Gigaton Problems Require Gigaton Solutions: Urban Systems and Technology Opportunities

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Outline

- What is Sustainability?
- What is the Gigaton Problem?
- Urban Development Simulation, Infrastructure Ecology
- Material Flow Analysis
- Air Quality, Heat Island, Noise, Carbon Foot Print Simulations
- Conclusions
Sustainable Urban Systems

- We need to recreate the anthrosphere to exist within the means of nature. That is, use resources that nature provides and generate waste nature can assimilate without overwhelming natural cycles.

- This will require us to examine the interactions between the engineered, social and economic systems.
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Great Acceleration: Increasing Human Activities

Environmental and Ecological Consequences (Could be 9 times worse)

CO\textsubscript{2} Target – 70\% Reduction by 2100, 30\% by 2050

NCAR study published in *Geophysical Research Letters*(2009)

• Supercomputer studies with the NCAR-based Community Climate System Model (CCSM)
• Negative effects of climate change are unavoidable, but...
• If CO2 stabilized at 450 ppm, worst effects could be avoided.
• Sea-level rise would be about 14 cm (thermal expansion).
• Permafrost and Land Based Glacier Melt would largely be avoided.
• Business-as-usual = 750 ppm by 2100
Need to cut to 3.2 TW to Achieve 70% Reduction

Not Meant as Nuclear Power - Bashing but Nuclear Option = 16,300 Plants (Build 1/day for 44 years, $163 trillion)

7300 Nuclear Power Plants (1/day for 20 years, $73 trillion)
WWIII - The Plan

• To power the world with 11.5 TW WWS energy
  – 51% by wind (5.8 TW)
    • 3.8 million large wind turbines (5 MW each), 0.8% in place
  – 40% by solar (4.6 TW)
    • 1.7 billion rooftop PV systems (0.003 MW each), <1% in place
    • 89,000 PV and concentrated solar power plants (300 MW each)
  – 9% by water (1.1 TW)
    • 900 hydroelectric plants (1,300 MW each), 70% in place

Jacobson and Delucchi, 2009
Importance of Construction

U.S. CONSUMPTION OF RAW MATERIALS

5% is renewable!

Source: U.S. Geological Survey

Importance of Construction

U.S. CONSUMPTION OF RAW MATERIALS

5% is renewable!

Source: U.S. Geological Survey
Resource Consumption for Material Production

Credit: Mike Ashby
Iron Intensity for Transportation Options (180 persons)

Bicycles 15 kg/cap
Gigaton Problems Require Gigaton Solutions!

Gigaton (billion ton, $10^9$ ton/year, Gt) problems

- 5% renewable
- 20% nuclear + renewable
- 80% fossil fuels

John Crittenden
Fundamental Question for Solving the Gigaton Problems

Which will give the biggest payoff for the same investment of resources?

Energy
1. Develop greener energy production systems.
2. Implementing existing renewable energy technologies.

Materials
1. Refine existing technologies to use less energy and materials. For example, can we improve concrete, plastic, steel, aluminum, glass, etc. production to reduce energy use and reduce material use. Can we use less?
2. Develop new (green field) technologies that use renewable materials and less energy for production.
Energy Intensity (MJ/$) - Includes Purchasing Price Parity

China

U.S.
There is no single answer. Conservation can play a role!

Cost of energy savings is 1.8 cent/Kwhr

Cost of providing new energy production is 10.5 cents/Kwhr
Gigaton problems need gigaton solutions

- A substantial fraction of the gigaton problems derives directly from the structure and operation of urban infrastructures
- Create market incentives or stipulate mandates that get gigaton-investors and gigaton-entrepreneurs on task
There are over 76 million residential and 5 million commercial buildings in the U.S.

Commercial and residential building construction constitutes $805 billion of our GDP (6.1% of $13.2 trillion).

