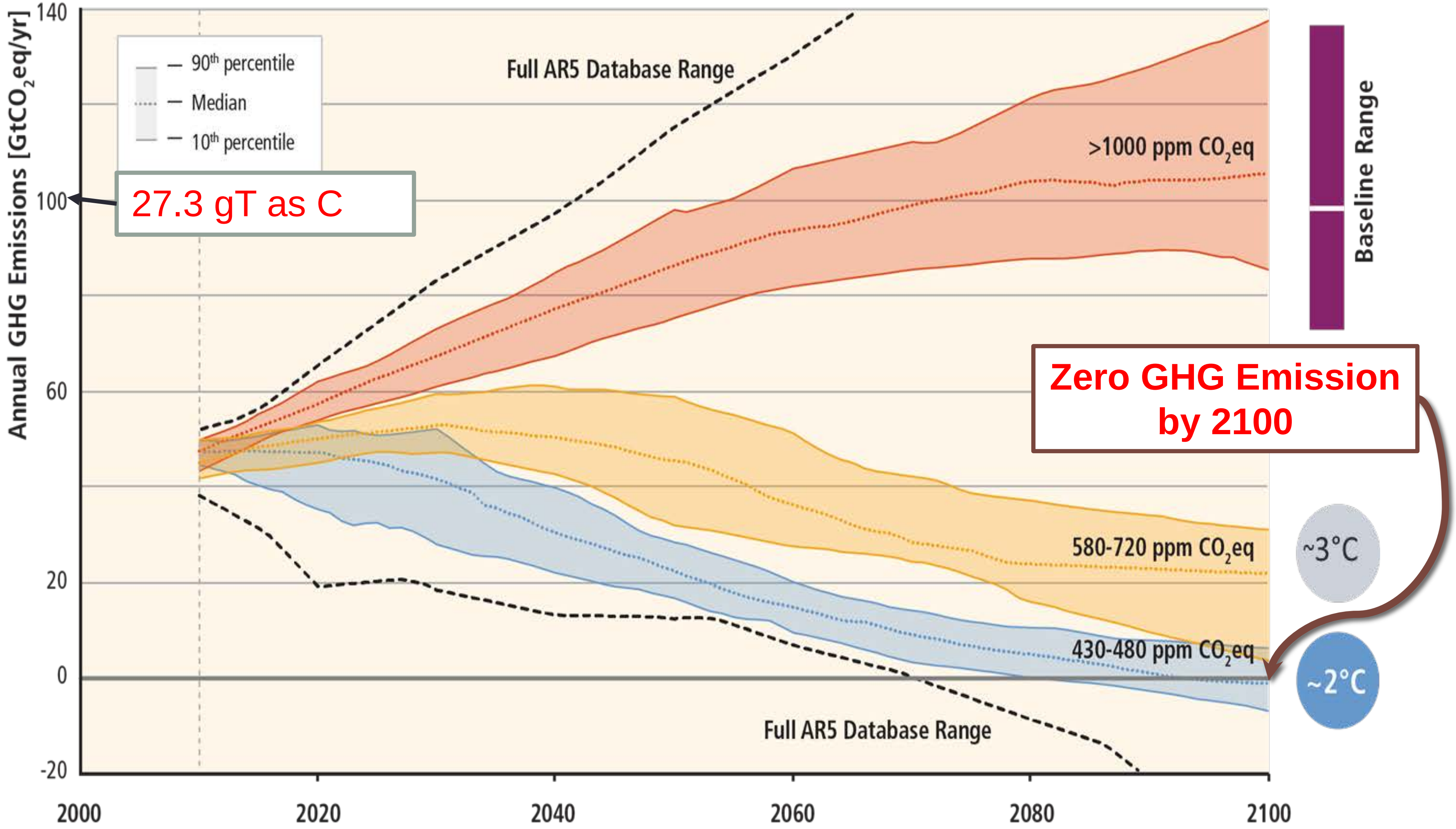
First Premise of ‘Sustainability’

- Generate waste that nature can assimilate without overwhelming natural cycles.
- Need to look at fate of toxics, Nitrogen, Phosphorus, Water, and Carbon cycles and more.

Nitrogen and Phosphorus Cycle

- **Nitrogen Cycle**
- The anthropogenic intervention to the Nitrogen-Cycle (One of the largest geoengineering experiment by humankind):
  - **⅔ rd N in the protein in human body** is from N fixed from the atmosphere through using an anthropogenic process (Haber Bosch Process)
  - Energy required to fix atmospheric N: 32 MJ (9 kWh)/kg NH_3-N (does not include energy required for steam reforming)
  - Energy required to remove N from wastewater: 18 MJ (5 kWh)/ kg NH_3-N
  - Total energy required to chemically fix 1 kg of N from and release it back to the atmosphere: **50 MJ or 14kWh/ kg**
  - Energy consumed for NH_3 production in 2010 = 1.82 TWh ≈ **1.2% of global total energy consumption**
- **Phosphorus Cycle**
  - With the current trend of increasing mining continuing, **the global reserve would last 125 years**, provided the current reserve estimate is accurate.
  - In certain sense, phosphorus is a more critical resource than Nitrogen. Unlike Nitrogen, it can't be harvested at will (the energy requirement notwithstanding).

What Needs to be Done to Limit Temperature Rise to 2°C (137.5 gT – C emission limit, 10 years?)



Unsustainable Animal Farming

Resource and pollution

- Livestock uses 30% of the world's ice-free landmass (geoengineering)
- Livestock produces 14.5% of all greenhouse emissions

Food and water consumption: 1kg (2.2lb) meat

2.5kg feed
5.5 lb

3.8m³ water
1000 gallons

5kg feed
11 lb

5.5m³ water
1500 gallons

10kg feed
22 lb

16.7m³ water
4400 gallons

Population growth

2015: 7.2 billion

2050: 9 billion

Growing appetite for MEAT!

Source: Green Food. Economist Technology Quarterly Q1 2015

Green Food

- Sustainable “Meat” and “Dairy” from Plants (400,000 species of plants and each plant species has tens of thousands of proteins)

Tech Startups are trying to create plant-based foods

- Cheaper
- Healthier
- Satisfying as animal-based products
- MUCH LOWER ENVIRONMENTAL IMPACT

Mimic the taste of animal-derived foods with plants

Enormous efficiency in terms of energy, water and other inputs

Source: Green Food. Economist Technology Quarterly Q1 2015

Examples of “Green Foods”

Plant-based chicken strips

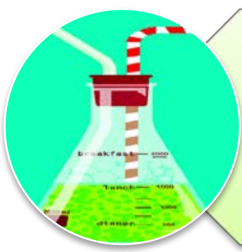
Beyond Meat

Eggless mayonnaise

Hampton Creek

Plant “beef” burger patty

Impossible Foods (Rancid Polenta)



Beverage as complete substitute for food

Soylent (Ocassional Recreational Eating)

Source: Green Food. Economist Technology Quarterly Q1 2015

Impossible Foods' "beef" patty now available

Available in Kroger and restaurants in many Cities

Eating a quarter-pound Impossible Burger will:

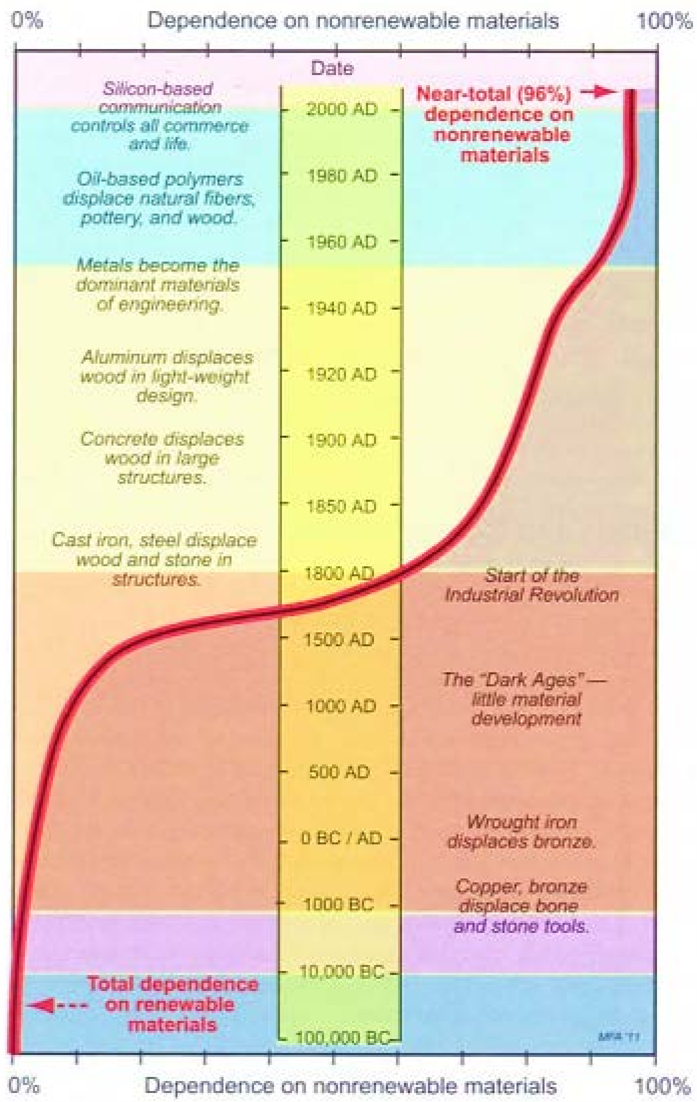
- Save the equivalent of a 10 minute shower
- Spare 75 ft^2 for wildlife
- Spare 18 driving miles-worth of green house gases

Source: Impossible Foods ™ 2017

Second Premise of ‘Sustainability’

- Use renewable resources/ recycle materials in commerce
  - Look at Materials in Commerce not including food and fuels
  - Look at all materials

Overwhelming Dependence on Nonrenewable Materials



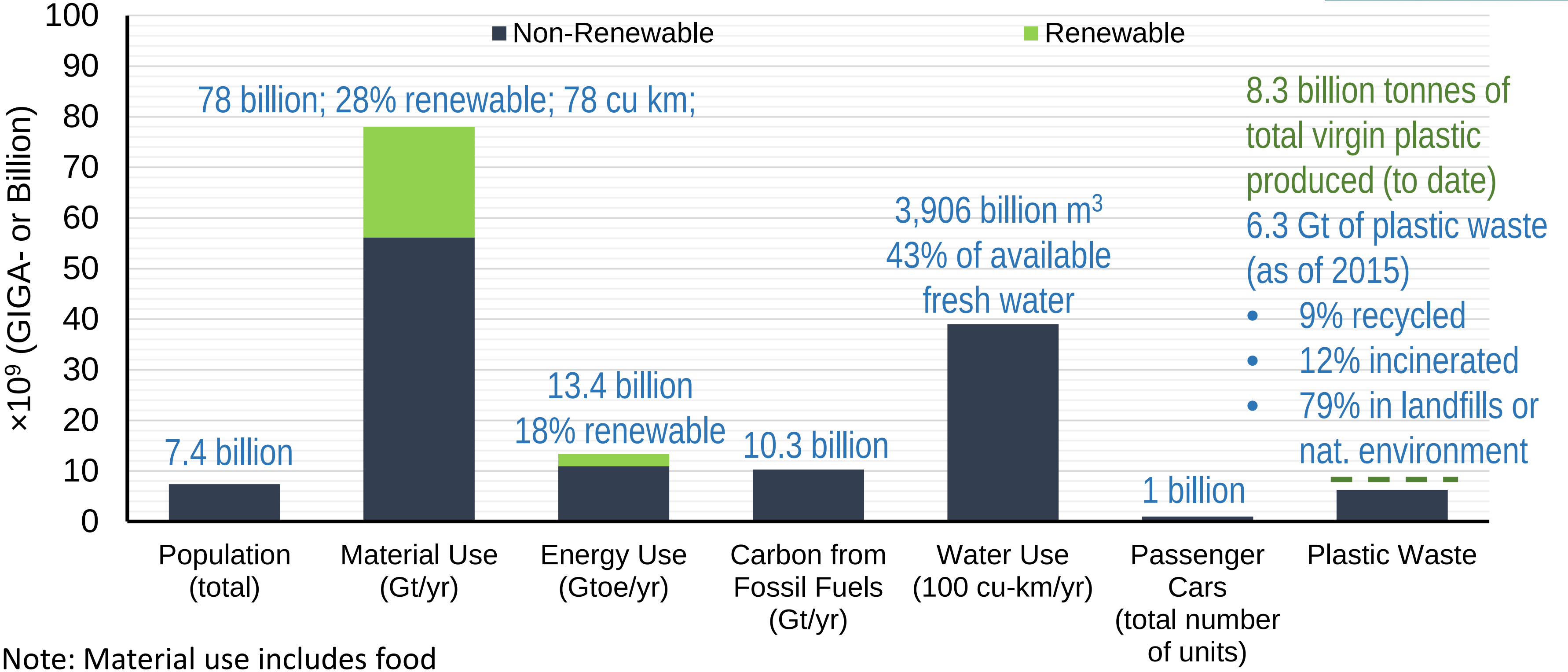
- **4% of material flow in commerce (by weight) is renewable (excluding food and biofuels)**

The increasing dependence on nonrenewable materials over time, rising to 96% by weight today. (Data in part from USGS [2002])*

*Michael F. Ashby, Materials and the Environment

Gigaton Problems Need Gigaton Solutions

- With ***1 billion people*** using ***78 Gt of materials***, ***13.4 Gtoe of energy***, ***3,906 Gm³ of water*** and emitting ***8.6 Gt of Carbon*** per year globally to produce ***71,000 G$ GDP***, a shift of scale and paradigm is needed to address the issues of global sustainability.
- From an egalitarian point of view, we should expect this to increase by a factor of 9 for 9 billion people in 2050, if every one has the same life style and uses today's technologies.
- 70% of the Fish in the Atlantic Ocean have plastic particles in their brains.



Note: Material use includes food

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Systems Engineering: Gigatech

Cities: Transport, Building, Water, Energy, and ICT	• 75% global greenhouse gas emissions • Consume 75% of natural resource • 54% global population; 82% US Population • 78% global energy use • 80% global GDP
Infrastructure	• Infrastructure requires $90 trillion investment by 2030 (UNEP) • Infrastructure lasts more than 50 years and 80-90% of its impact occurs in use phase • Global infrastructure needs to double in the next 35 years and it took 5500 years to get to this point • Surface Transport: 10 trillion USD per year • US infrastructure will increase 40% by 2030 • US housing market is valued at approximately 27 trillion dollars
Adaptation to Climate Change	In 2014, Farmers paid insurance claims resulting from strong storms a year earlier that had overwhelmed sewer systems around Chicago and flooded homes and businesses. Farmers claimed that the municipalities knew about climate change and its increased potential to cause flooding and yet failed to take reasonable preventative actions.

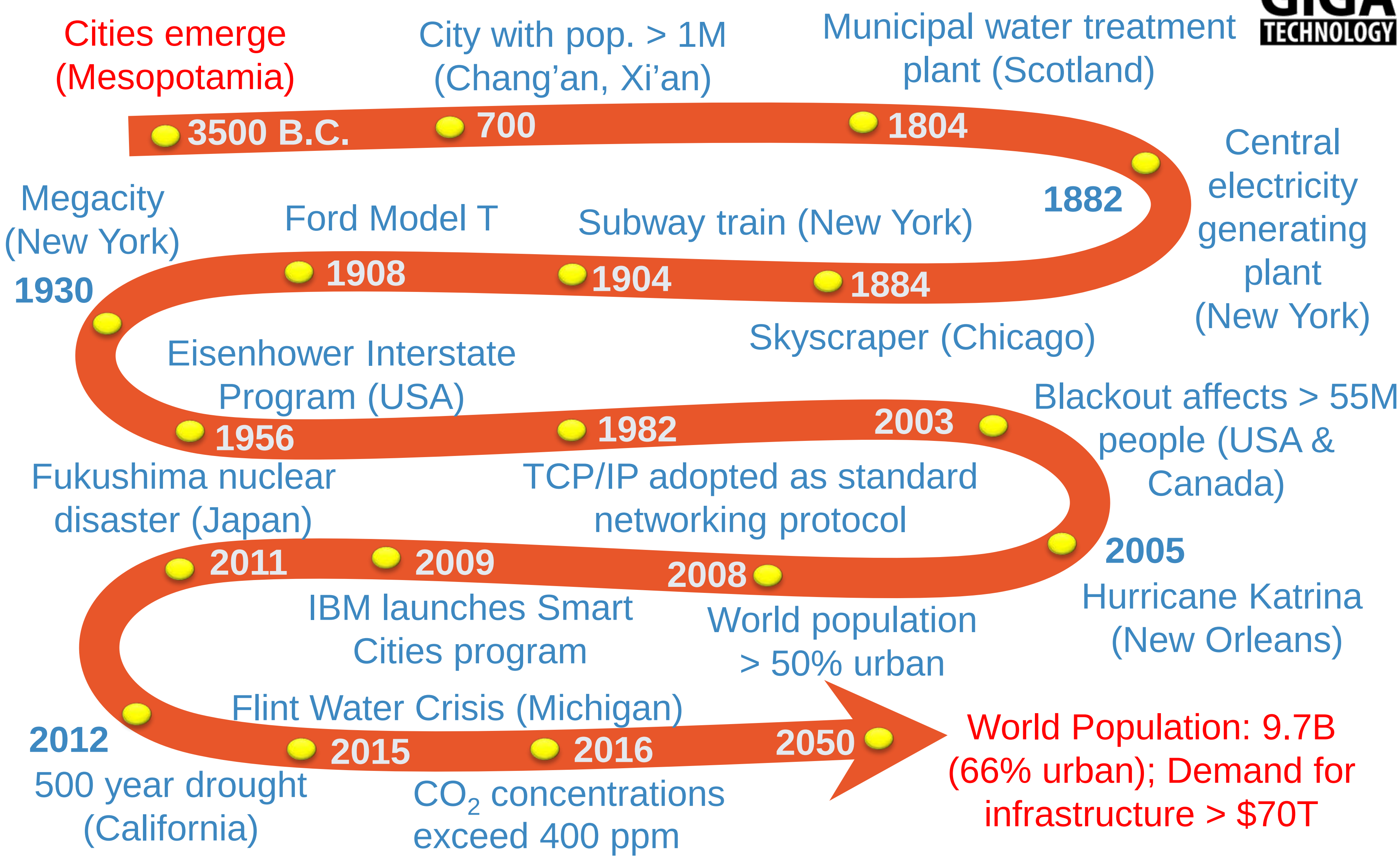
ICT: Information and Communication Technology

China’s Infrastructure Challenge

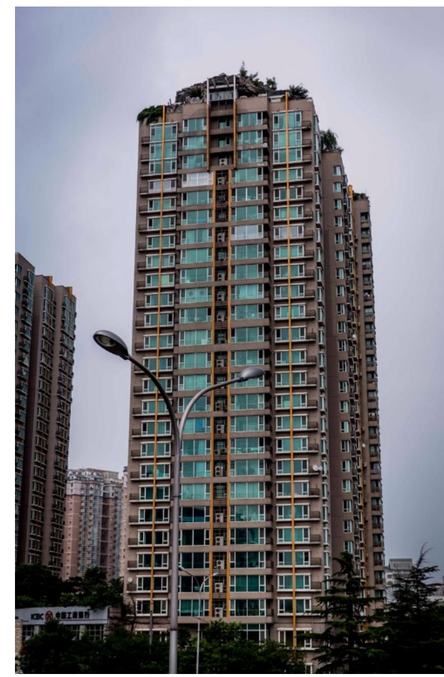
By 2025:

- 5 billion square meters of road will be paved.
- 170 mass-transit systems could be built
- 40 billion square meters of floor space will be built in five million buildings
- Build between 700 and 900 Gigawatts of new power capacity

Landmarks in Gigatech: A study in innovation, progress, and catastrophe (US centric view)



We Can Build Infrastructures that:
(1) Are More Sustainable and Resilient
(2) Create More Wealth and Comfort
But How?



State of the Art: Integration has not yet come to infrastructure

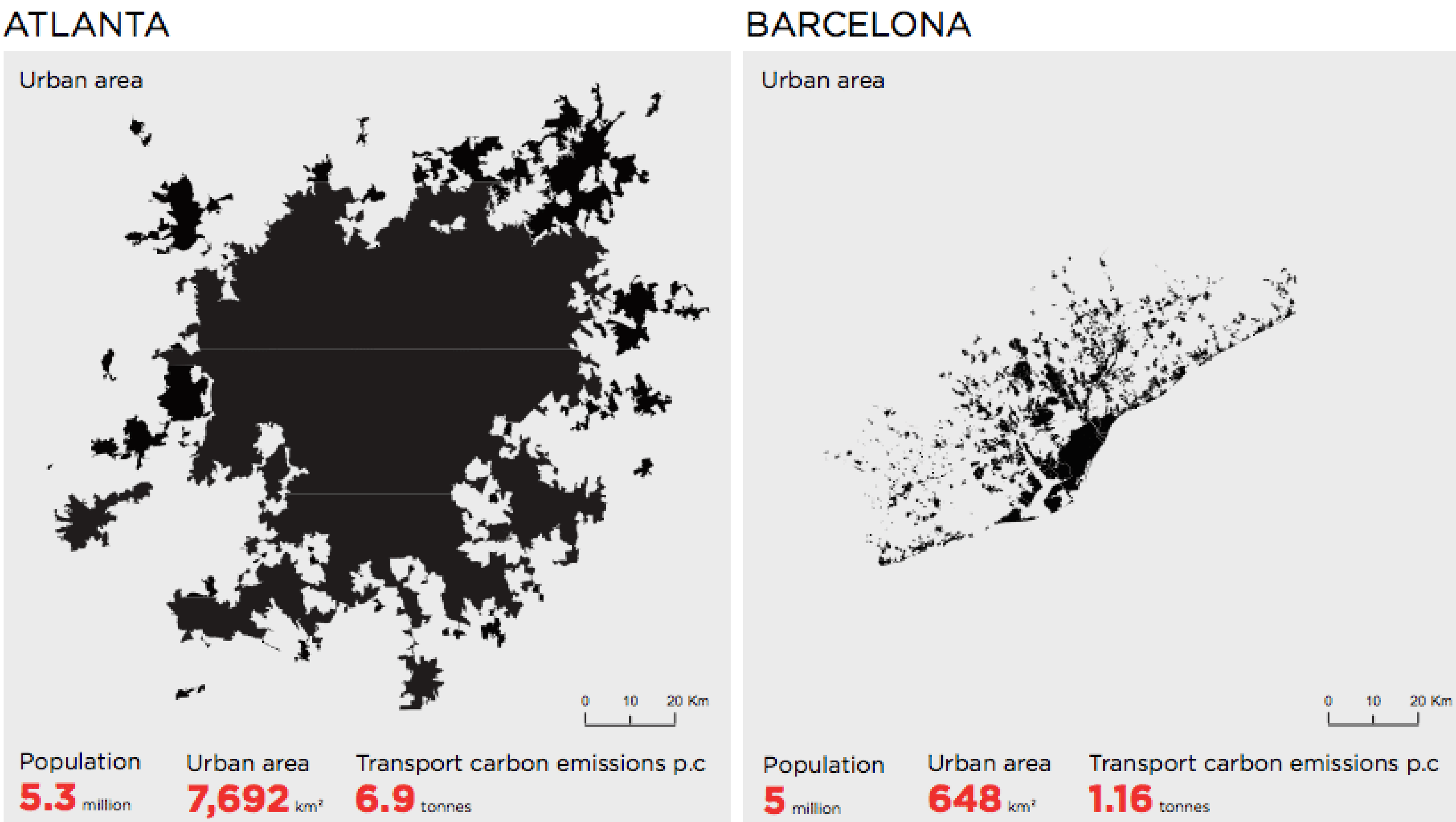
Solution: System of Systems Engineering Approach

Communications are information and communications technology (ICT).

New Transdiscipline: Infrastructure Ecology

- **Infrastructure Ecology** views the *city as a complex adaptive ecosystem* composed of physical, material, and human infrastructures. We need to reorder this ‘system of systems’ to reduce energy and resource flows, and drive the creation of infrastructure to increase wealth and comfort, while fostering sustainable, equitable, and resilient cities.
  - ✓ Improve diversity of infrastructure, and improve energy and material flow to mimic natural ecosystems.
  - ✓ Integrate socio-economic dynamics, stakeholders and governance networks to enable livability, equity, and welfare.

Emergent Properties? What Causes Them to Emerges



Source: LSE Cities 2014

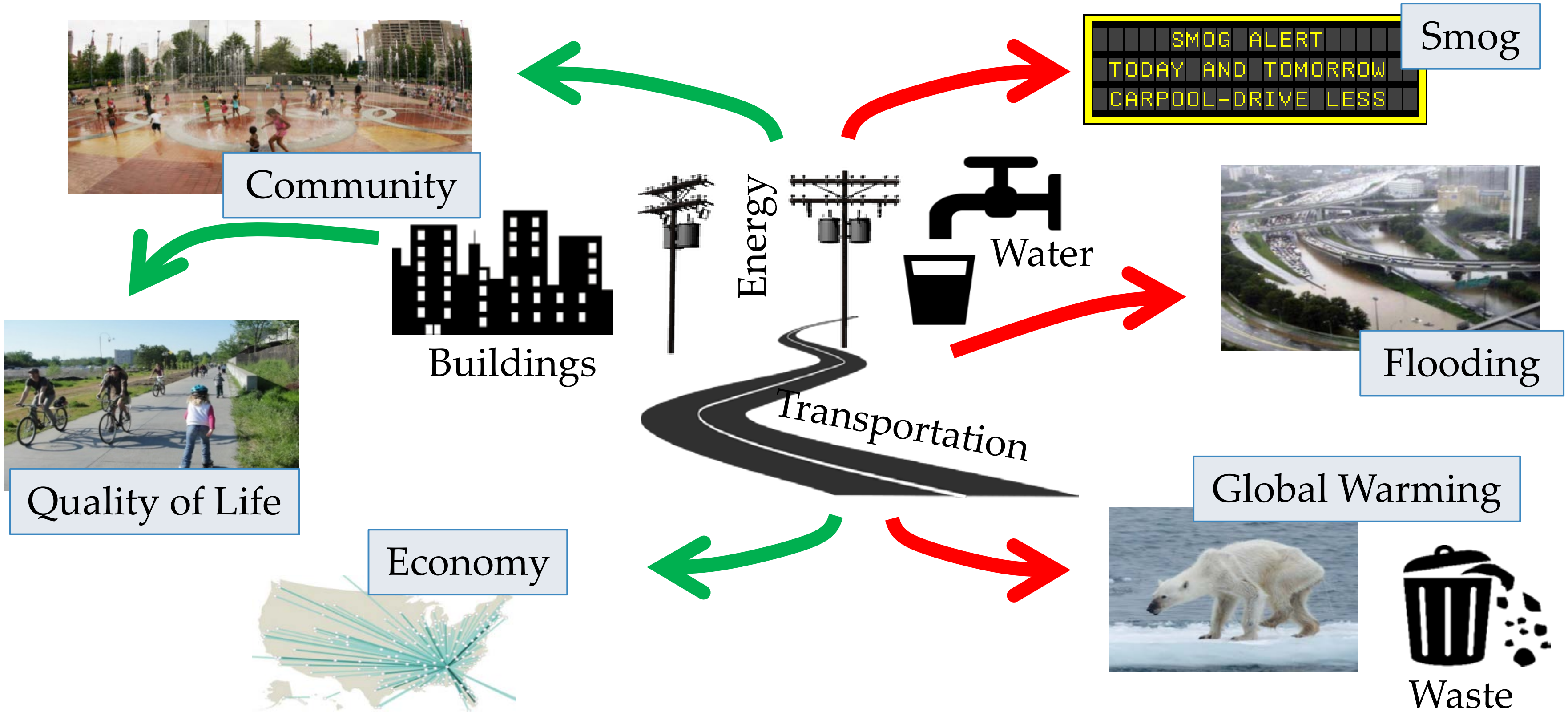
Emergent Properties of Complex Urban Systems

Social	Economic	Environmental	Built Environment
• Quality of life • Social equity • Social segregation	• Gross domestic product • Economic structure • Economic resilience	• Water consumption • Energy intensity • Material intensity • Toxic emissions • Pollutant emissions • Green gas emissions	• Land use • Accessibility • Mobility • Congestion • Fractal

Reference: Schwarz, et al, 2002

Engineered Urban Infrastructures

Good | Undesirable
Emergent Properties | Emergent Properties



Manage Infrastructures as a Whole for Better Future

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Energy and Water

‘Water for Energy’ and ‘Energy for Water’ in US

Water for Energy

- 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 2.0 Gal/kWh.

Energy Source	Gal/kWh (Evaporative loss)
Hydro	18.27
Nuclear	0.62
Coal	0.49
Oil	0.43
PV Solar	0.030
Wind	0.001

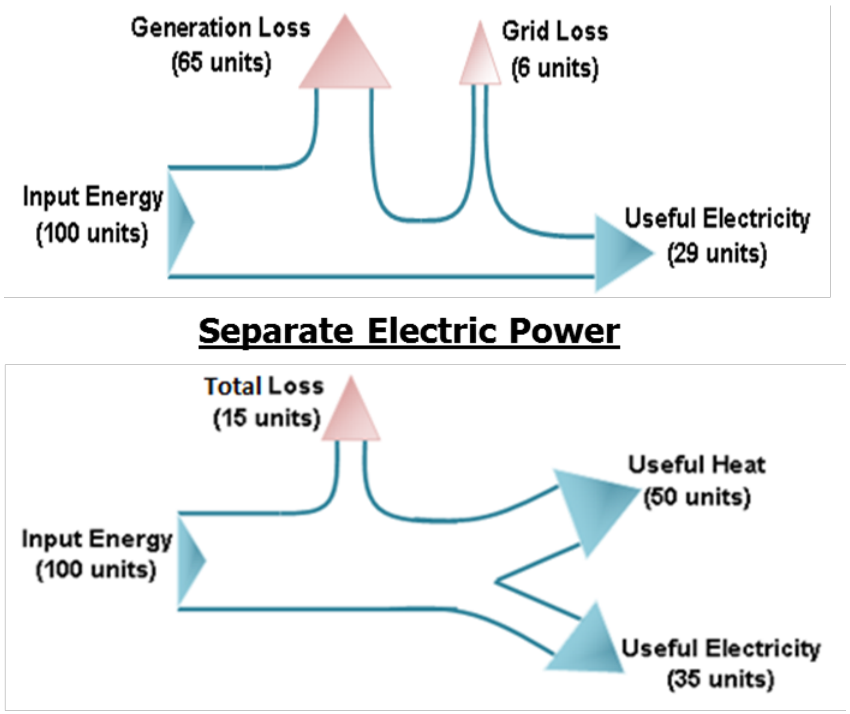
Energy for Water

- About 4% of the total electricity consumption in the US is for the water and wastewater sector1
- Of the total energy required for water treatment, 80% is required for conveyance and distribution