According to the US Green Building Council/EPA, in the United States, buildings account for:

- 72% of electricity consumption,
- 39% of energy use,
- 38% of all carbon dioxide (CO$_2$) emissions,
- 40% of raw materials use,
- 30% of waste output (136 million tons annually),
- 14% of potable water consumption.
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Urban Transformation

- Double the urban infrastructure in the next 35 years (Took 5,000 years to get to this point)
- Challenge will be to develop long term social, economic and environmental assets and not liabilities.
- 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, 2030 (UNEP, 2005)
Urban Landscape a System of Systems:

- Water System
- Energy System: Electrical, Gas
- Solid waste
- Heat Island
- Built Environment
- Air Quality
- Land use/Transportation
Infrastructure ecology

- Reorganizing the linkage among individual infrastructure systems is like changing food chains in ecology. The analogy is infrastructures are species and the urban system is an ecosystem.

- This *infrastructure ecology* has a high potential to significantly contribute to solving the gigaton problems.

- The engineering community needs to lead in studies of *infrastructure ecology* and solutions to the gigaton problems through the development of integrated and efficient infrastructure.
Reorganizing the infrastructure ecology

- Waste heat from electricity production could be utilized as heat through use of district heating systems or through application to food production systems or industrial processes
  - In the U.S., combined heat and power could potentially provide 20% of U.S. electricity by 2030, reducing CO$_2$ emissions by 0.8 gigatons annually
- Use of biomass to produce combined heat and power is more efficient than use of biomass to provide electricity or heat alone
- Recovery and reuse of nutrients from urban wastewater can contribute to reducing long-term water contamination problems and can simultaneously reduce water consumption
- Linking transportation and energy systems via instruments like a gas tax suggest that an “optimal” gas tax in the U.S. alone would reduce gasoline consumption by roughly 13%.
- Linking land use and built environment, water, and energy systems via a policy tool like impact fees (or land use regulations) can also encourage the innovation and adoption of more sustainable technologies and systems
Two of the largest components of the urban system can make big difference by combining them together to increase efficiencies. E.g., plug-in hybrid electric vehicles (PHEVs).
Plug-in Hybrid Electric Vehicles (PHEVs)

73% of the U.S. light duty vehicle fleet (cars, pickup trucks, SUVs, and vans) can be supported by existing electric power infrastructure

- 43% if only charging vehicles between 6pm-6am

This is equivalent to 52% of the nation’s oil imports (we import 50% of our oil)

27% of total greenhouse gas emissions can be reduced even if we use coal fired power plants

- Key driver: overall improvement in efficiency of electricity generation compared to the conversion process from crude oil to gasoline to the combustion in the vehicle

Utility cost (life-cycle) can be reduced between 7%~26%

Credit: PNNL 2007
Atlanta: Preliminary Results

- Poor environmental performance of electric vehicles, all sizes, due to coal fired powerplants
  - Georgia Power’s Plant Bowen emits about 0.9kgCO₂/kWh and consumes (evaporates) about 0.4 gallons H₂O/kWh
- Marta rail & bus performance bad due to low ridership

In progress: Addition of water assessments
System Combinations Land Use, Water Use, Transportation, Economic Flows

- Land Use
- Distributed Energy and Water Production
- Transportation
- Urban Form and Planning
- Real estate and other tax revenues
- Separate storm water treatment systems – Vancouver turning 4 billion dollar expense into a 400 million dollar advantage
Sustainable Urban Systems - Our Goals

- Predict the emergent properties of urban systems (e.g., economic structures, material, energy use, traffic and transportation patterns, urban health, heat island, land use and density, air quality, local regional and global impacts of the resource demands and waste generation)

- Understand how the flows of resources (information, energy, and materials) are utilized within the urban system of systems (Urban Metabolism) and reduce material and energy investments

- Develop the cyber infrastructure to gather information monitor, model and visualize the complex emergent properties

- Develop the pedagogy of engineering complex systems in the context of sustainability of urban systems
Framework of agent based models

Environmental Impacts
- Energy
- Material Flow
- Air Quality
- Water Quality
- Solid Waste
- Global Warming
- Ozone Depletion
- Urban Heat Island
- Others

Economic Models / Urban Land Use
- Macroeconomic Model
- Economic and Demographic Transition Model
- Accessibility / Mobility Model
- Location Choice Model
- Real Estate Development Model
- Land Price Model

Social Decision-making
- Agents
  - Household
  - Developer
  - Policy Maker
  - Business
  - Others

Knowledge Presentation/Dissemination
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
Parcel-based Spatial Data
SMARTRAQ DATA AND ATTRIBUTES

- 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

- Residential Units
- X,Y Coordinate
- Estimated Sq Feet
- Total Sq Feet
Land use and Employees per acre were predicted based on the input datasets, weight, and rating.

<table>
<thead>
<tr>
<th>Year</th>
<th>Scenario 1. Business as Usual</th>
<th>Scenario 2. Compact Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Land Use**
- Residential
- Employment
- Open Water
- Undeveloped
- Wetlands
- Undevelopable

**Employees /Acre**
- 0.0 - 1.000
- 1.001 - 2.000
- 2.001 - 5.000
- 5.001 - 10.00
- 10.01 - 200.0
Access to the Top 500 Employers

Population

30 km

0 km
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Cumulative Residential Construction Material Demands From 2002 to 2040 – Business as Usual for Phoenix

Year

Demand (thousand tons)

Aluminium
Cement
Gypsum
Iron and steel
Clay & shale
Sand
Wood material
Limestone
Coarse aggregate
Fine Aggregate
Future Work - Land and Material Use Scenarios, e.g., for Development

- Three General Plan Scenarios (slow growth, General Plan growth, fast growth)
- Dispersed Polynucleated City
- Strong Central City
- Resort Mecca
- Transportation Influenced
Importation: Scottsdale

- Receives water from Central Arizona Project (CAP Plant)
  - 200 mile canal
  - Conventional water treatment processes
  - Portion of the impacts based on portion of total water received (3%)
Desalination: Scottsdale

- Seawater is desalinated at the Sea of Cortez and then transported to Phoenix
  - Desalination plant at the Sea of Cortez
  - Pipeline system for water transportation (165 miles)
Reclamation: Scottsdale

- Reclaims wastewater for use (Reclaimed Plant)
  - Wastewater treatment, advanced water treatment, and groundwater recharge and extraction
  - Supplemented by groundwater
CAP Plant - System Diagram

CAP Canal → Screen → Coagulation → Flocculation → Sedimentation → Filtration → Disinfection → Use
## CAP Plant Inputs

<table>
<thead>
<tr>
<th></th>
<th>Per 120,000 gallons of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete ((10^{-3}m^3))</td>
<td>5.89</td>
</tr>
<tr>
<td>Steel (kg)</td>
<td>0.36</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>637</td>
</tr>
<tr>
<td>PAC (kg)</td>
<td>4.48</td>
</tr>
<tr>
<td>KMnO(_4) (kg)</td>
<td>0.37</td>
</tr>
<tr>
<td>Cationic Polymer (kg)</td>
<td>0.37</td>
</tr>
<tr>
<td>Alum (kg)</td>
<td>13.6</td>
</tr>
<tr>
<td>Chlorine (kg)</td>
<td>2.24</td>
</tr>
</tbody>
</table>
Scree > ReClamation Plant - System Diagram

1. Scree
2. Primary Clarification
3. Aeration
4. Secondary Clarification
5. Filtration
6. Disinfection
7. Reverse Osmosis
8. Stabilization
9. Aquifer Storage and Recovery
10. Use
# Reclamation Plant Inputs

<table>
<thead>
<tr>
<th></th>
<th>Per 120,000 gallons of water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete</strong> (10^{-3} \text{m}^3)</td>
<td>2.45</td>
</tr>
<tr>
<td><strong>Steel</strong> (kg)</td>
<td>0.145</td>
</tr>
<tr>
<td><strong>Energy</strong> (kWh)</td>
<td>427</td>
</tr>
<tr>
<td><strong>Chlorine</strong> (kg)</td>
<td>5.60</td>
</tr>
<tr>
<td><strong>Sulfuric acid</strong> (kg)</td>
<td>77.0</td>
</tr>
<tr>
<td><strong>Anti-scalant</strong> (kg)</td>
<td>2.21</td>
</tr>
<tr>
<td><strong>Lime</strong> (kg)</td>
<td>117</td>
</tr>
</tbody>
</table>
Desalination Plant - System Diagram