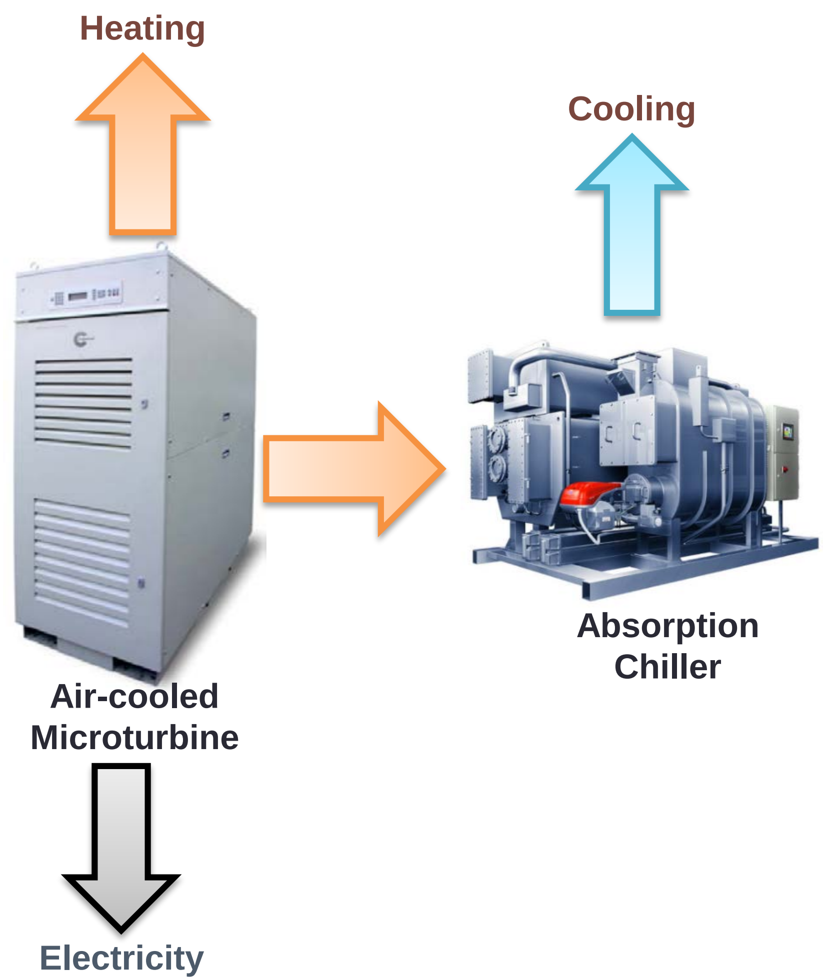
Water Treatment*	kWh/MGal
Surface Water Treatment	220
Groundwater Treatment	620
Brackish Groundwater Treatment	3,900-9,700
Seawater Desalination	9,700-16,500

*Includes collection but does not include distribution

Breaking the Water Energy Nexus: Recapturing Lost Heat in Decentralized Combined Heat & Power System; Air Cooled (No water needed)



Combined Heat and Power



Possible Future: Carbon Neutral Natural Gas Grid!!!

Decentralized Energy Production at Perkins + Will, Atlanta Office (45000 sq. ft.)

- Air Cooled Microturbines are used to for heating and cooling using Absorption Chillers and supply 40% of the total electricity.

Adding Distributed Generation as part of the Grid:

Water Reduction:	**>50%**
CO_2 Reduction:	**15 - 40%**
NO_X Reduction:	**~90%**

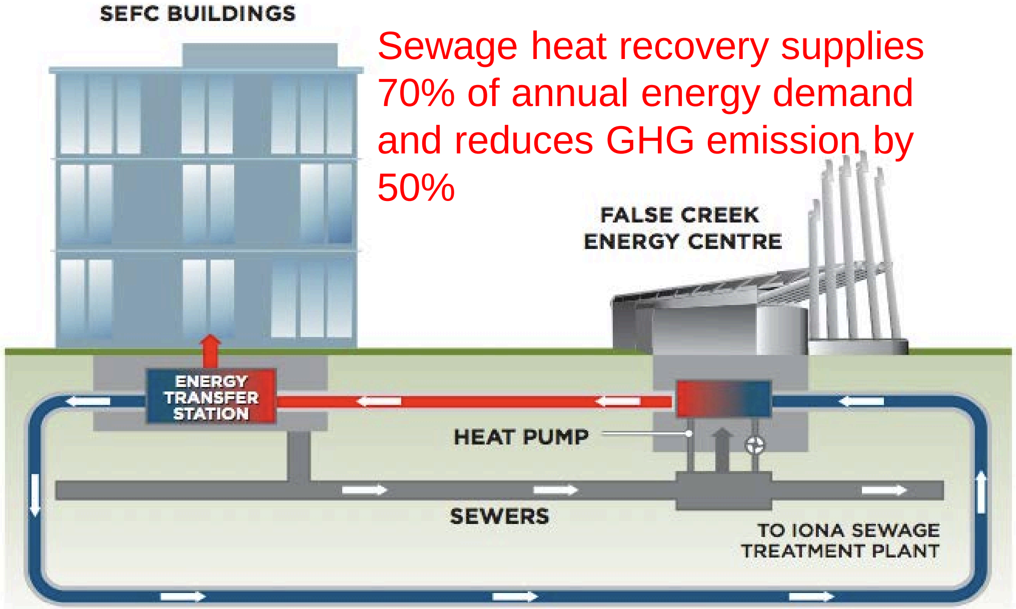
Adsorption Chiller

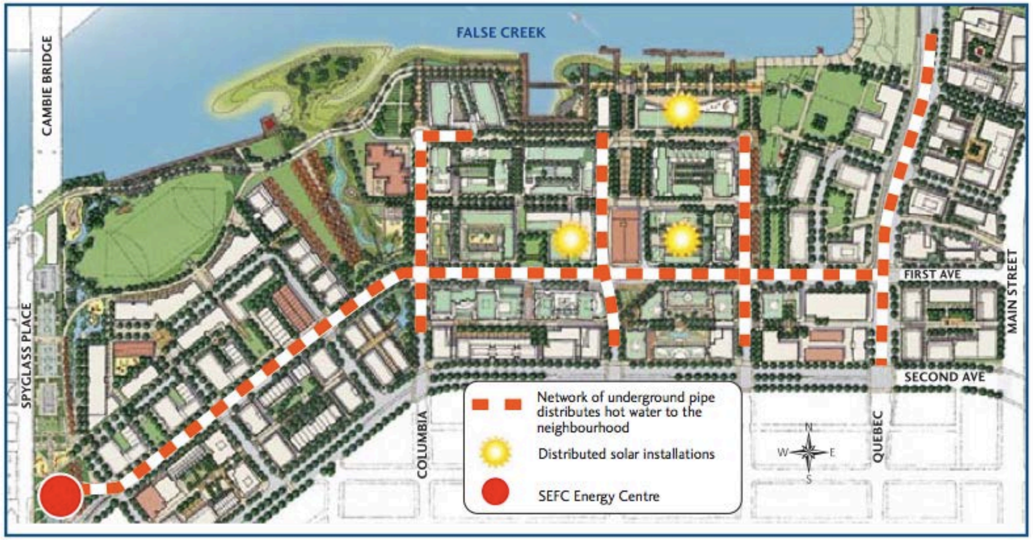
65 kW Microturbine

Perkins+Will Office Building

Water as a Heat Source: False Creek Neighborhood Energy Utility Vancouver, BC

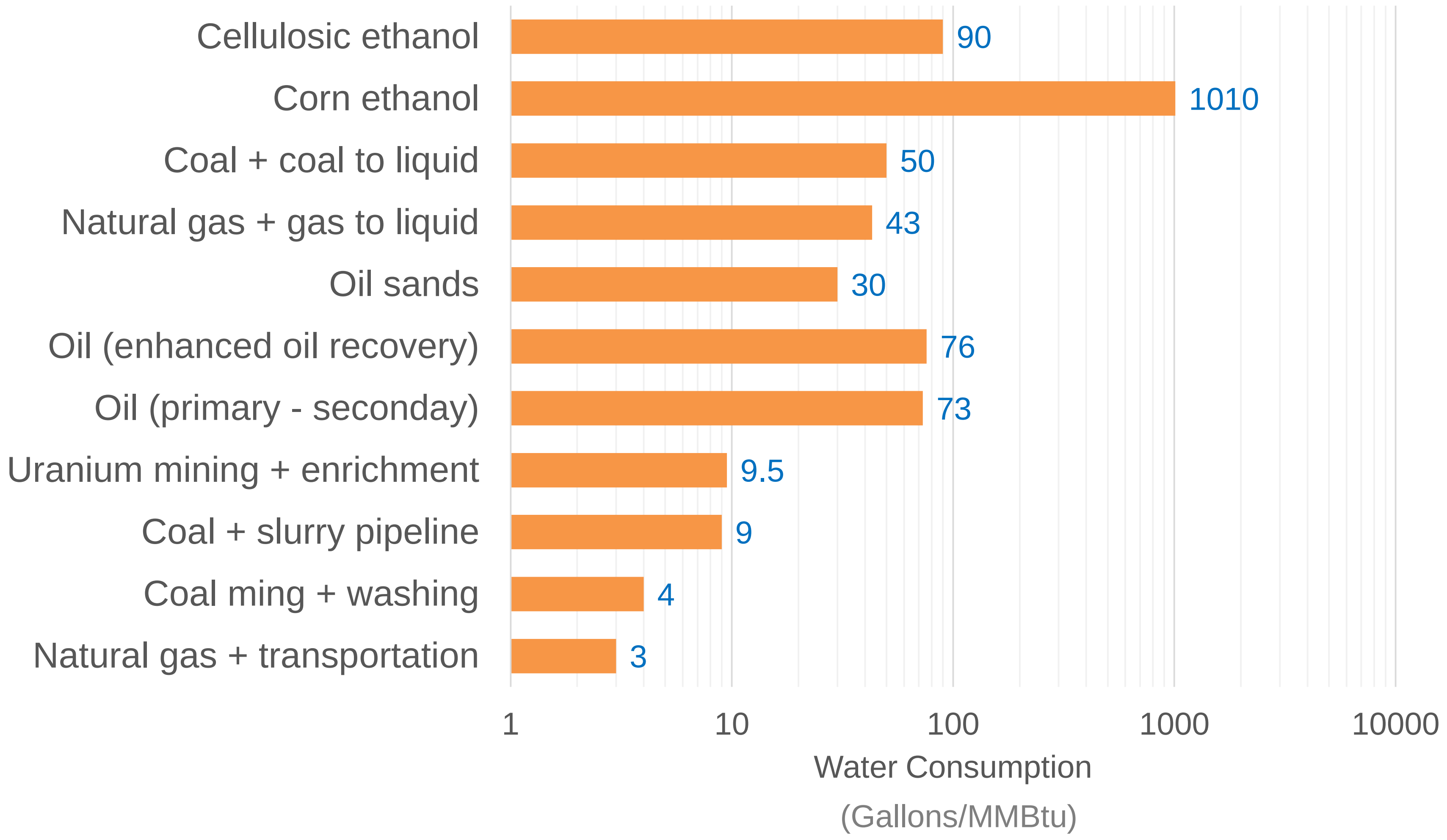
Sewage heat recovery supplies 70% of annual energy demand and reduces GHG emission by 50%





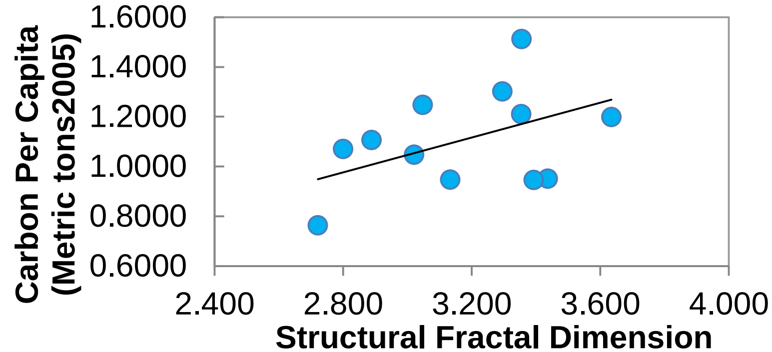
Water for Energy in US

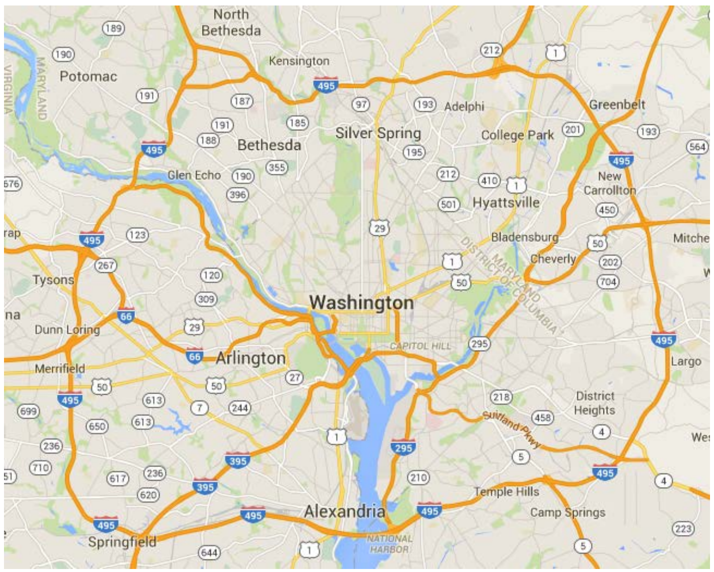
Water for Fuel Extraction and Processing



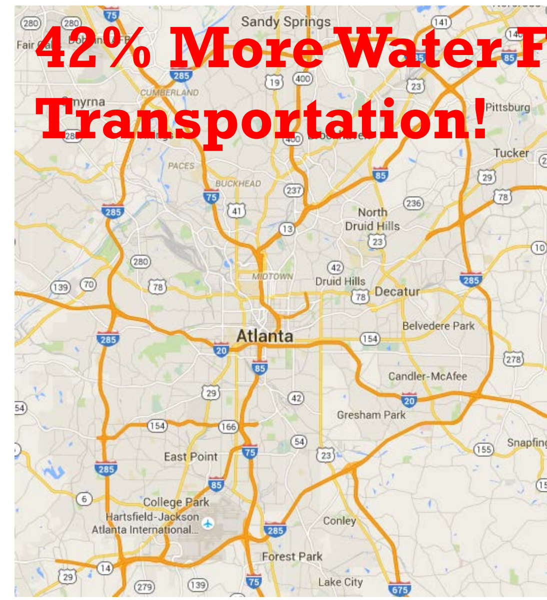
Transportation, Energy, Land Use, Water, Air Quality

The Impact of the Hierarchy of Transportation Network On Land Development and Transportation Carbon Emissions





2 miles



3,258 Person Per Square Mile

1.07 metric ton per capita per year

Structural Fractal Dimension = 2.80

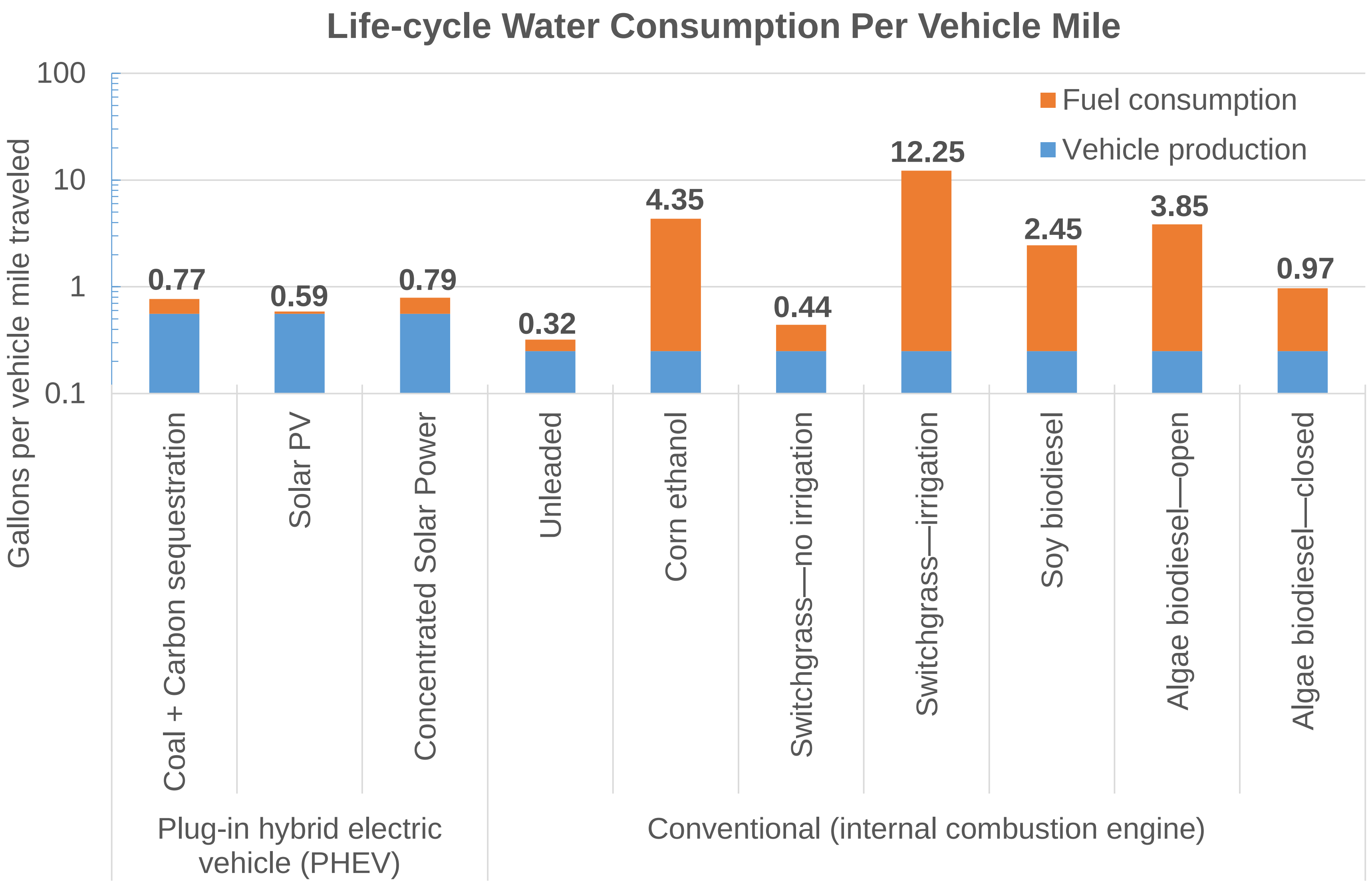
1,378 Person Per Square Mile

1.52 metric ton per capita per year

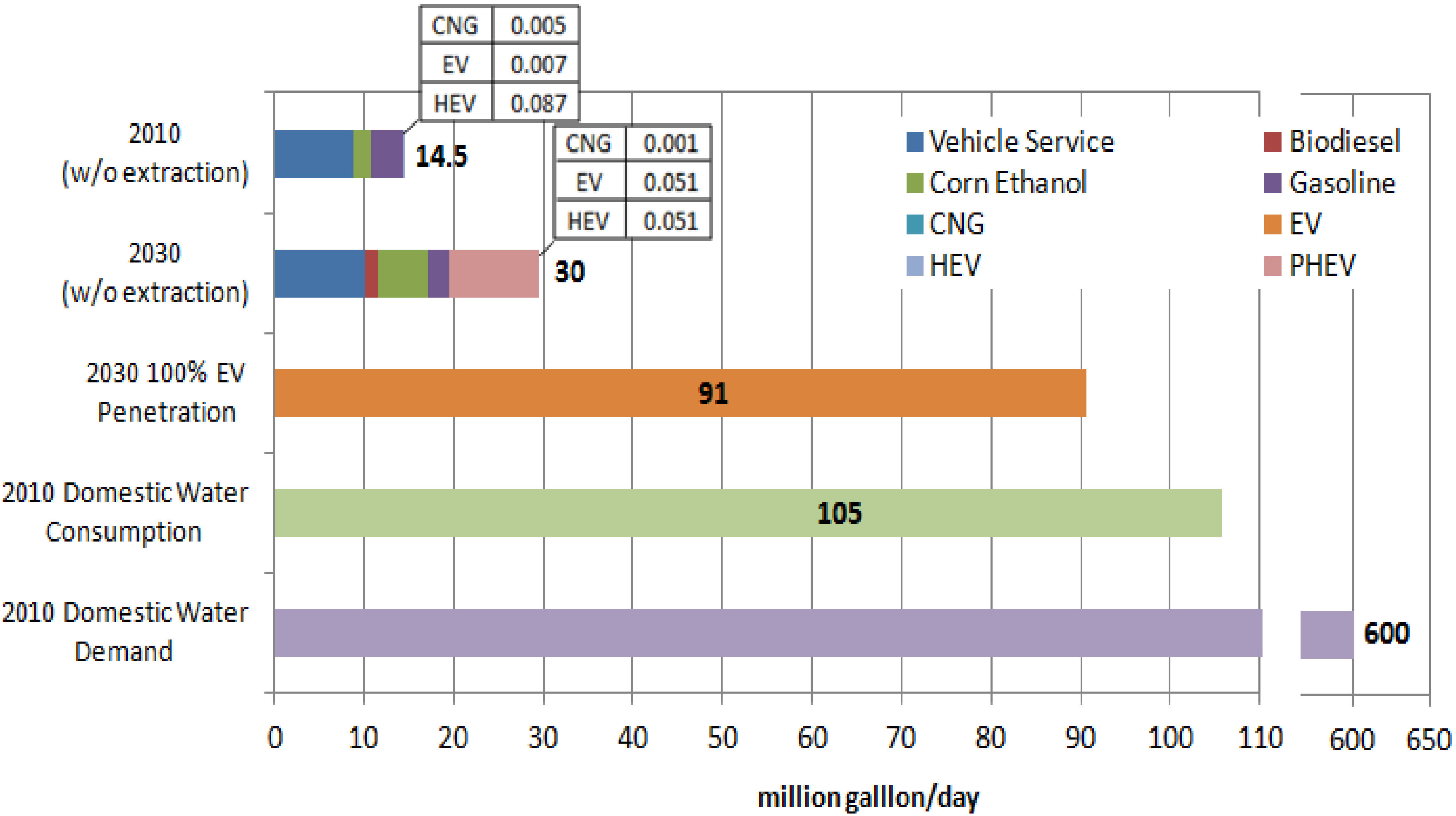
Structural Fractal Dimension = 3.36

The geometric form of road network is similar between Washington DC and Atlanta. The difference in the hierarchy of transportation network accounts for *30%* of density difference and *20%* of carbon difference between Washington DC and Atlanta.

Water for Transportation: Impact of Fuel Types and Vehicle Technologies

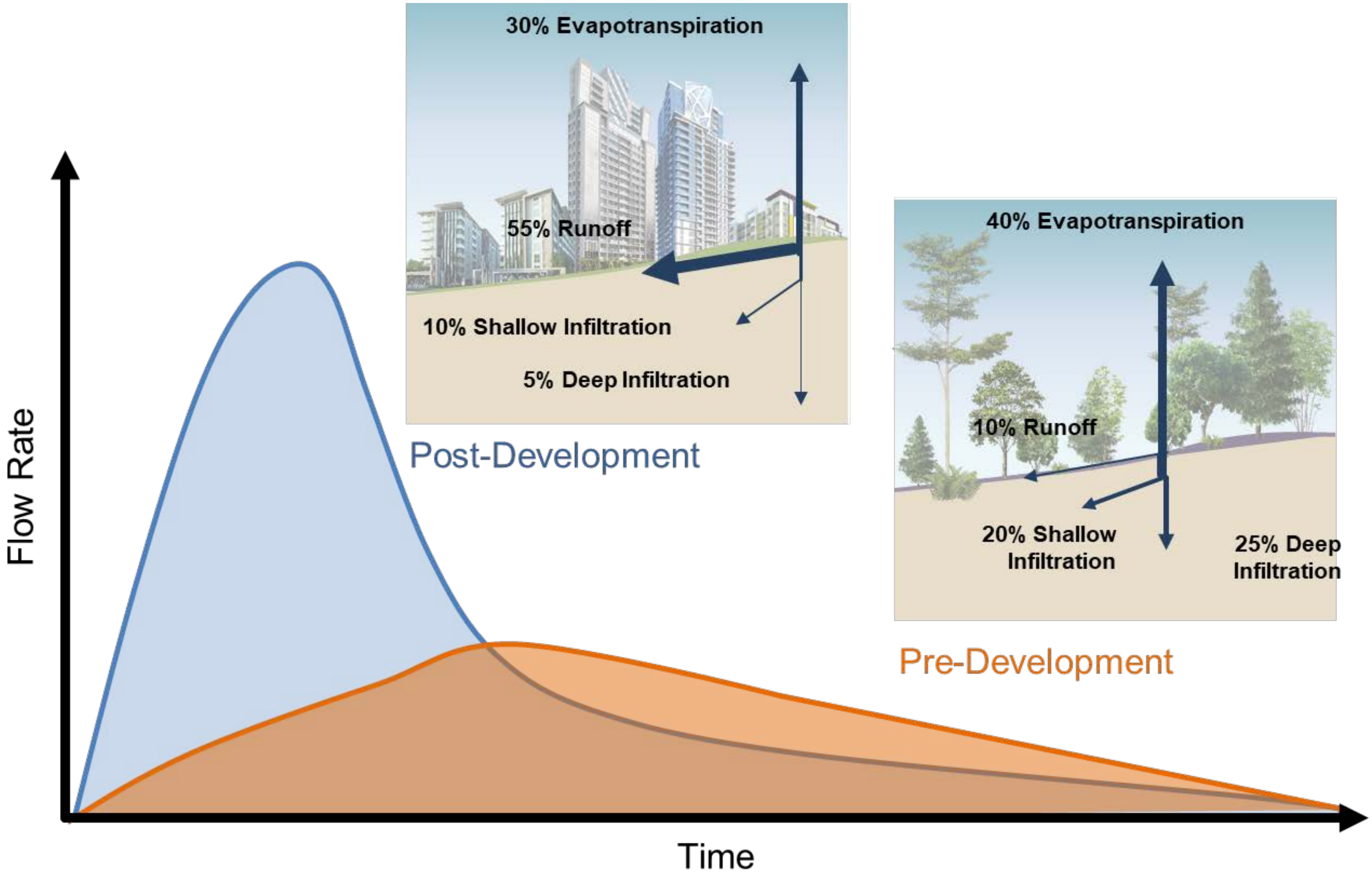


Water for Vehicle Electrification Metro Atlanta, 2010 and 2030 Conditions



Source: Jeffrey Yen (2011) A system model for assessing water consumption across transportation modes in urban mobility networks, Masters thesis

Low Impact Development



Low Impact Development (Reducing Stormwater Runoff, Erosion and Surface Water Contamination) - LID Best Management Practices (BMPs)

Rain Gardens for local flood control at Cuyahoga Falls, OH[1].

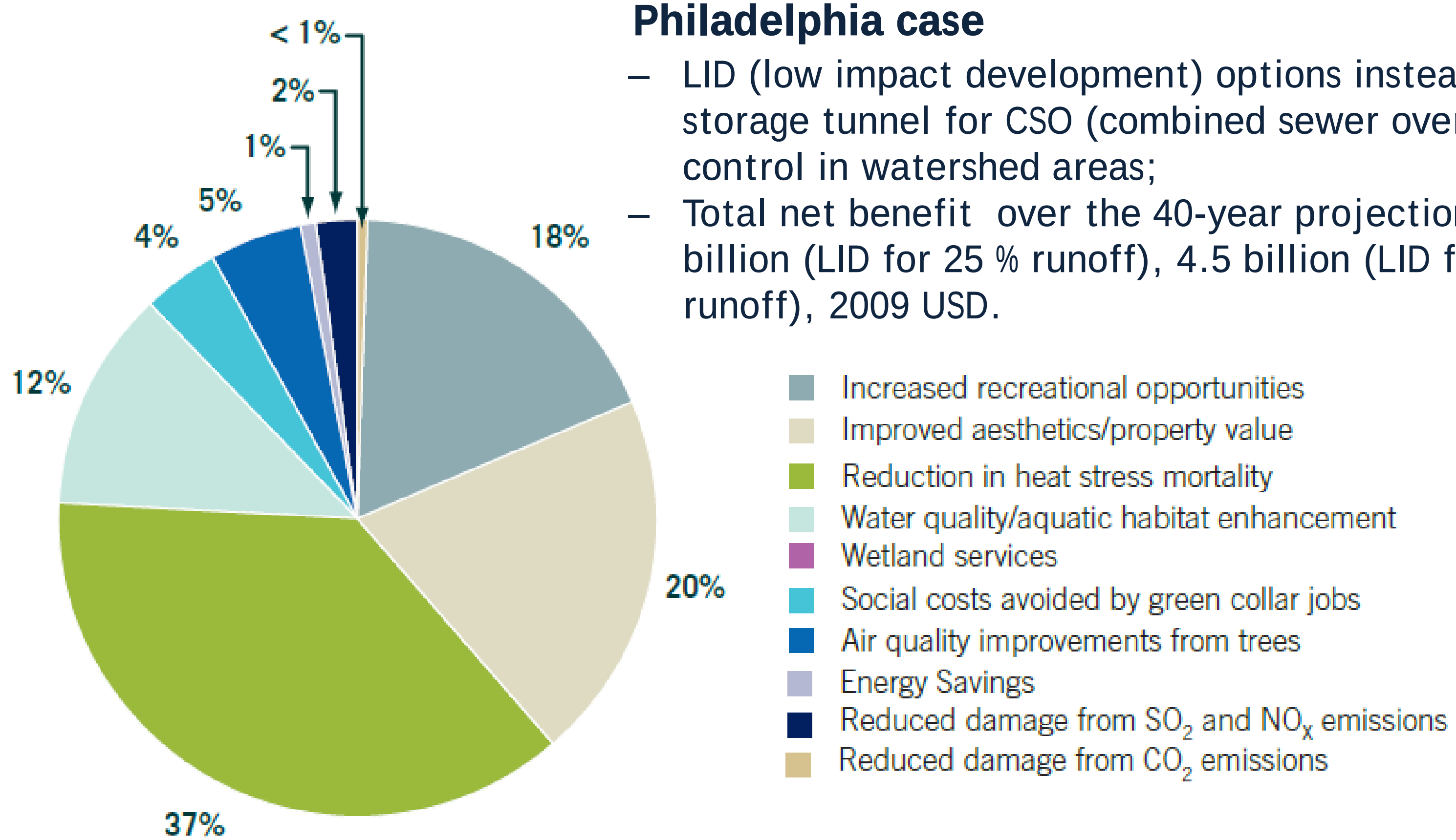
Green roof of City Hall in Chicago, IL.

Rainwater Harvesting tanks for residential water supply at Perth, Australia[2].

Increased walkability through greening of alleyways at Vancouver.

Porous parking lot at the Reliant stadium, Houston, TX[3].

Interdependency between Water Infrastructure and Socio-Economic Environment



Philadelphia case

- LID (low impact development) options instead of storage tunnel for CSO (combined sewer overflow) control in watershed areas;
- Total net benefit over the 40-year projection : 2 billion (LID for 25 % runoff), 4.5 billion (LID for 100 % runoff), 2009 USD.