Sea of Cortez

- Seawater Intake
  - Screen
  - Chlorine
  - Filtration
  - Reverse Osmosis
  - Storage

Water Transportation Pipeline to Phoenix

Use

Connection to Phoenix Distribution System near Buckeye, AZ
# Desalination Plant Inputs

<table>
<thead>
<tr>
<th>Material</th>
<th>Per 120,000 gallons of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete ($10^{-3}m^3$)</td>
<td>0.459</td>
</tr>
<tr>
<td>Steel (kg)</td>
<td>18.8</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td><strong>3133</strong></td>
</tr>
<tr>
<td>Chlorine (kg)</td>
<td>0.22</td>
</tr>
<tr>
<td>Sulfuric acid (kg)</td>
<td>9.10</td>
</tr>
<tr>
<td>Sand (kg)</td>
<td>0.377</td>
</tr>
<tr>
<td>Anthracite (kg)</td>
<td>1.13</td>
</tr>
<tr>
<td>Lime (kg)</td>
<td>91.0</td>
</tr>
</tbody>
</table>
Material and Energy Inventory/ Person Year

- Materials:
  - Cap Plant: 35.6 kg
  - Reclamation: 208 kg
  - Desalination: 122 kg

- Energy:
  - Cap Plant: 637 Kwh
  - Reclamation: 427 Kwh
  - Desalination: 3133 Kwh
Eco-Indicator 99 Calculations

Mining
- Extraction of minerals and fossil fuels
- Land use and land conversion
- NOx, SOx, NH₃, Pesticides, Heavy metals, CO₂, HCFC, Nuclides, SPM, VOC, PAH

Converter
- Concentration of ores
- Concentration in soil
- Concentration of greenhouse gas
- Conc. ozone depleting substances
- Conc. radionuclides
- Conc. fine dust, VOC
- Conc. air, water and food

Milling
- Availability of fossil fuels
- Decrease of nat'l areas
- Altered pH & available nutrients

Pressing
- Surplus energy at future extraction
- Regional effect on species numbers
- Effect on target species
- Ecotoxicity: toxic stress (PAF)

Transport
- Surplus energy at future extraction
- Local effect on species numbers
- Climate change (disease + displacement)
- Ozone layer depletion (cancer + cataract)

Disposal
- Radiation effect (cancer)
- Respiratory effects
- Cancer

Inventory Analysis
Resource Analysis
Land-Use Analysis
Fate Analysis
Exposure and Effect Analysis
Damage Analysis
Damage to Resources
Damage to Ecosystems
Damage to Human Health
Comparison- Total Damages

<table>
<thead>
<tr>
<th></th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAP Plant</td>
<td>33.6</td>
</tr>
<tr>
<td>Reclamation Plant</td>
<td>25.7</td>
</tr>
<tr>
<td>Desalination Plant</td>
<td>164.0</td>
</tr>
</tbody>
</table>

- Damage to Resources
- Damage to Ecosystem Quality
- Damage to Human Health
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Total carbon footprint in 2010

Table 1: total number of different units

- Households: 1500000
- Cars: 40000000

Table 2: total CO2 emissions (tons) by different units

- Households: 500000
- Cars: 40000000

DigitalPhoenix:

[Image of a map or data visualization with bar charts showing the total carbon footprint in 2010 for different units and CO2 emissions]
Total carbon footprint in 2030

Table 1: total number of different units

<table>
<thead>
<tr>
<th>Units</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td>2500000</td>
</tr>
<tr>
<td>Cars</td>
<td>4500000</td>
</tr>
</tbody>
</table>

Table 2: total CO2 emissions (tons) by different units

<table>
<thead>
<tr>
<th>Units</th>
<th>Emissions (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td>3000000</td>
</tr>
<tr>
<td>Cars</td>
<td>4000000</td>
</tr>
</tbody>
</table>

Image © 2007 DigitalGlobe, Inc. All rights reserved.
Ground-level ozone distribution
1999 VS. 2015

The animation shows a shortened ozone distribution in 2015 compared to 1999.
Difference in Temperature Contour in 1998 and 2040 (Predicted by UrbanSim)

Zehnder, Clarke, Guhathakurta, Li Crittenden
Noise – Predicted from Development Patterns and Traffic Patterns

Martin Rumberg and Ariane Middel, TU Kaiserslautern
Resilience of the U.S. Economy

What happens if the financial sector drops 1%?