Source: Philadelphia Water Department (2009) Philadelphia combined sewer overflow long term control plant update, supplemental document volume 2; Triple bottom line analysis

The Connection between Autonomous Vehicles, Green Space and Water

80% penetration of autonomous vehicles

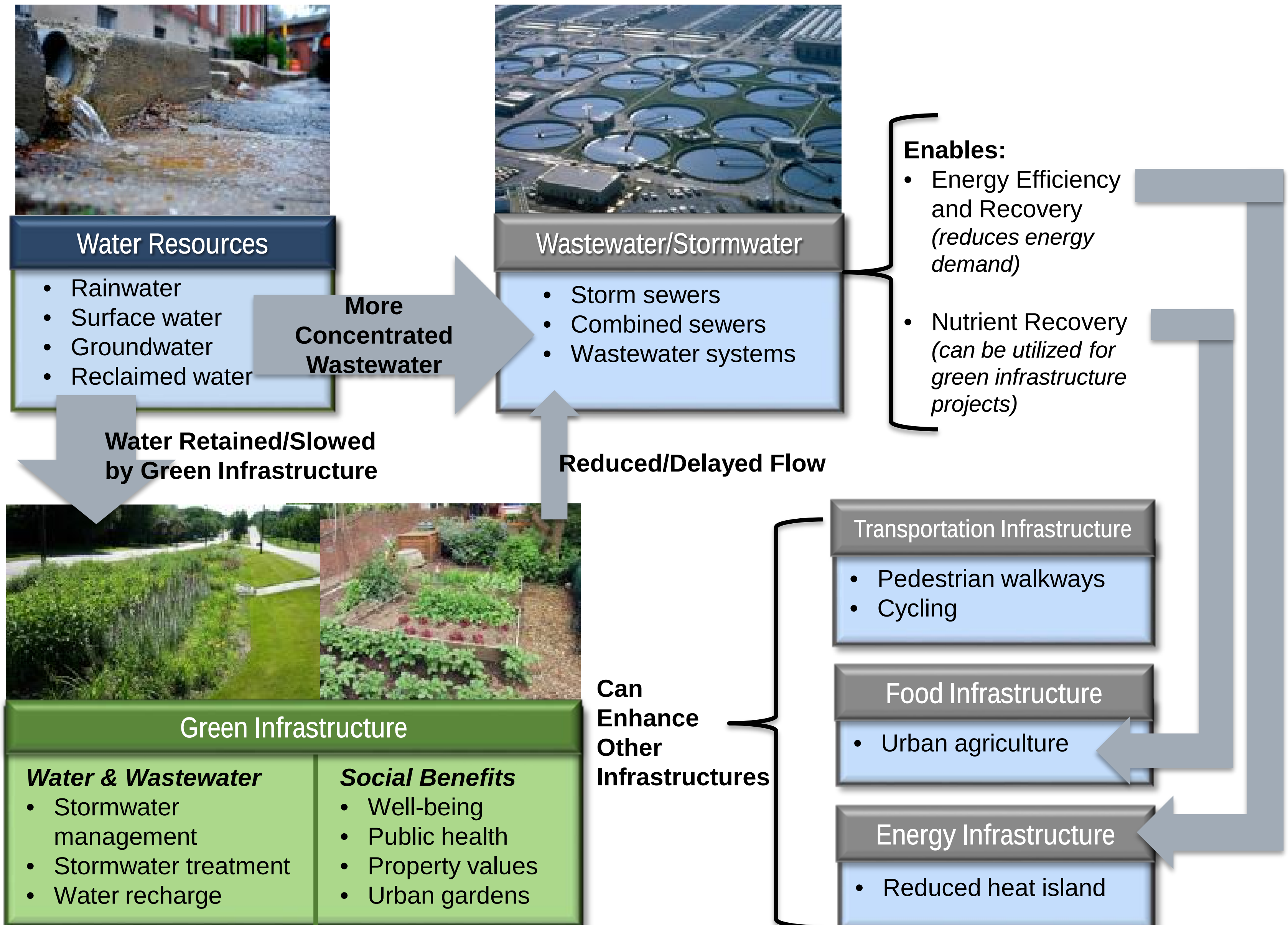
28% of the cars we have today

At least 72% reduction in parking space

24.7% reduction of impervious area and stormwater runoff

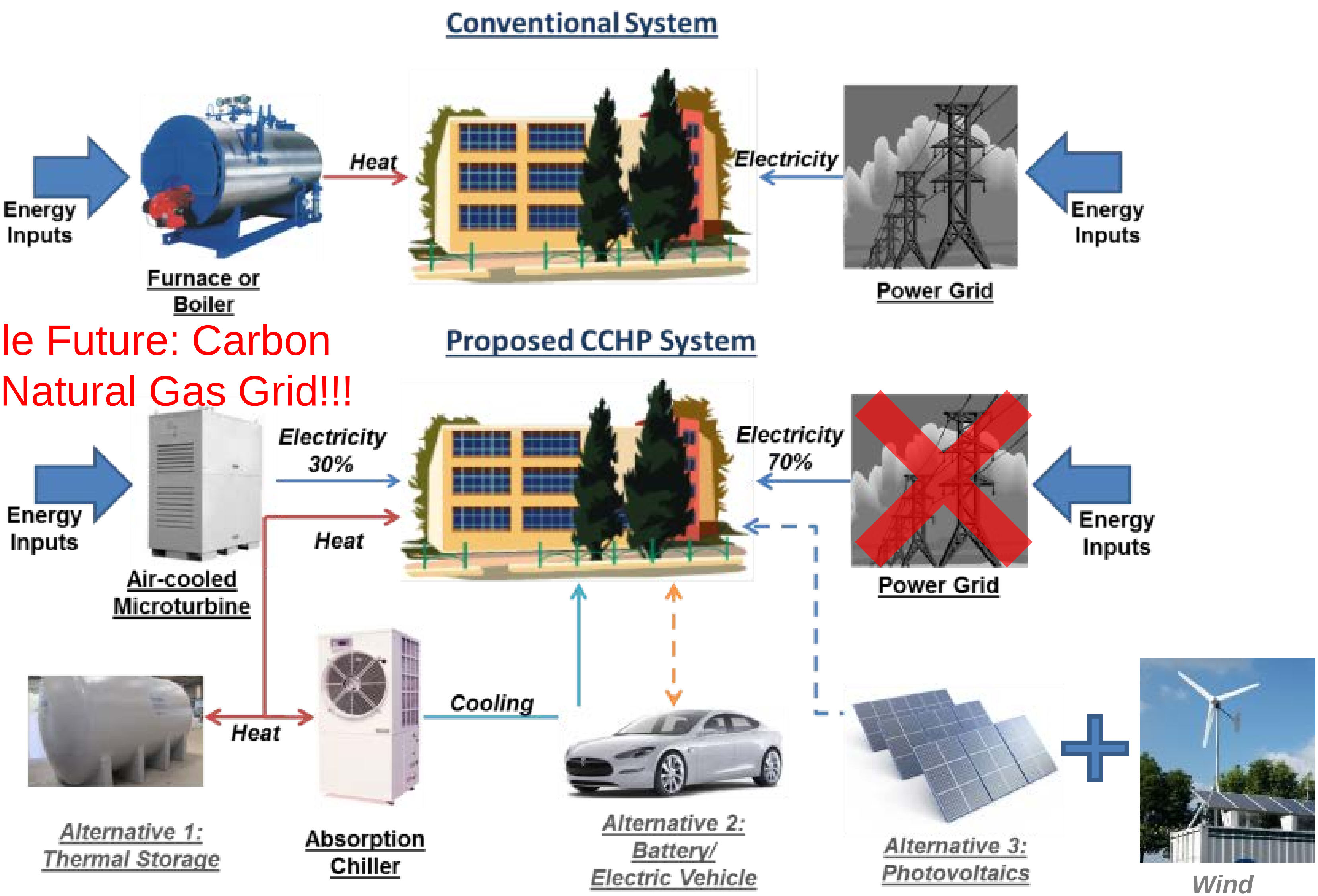
Additional 17% of city land for green space and stormwater management

System-based Benefits of LID Best Management Practices



Future Research: Expanding the Current CCHP System 2.0

Possible Future: Carbon Neutral Natural Gas Grid!!!



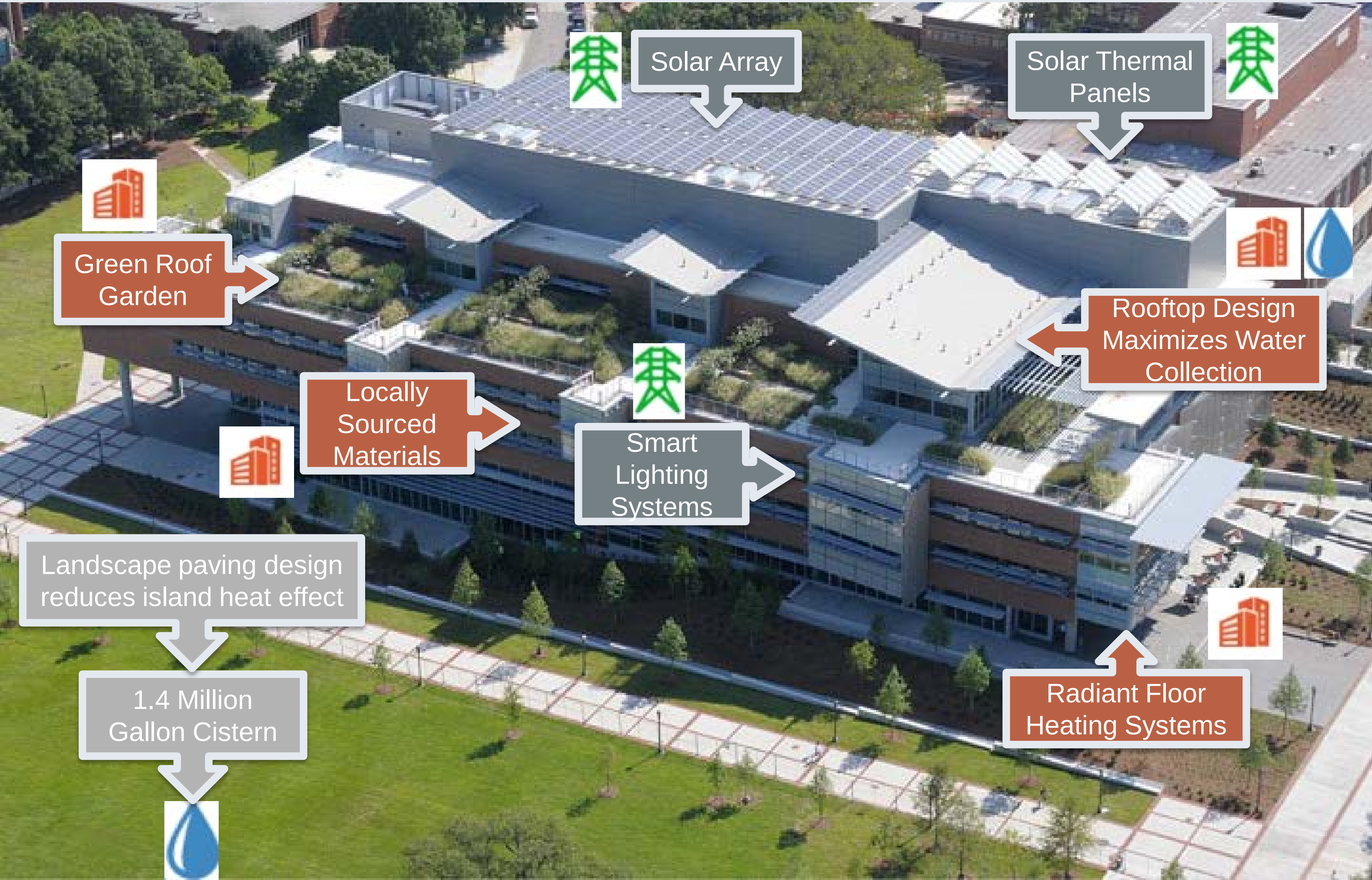
Transit-oriented Development (TOD)

- Creation of compact, walkable, mixed-use communities centered on high quality public transit services

- Affordable house
- Walkable community
- Mixed land use
- Reasonable density
- Multiple modes of transport

Buildings and Communities

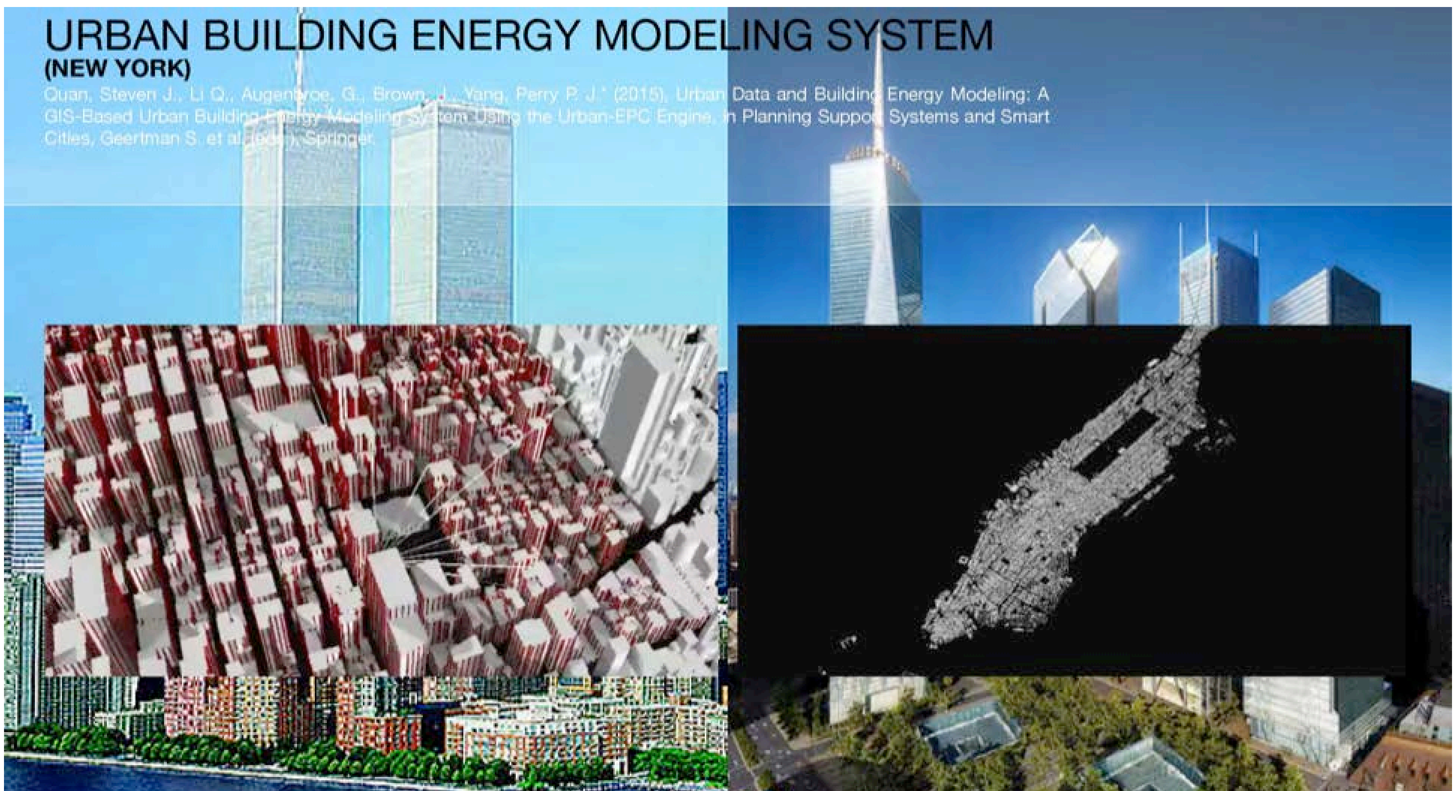
Georgia Tech Clough Undergraduate Learning Commons



Urban building energy modeling (UBEM)

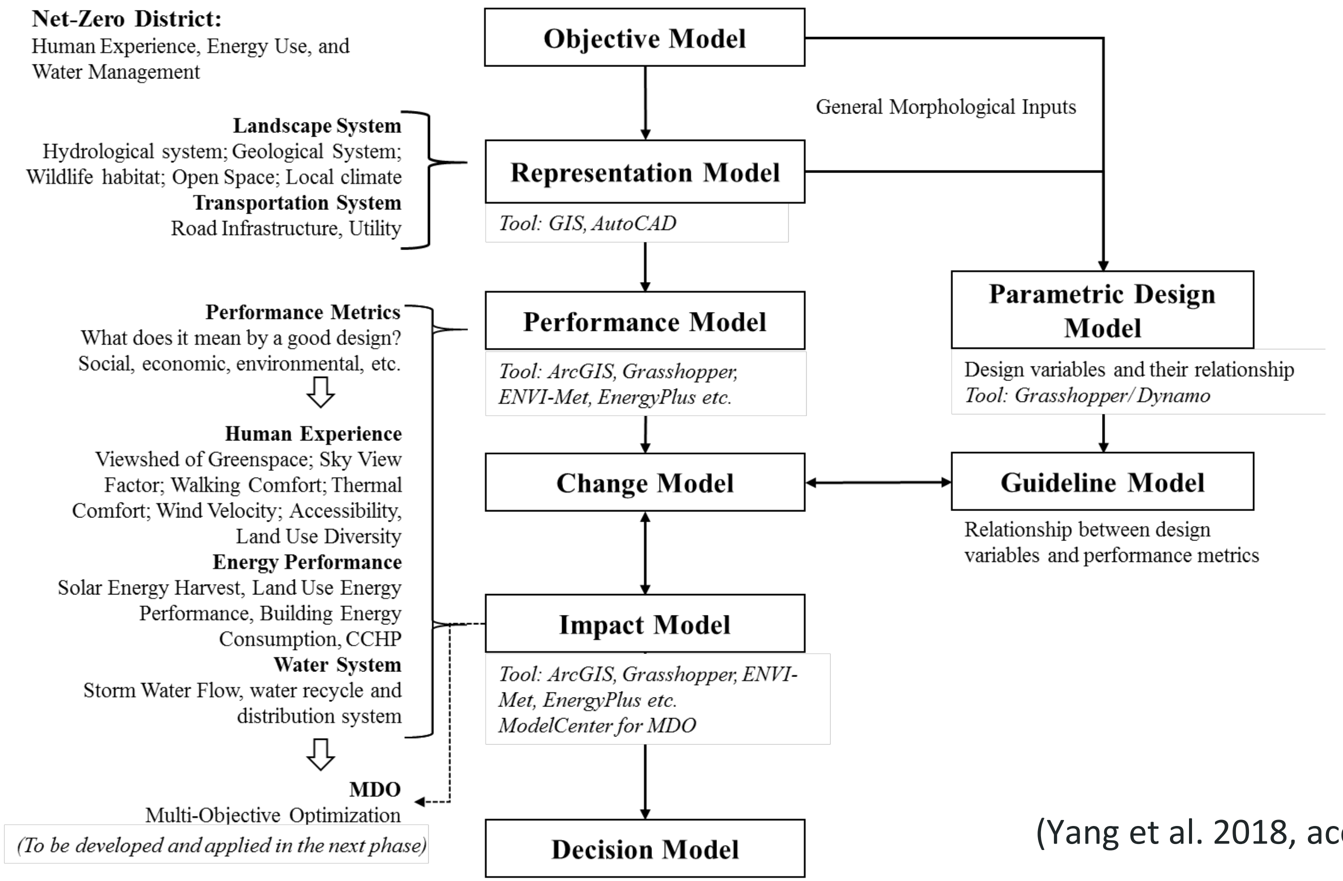
UBEM is a GIS-based urban energy balance modeling system. This method integrates the building energy modeling and solar potential modeling to provide energy consumption and production estimates, which leads to the energy balance and energy resilient ratio of cities.

-- Quan, S. Qi L, Godfried, A, Brown, J, Yang P. P. J. 2015. Urban Data and Building Energy Modeling: A GIS-based Urban Building Energy Modeling System Using the Urban-EPC Engine, in *Planning Support Systems and Smart Cities*, Springer.
- Yang, Perry P J, Quan, Steven J. 2016. Urban form and energy resilient strategies: A cast study of the Manhattan grid, in Urban Resilience – A Transformative Approach, Yoshiki Yamagata and Hiroshi Maruyama eds., Springer.

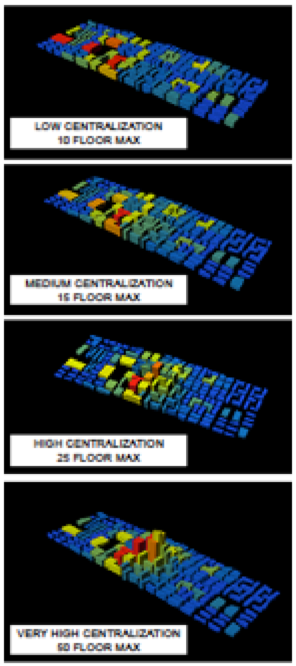


Modeling Energy Use in 40,000 Building in Manhattan

A Geodesign Model of Energy-Water-Human-Mobility Interactive Systems (2016 Disney near Zero District Project)



PARAMTRIC VARIATIONS



(Yang et al. 2018, accepted by *Engineering*)

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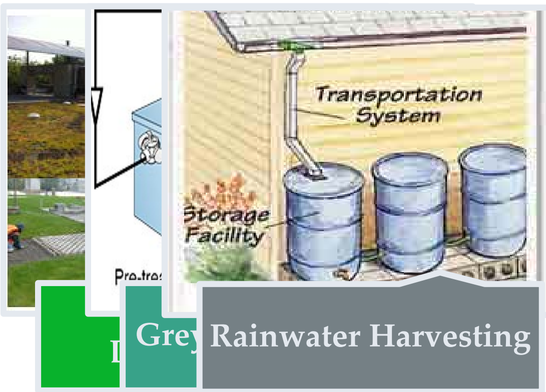
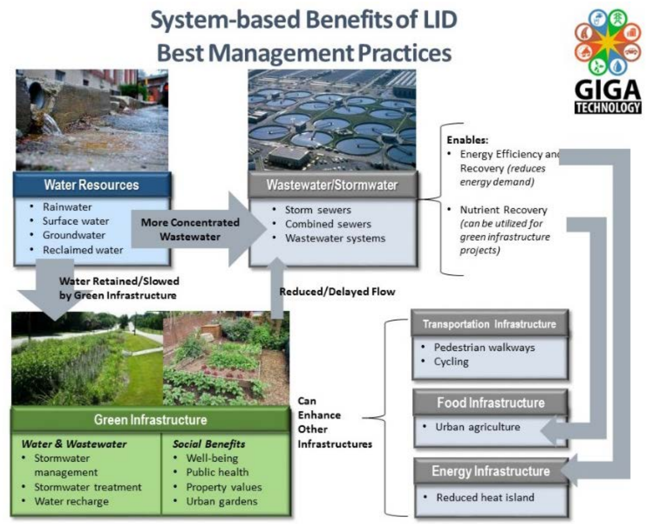
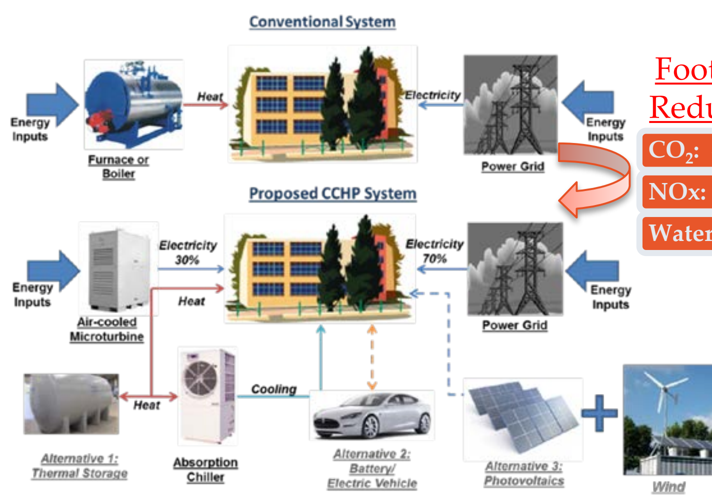
Synergistic Effects of "Infrastructure Ecology"

More than 50 Technologies ▶ Gigatech Platform Enabled Multiple Design Optimization (MDO) ▶ Desirable Amenities for a Given Climate, Topology and Location







Footprint Reduction

CO_2: -23%

NOx: -65%

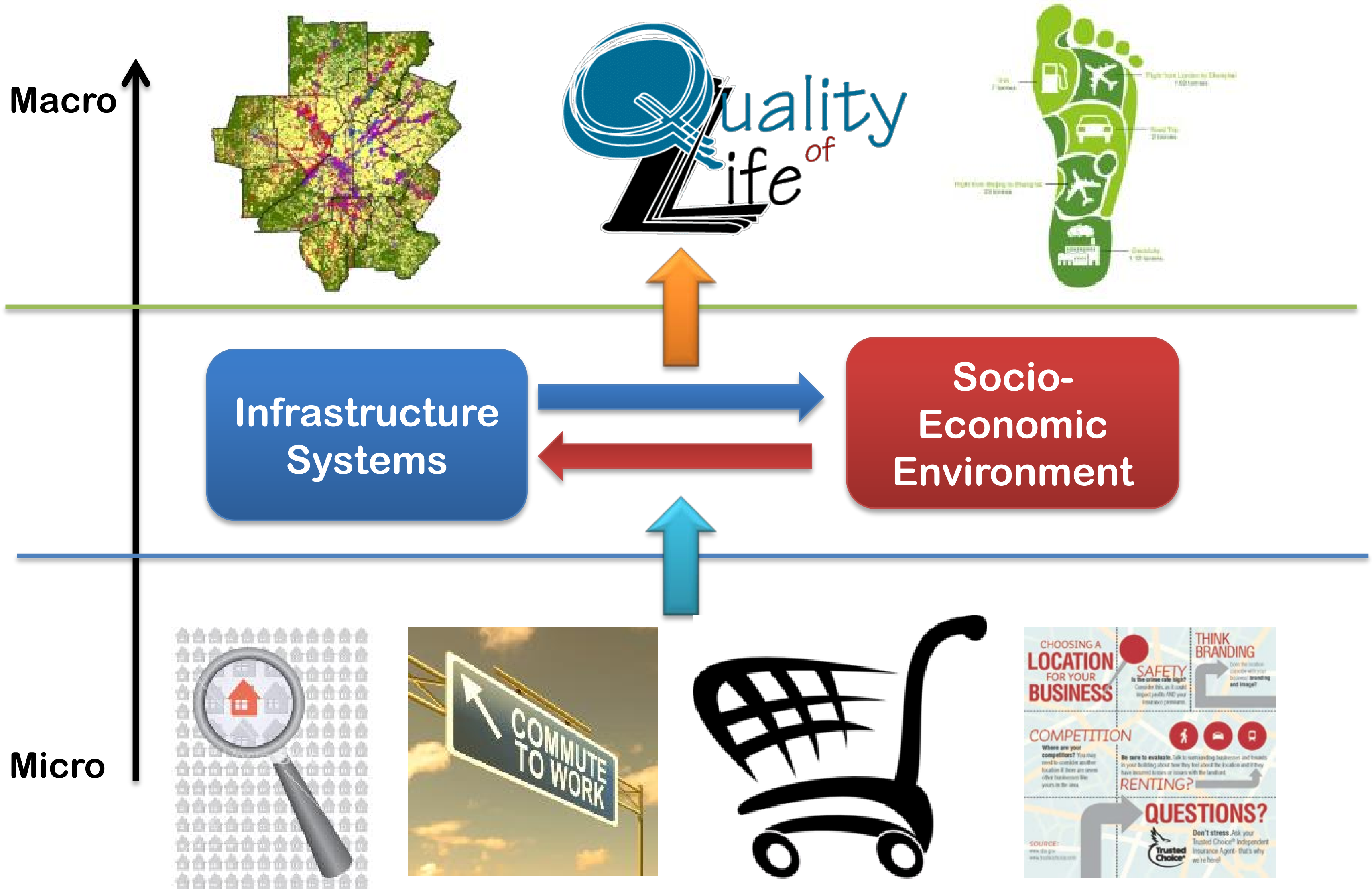
Water: -52%

The Potential Synergistic Effects

- Improve air quality and health
- Livable environment
- Reduced water and energy consumption
- Lower dependence on centralized systems
- Larger share of renewables in the electricity mix
- Reduced vehicle-miles travelled
- An increase in tax revenue
- Enhanced system resilience

Urban Systems Complexity

Emergence of desirable amenities (high Tax Revenue and Quality of Life) & undesirable amenities (e.g., poor air quality, low tax revenue, traffic congestion, flooding, etc.)



Big Data for Social Decision and Urban Complexity Modeling

Topic Modeling

Collect

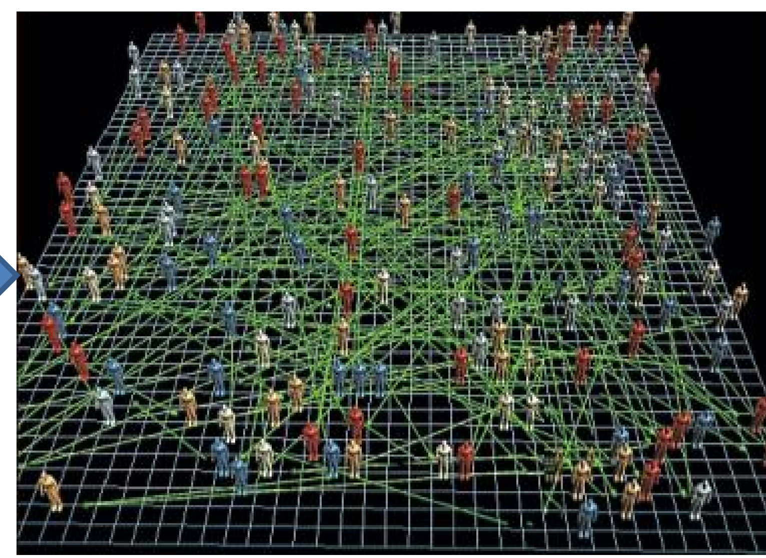
- Social Media
- Blogs
- Twitter
- News
- Product Reviews

Analyze

- Enrich and prepare social media content with metadata

Modeling

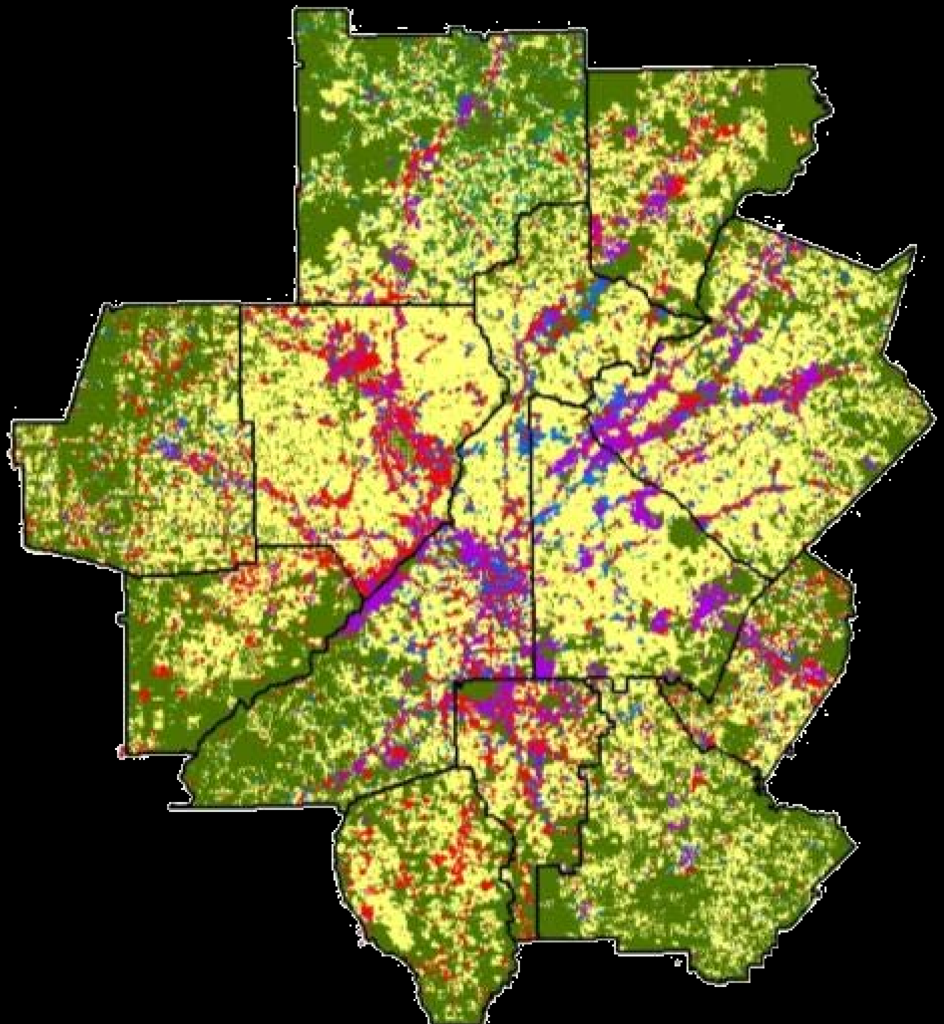
- Agent-based urban model and visualization