Network visualization of the U.S. economy

“Skeleton and Backbone” of the U.S. economy

Ming Xu
Remote Sensing

- Can we develop a taxonomy of growing cities?
- How can cities minimize their environmental impact?
- How can urban security threats be minimized?
- How can technologies promote sustainability?
Remote Sensing of Urban Features

Las Vegas, NV, 17-Oct-2000

Visible to near-infrared
15 m/pixel

Major land cover classes
- Vegetation health
- Soil properties
- Soil contamination

Shortwave infrared
30 m/pixel

Urban surface materials
- Rooftop materials
- Energy use
- Fugitive dust production
- Metal contamination
- Ecological communities

Thermal infrared bands
90 m/pixel

Surface energy balances
- Regional climate models
- Anthropogenic heat sources
- Heat island development
Cyber Infrastructure

- Tremendous Opportunity to Influence it for Urban Sustainability
- NAE Definition
  - Human
  - Hardware
  - Software
- Wireless Communication
- Sensors (Remote and Embedded)
- Modeling
- Data Mining and Fusion
- Visualization
Computable tags for material flow and recycling

Radio Frequency Induced Device Indentification tag could be used for material flow analysis and include environmental, social and economic performance information.
Plastic Container of Liquid Soap

Deployed on Sep 05, 2009 in New York

Traveled 18.3 Miles

Category: Plastic
Tuning Fork Ozone Detector for a Cell Phone

Real-Time Ozone Detection Based on a Microfabricated Quartz Crystal Tuning Fork Sensor

Rui Wang $^{1,2}$, Francis Tsow $^{1,2}$, Xuezhi Zhang $^3$, Jhih-Hong Peng $^2$, Erica S. Forzani $^{1,2}$, Yongsheng Chen $^{3,8,*}$, John C. Crittenden $^{3,8}$, Hugo Destaillats $^{3,4,*}$ and Nongjian Tao $^{1,2,*}$
What’s Next? 3D modeling and Visualization
Los Angeles 1950s versus Today
Credit: WRI. Air and Water Quality has improved dramatically
Thoughts on Solving the Gigaton Problem

• High performance buildings
• Efficient power generation
• Electrification of transportation
• Enhancing ecosystem services or avoiding their destruction
• Mandates for product performance and take back
• Market drivers for energy efficiency (SEAR 16 versus 13 etc.)
• Smart grid
• Distributed power and water generation
• Biomass reforming to create fuels, commodity chemicals, specialty chemicals
• Integrated resource recovery (metals, nutrients, energy etc from waste or shall I say byproducts)
• Policy issues that relate to the above
• Econometrics and economic flows that favor the above
• Devise a market or stipulate mandates that gets gigainvestors and gigaentrepreneurs on task.
Experience Curve for PV

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- Concluding Remarks
Two Planets meet in Space

- Arranging our ideological deck chairs on the Titanic
- Sooner or later, the earth will come into equilibrium; that is, resources generated will equal resources used. There are two fundamental questions: 1) Will humans be part of the new earth that is in equilibrium. 2) If humans are, will it be a comfortable place or a place wrought with armed conflict and social injustice because of limited resources.

Credit: Volker Karthopf

Inspired us to sacrifice for the greater good. Why not now?

Create an anthrosphere that exists within the means of nature. Uses resources that Nature can provide and generates wastes the Nature can assimilate.

Provide the developing world opportunities to lead useful and productive lives

Become a global leader in developing more sustainable technologies

Achieve energy self-sufficiency by 2020 with efficiency, renewables and reduce Carbon Emissions 70%

America’s Grand Challenge - A Sustainable Future

Become the most generous country in the world again by providing medicines, technology transfer, and aid to people in developing nations everywhere

Obama?

Sustainable Differentiation = Innovation (e.g., Carbon Advantage)