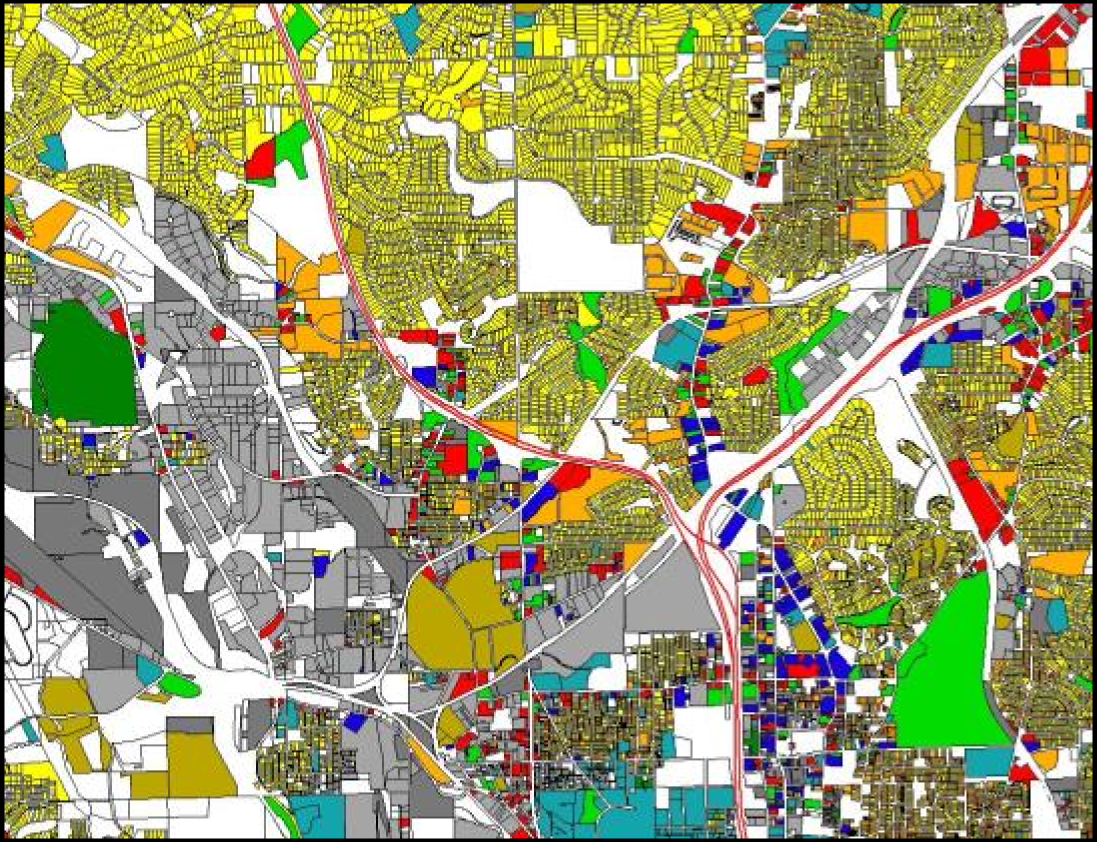
Water, Energy, Cost and Air Quality

■ Spatial Databases for Urban Modeling - 1

- The SMARTRAQ project
  - Supports research on land use impact on transportation and air quality
  - 1.3 million parcels in the 13 metropolitan Atlanta non-attainment counties



■SMARTRAQ DATA AND ATTRIBUTES

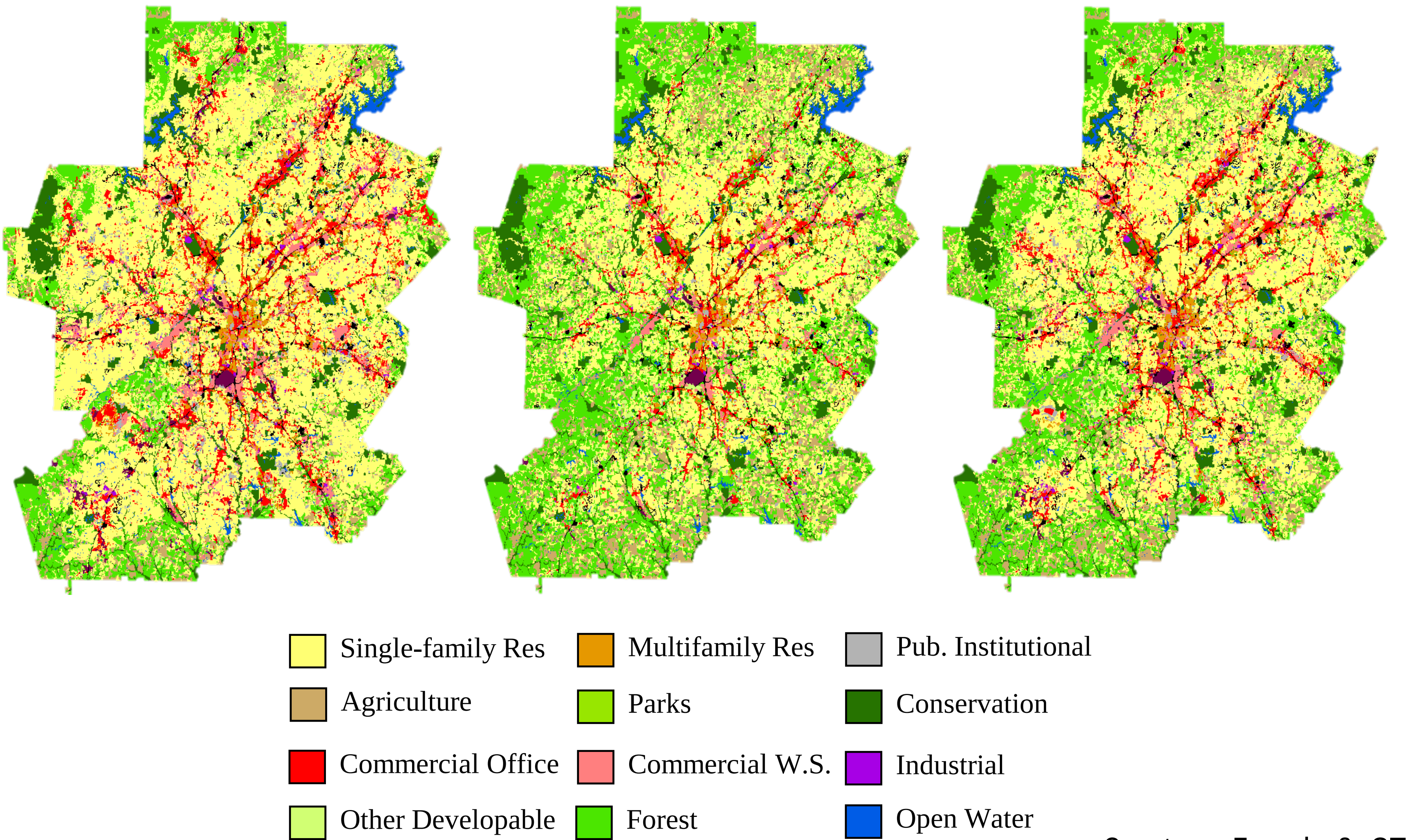


- Land Use Type
- Number of Units
- X,Y Coordinate
- Estimated Sq Feet
- Total Sq Feet

- Address
- Road Type
- City
- Zip Code
- Owner Occupied
- Commercial/Residential
- Zoning
- Sale Price
- Sale Date
- Tax Value
- Assessed Value
- Improvement Value
- Land Value
- Year Built
- No. of Stories
- Bedrooms
- Parking
- Acreage

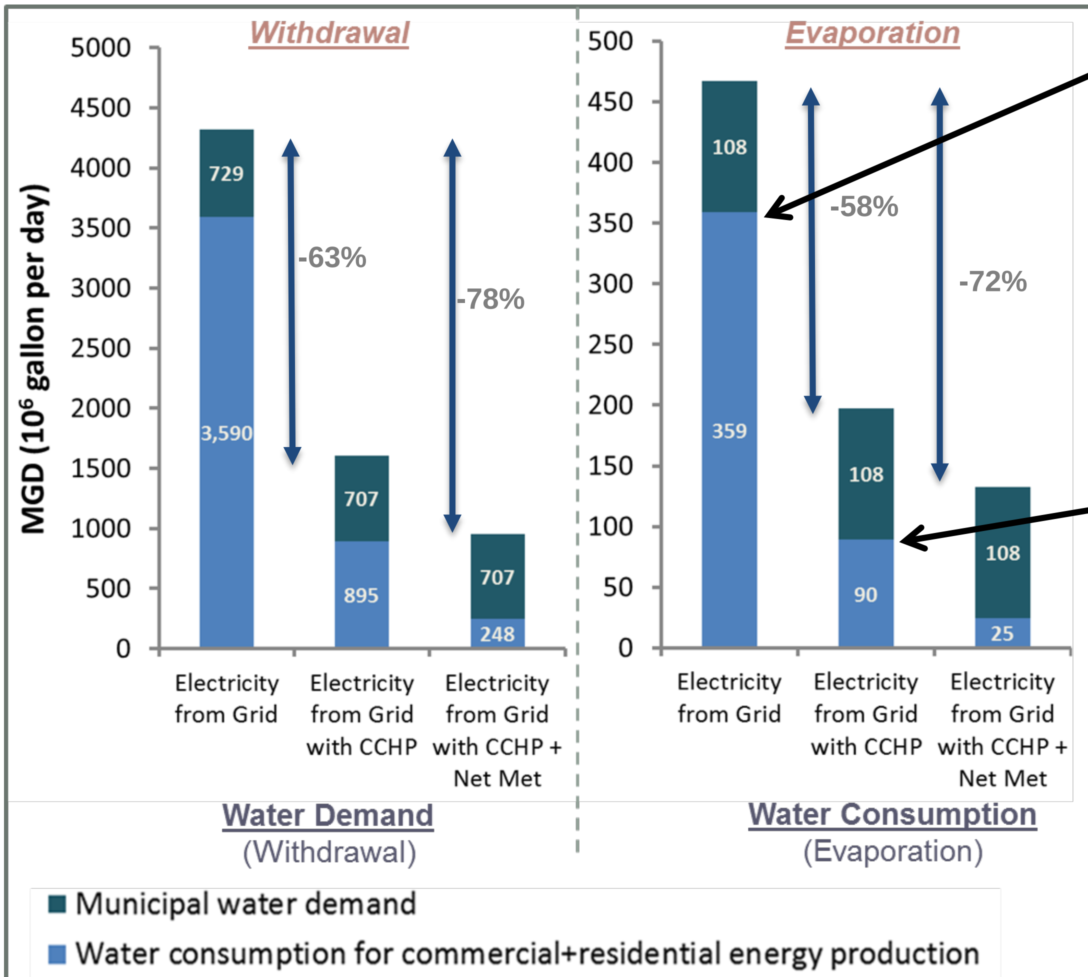
Growth Scenarios in Atlanta

Business As Usual 2030 | **Base Year 2005** | **More Compact Growth 2030**



Courtesy: French, S; GT

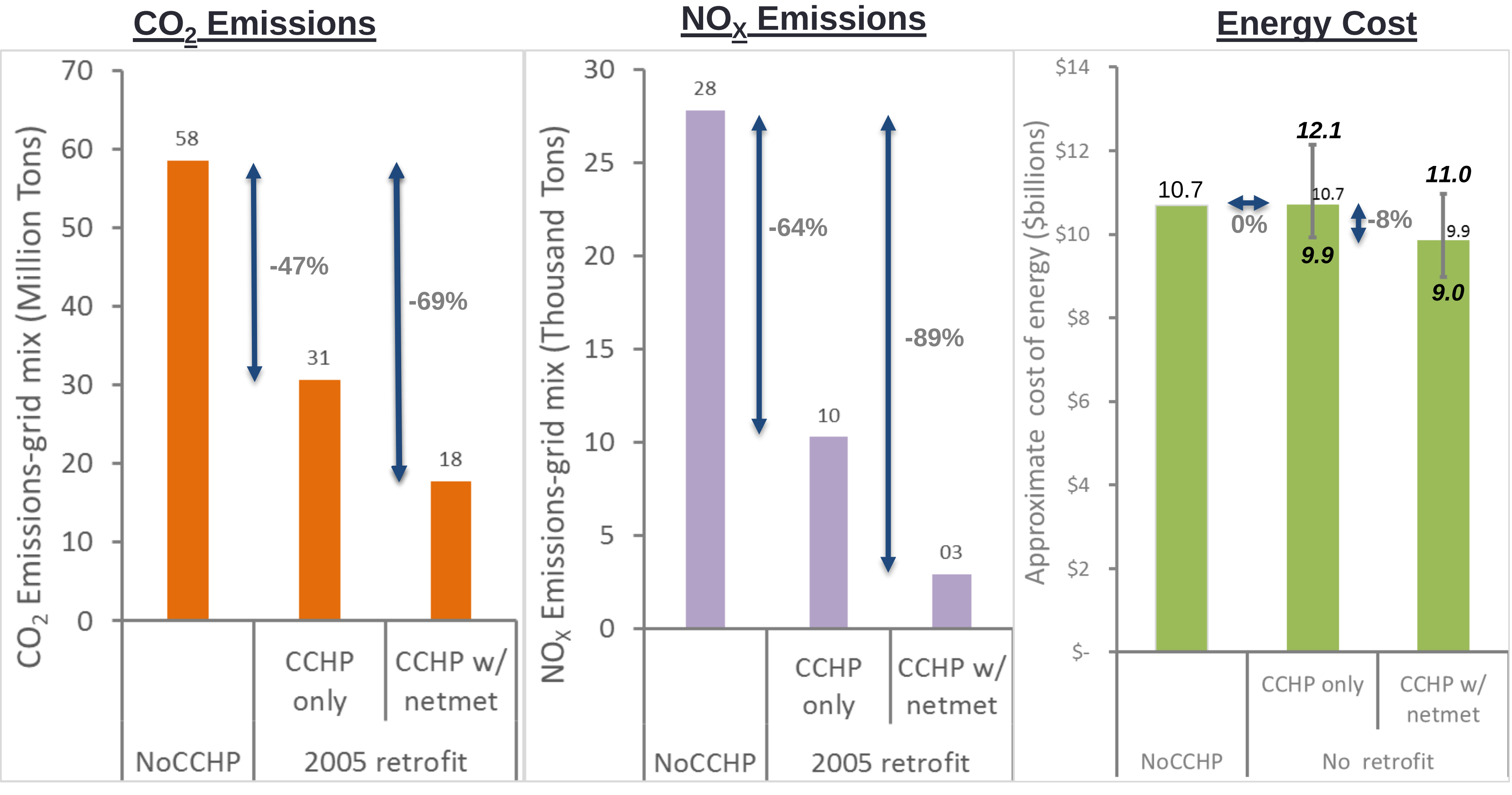
Atlanta Water Demand for New Residential and Commercial Buildings in More Compact Growth Scenario (with low flow fixtures + decentralized CCHP system)



Installation of Air Cooled Microturbines save 2.8 times the amount of water used for domestic consumption

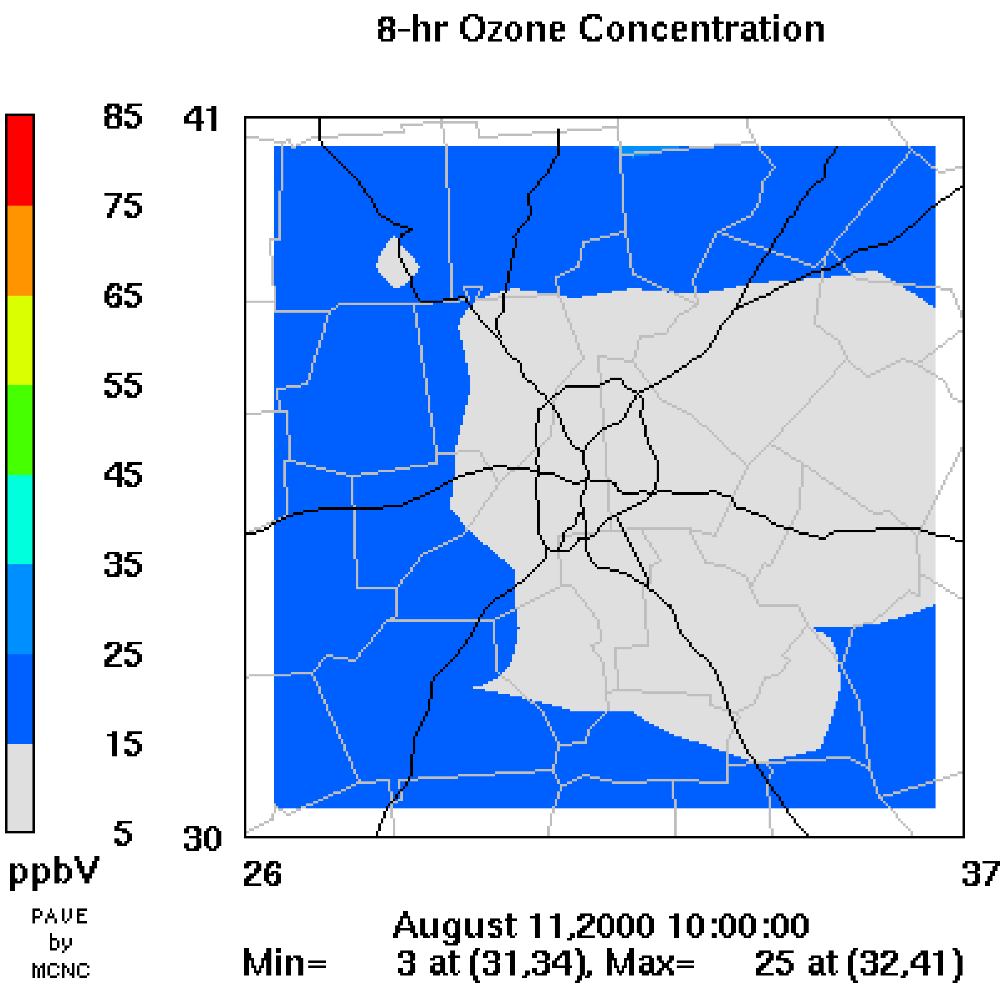
Potential GHG and Cost Reductions in 2030

By 2030, implementation of CCHP in all new and existing residential and commercial buildings could reduce CO_2 emissions by~ 0.04Gt CO_2, NOx emissions by ~ 25000 Tons ,and decrease energy costs by $600 million per year for the Metro Atlanta region.



Emergent Property: Ozone in ATL

Credit: Ted Russel



Outline

- What is Sustainability and the Gigaton Problem?
- How to Create More Sustainable and Resilient Urban Infrastructure:
  - Infrastructure Ecology
  - Emergent Properties
- The Hyper Nexus of Water, Energy, Land Use, Transport, Buildings, Citizens, etc., and Technological Options
- Managing Complexity and Putting It All Together
- Summary

What Could Future Cities Look Like

How your City could look in Future

The top 10 most likely architectural advancements within the next 100 years were:

- **Super-deep basements**
- **Floating sea cities**
- **High-rise or rooftop farms**
- 3D printed homes
- Buildings with their own micro-climates
- Bridges that span entire cities
- Spaceports with easy access to the moon and Mars
- Super-high buildings - 'cities in the sky'
- Underwater cities
- Collapsible/stackable living pods

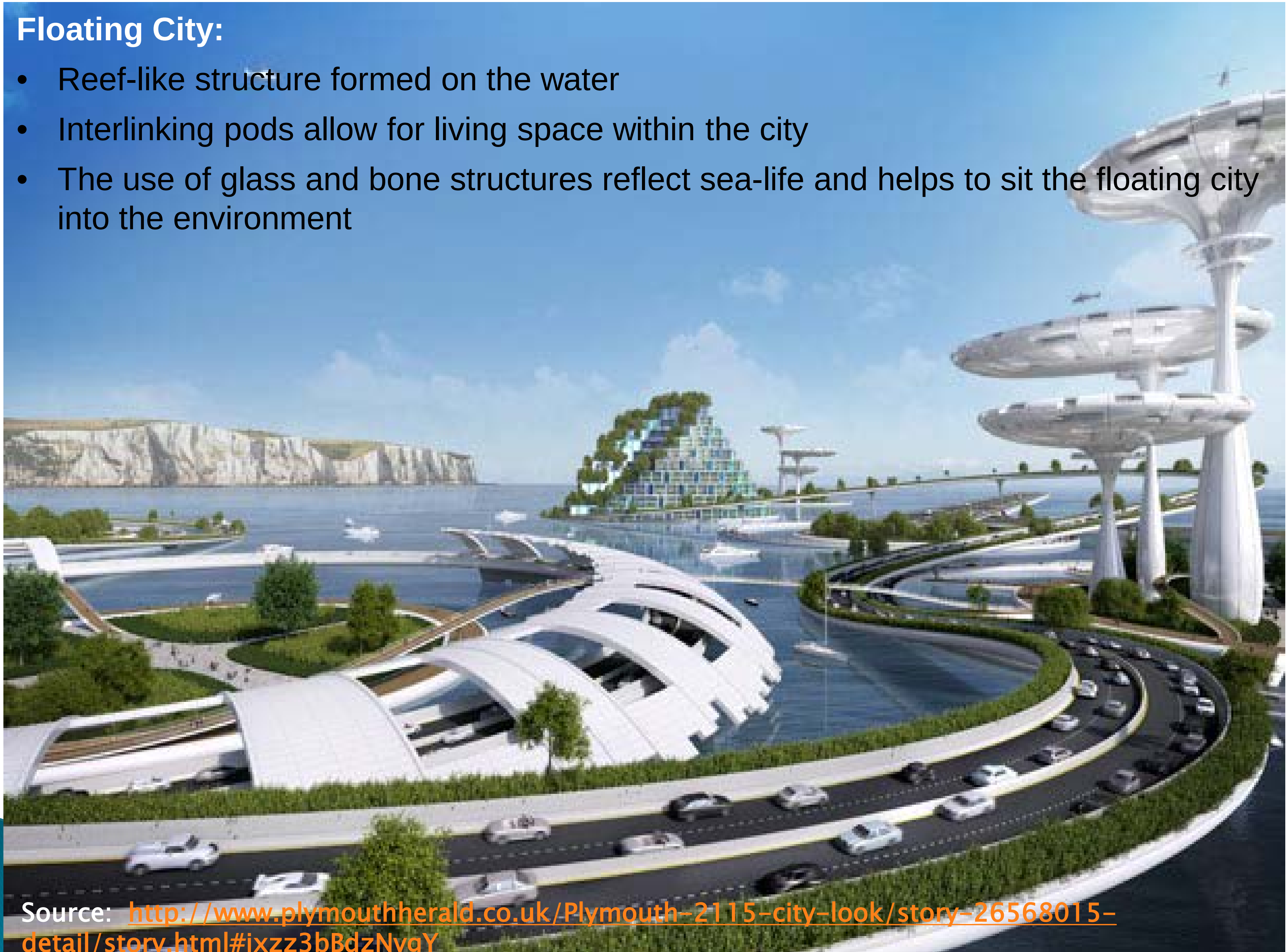
Many of the predictions were influenced by environmental conditions, with global warming and rising sea levels encouraging a focus on water-based architecture.

The predictions came from a distinguished panel including Dr. Rhys Morgan, Director of Engineering and Education at the Royal Academy of Engineering and award-winning architects and lecturers at the University of Westminster.

Source: http://www.plymouthherald.co.uk/Plymouth-2115-city-look/story-26568015-detail/story.html#ixzz3bBdzNvgY

Floating City:

- Reef-like structure formed on the water
- Interlinking pods allow for living space within the city
- The use of glass and bone structures reflect sea-life and helps to sit the floating city into the environment



Source: http://www.plymouthherald.co.uk/Plymouth-2115-city-look/story-26568015-detail/story.html#ixzz3bBdzNvgY

High Rise Farm:

- Animals graze on pastures on top of high-rise London buildings with familiar landmarks in the background.

Source: http://www.plymouthherald.co.uk/Plymouth-2115-city-look/story-26568015-detail/story.html#ixzz3bBdzNvgY

Los Angeles 1950s versus Today

Air and Water Quality have improved dramatically

Credit: WRI.

Pessimist

Optimist

Pragmatic
Possibilist

Summary

- Urban Systems Are All Connected and More Efficiency Can be Achieved by Looking at Their Interactions
- Decentralized Energy and Combined Heat and Power Can Save Energy and Water
- Decentralized Water / Low Impact Development Can Save Water, Energy and Money
- Land Use/ Planning Is Vital in Reducing the Impact Of Urban Systems and Examining Their Interactions
- Agent Based Models May Be Useful to Examine the Adoption Rate of Policy Instruments

Georgia Tech Clough Undergraduate Learning Commons

Final Thoughts

- Admittedly, the challenges are daunting and the magnitude of what we have to do is frightening.
- Unless we act upon now, the future would be much scarier.
- Even at Less than 2°C
  - Arctic sea icecap disappears; Droughts spread through the sub-tropics, accompanied by heat waves and intense wildfires.
- At 5°C-6°C
  - Global average temperatures would be hotter than for 50 million years.
  - The entire Arctic would be ice-free all year round.
  - Most of the tropics, sub-tropics and lower mid-latitudes would be too hot to be habitable.
  - Sea level rise would be sufficiently rapid that coastal cities across the world are largely abandoned.

- *"Even if we can't know what future citizens will actually value and believe in, we can still consider their interests, on the reasonable assumption that they will somewhat resemble our own (everybody needs breathable air, for example),"* and since our ethical and political values do always align, we *"should consider introducing agents who can vote in a far-seeing and impartial way."* – Thomas Wells
- **We as Engineers, Academics and Decision-makers have a much greater role to play to steer us and the world in the right direction.**

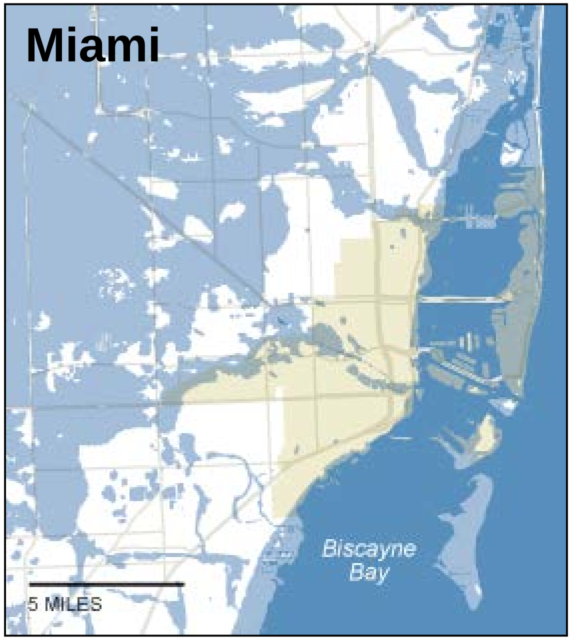
If all the Ice Melted: Sea Level Rise by 216 ft.

What Could Disappear with 5 ft. Sea Level Rise

(Probable in 100-300 years)

Logan Airport starts to disappear. Boston Harbor begins to encroach on downtown; the Charles River floods southern Cambridge.

If levees breach, almost all of the city would flood. The surrounding region is also mostly flooded.



Much of suburban Miami and the area's barrier islands, including Miami Beach, are submerged.

Reminder of the Past:
Cuyahoga River (Ohio) on Fire
November 4, 1952

Acknowledgements

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- Georgia Institute of Technology

PV System at Georgia Tech Aquatic Center (1996)

THANK YOU!

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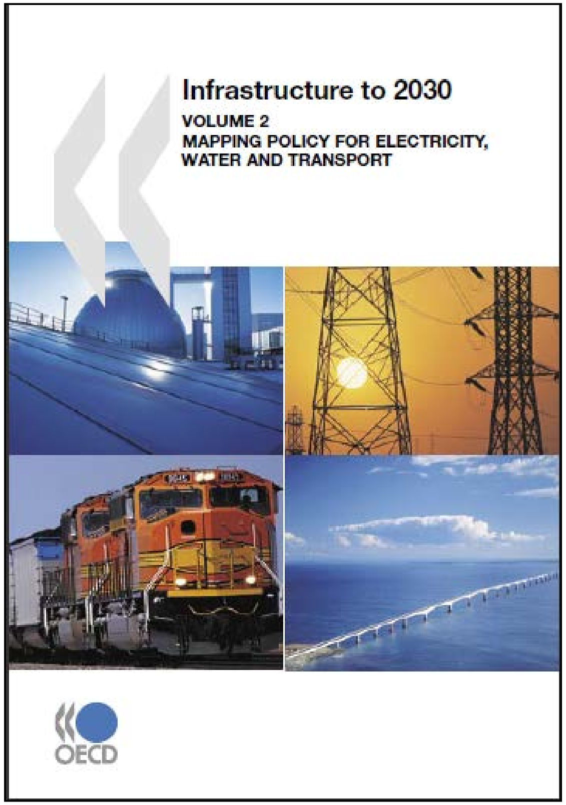
Lets Look at CARBON Cycle in Detail

Urban Transformation

- ***Double the urban infrastructure in the next 35 years*** (Took 5,000 years to get to this point)
- *US will increase 30 to 40% by 2030*
- It will last ***more than 50 years*** and ***80 to 90% of the impact is during the use phase.***
- Currently ***49% of the world's population and 81% of the US population lives in urban areas***, a figure which is expected to ***grow to 61% and 87%, respectively***, by ***2030*** (UNEP, 2005)



- ***Investment requirement in Urban Infrastructure***
  - Total cumulative infrastructure requirements in the five sectors [telecom, road, rail, water, and electricity (transmission and distribution only)] through to 2030 would amount to about ***USD 53 trillion.***
  - Adding in electricity generation would raise the figure to around ***USD 65 trillion***, and other energy-related infrastructure investments would take it up to more than ***USD 70 trillion.***

Our Vision for the Infrastructure Technology Genome

Infrastructure Classification	Novel Technology	Performance Metrics
Energy	Sewer Heat Mining	Heating Energy Supply (GJ) GHG Mitigation (t $CO_{2Eqv.}$) …
	…	…
Water	Low-Impact Development	Stormwater Retained (inches of rainfall) Total Phosphorus removed (lbs/year) Total Nitrogen removed (lbs/year) …
	…	…
Transport	Roadway Connectivity	Fractal Dimension (dimensionless)
	Transit Oriented Development	Reduction in vehicle miles travelled (vmt) …
	…	…
Buildings	Living Building	Reduction in water use (Gal/yr) …
	…	…