Nexus of Energy, Water and Land Use: A Blueprint for Sustainable Urban Systems

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Sustainable Urban Systems

• We need to *recreate the anthrosphere 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.

• This will require us to examine the interactions between the natural, engineered, social and economic systems.
Sustainable Urban Systems

• Generate waste that nature can assimilate without overwhelming natural cycles.
• Need to look at fate of toxics, Nitrogen, Phosphorus, Water, Carbon, etc. cycles.
• Lets look at **Carbon**.
IEA BLUE MAP SCENARIO FOR 2050
Key technologies to reduce Global CO₂ emissions

Source: Energy Technology Perspectives 2010, Key Graphs, IEA 2010
Additional investment needs:
BLUE Map vs. Baseline ($48 Trillion, 2% GDP)

Transport is the most important category!

Source: Energy Technology Perspectives 2010, Key Graphs, IEA 2010
Sustainable Urban Systems

• Use renewable resources that nature provides.
• Of the 14 gigatons/year of material is used in world economy and only 5% is renewable
Resource Consumption for Material Production

(Energy Required for top 7 materials 1.5 TW - ~10% of total global energy use)

*Ratio based on mix design for 30 MPa compressive strength at 28 days (http://www.ctre.iastate.edu/pubs/sustainable/strublesustainable.pdf)
Iron Intensity for Transportation Options
(180 persons)

<table>
<thead>
<tr>
<th>Bicycle</th>
<th>Walking</th>
<th>Bus</th>
<th>Personal Car</th>
</tr>
</thead>
</table>

- 15 kg Fe/cap

Credit: Tom Graedel
Gigaton Problems Need Gigaton Solutions

- With 1 billion people using 14 Gt of materials, 12 Gtoe of energy, 2*10^6 billion Gal of water and emitting 8 Gt of Carbon per year globally, 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.
- With more than half of the population being urban dwellers, urban infrastructure plays a crucial role in the approach toward sustainability.
- Reduce Childhood mortality as a solution to population growth

<table>
<thead>
<tr>
<th>Population (Total)</th>
<th>Material Use (Gt/yr)</th>
<th>Energy Use (ton of oil equivalent)</th>
<th>Carbon from fossil fuels (Gt/yr)</th>
<th>Water Use (10Km^3/yr)*</th>
<th>Passenger Cars (Total number of units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 billion</td>
<td>14 Gt</td>
<td>12 Gtoe</td>
<td>2*10^6 billion</td>
<td>8 Gt</td>
<td>54% of available freshwater</td>
</tr>
</tbody>
</table>

5% renewable

20% nuclear + renewable

54% of available freshwater
Childhood Mortality and Population Growth

Source: Gapminder.org
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 giga-researchers, giga-investors and giga-entrepreneurs on task

**Thoughts on solving the Gigaton Problem:**

- High performance buildings
- Efficient power generation
- Electrification of transportation
- Enhancing ecosystem services and/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)
- Implementation of socio-economic policies to favor the market for sustainable solutions.
Urban Transformation

- **Double the urban infrastructure in the next 35 years** (Took 5,000 years to get to this point)
- 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**.
Q: With the next generation of infrastructure, what are the implications if we design, build, and operate these systems separately, as we have done in the past?
Infrastructure Ecology

- $Y = Y_0 \times N^\beta$: observation, $Y$ is system indicator, $N$ is population number;
- Infrastructure ecology is a metaphor to describe the complex interdependence between infrastructural, environmental, economic and social components in urban areas.

### Scaling exponents for urban indicators vs. city size

<table>
<thead>
<tr>
<th>Indicator</th>
<th>$\beta$</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>New patents</td>
<td>1.27</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Inventors</td>
<td>1.25</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Private R&amp;D employment</td>
<td>1.34</td>
<td>U.S. 2002</td>
</tr>
<tr>
<td>&quot;Supercreative&quot; employment</td>
<td>1.15</td>
<td>U.S. 2003</td>
</tr>
<tr>
<td>R&amp;D establishments</td>
<td>1.19</td>
<td>U.S. 1997</td>
</tr>
<tr>
<td>R&amp;D employment</td>
<td>1.26</td>
<td>China 2002</td>
</tr>
<tr>
<td>Total wages</td>
<td>1.12</td>
<td>U.S. 2002</td>
</tr>
<tr>
<td>Total bank deposits</td>
<td>1.08</td>
<td>U.S. 1996</td>
</tr>
<tr>
<td>GDP</td>
<td>1.15</td>
<td>China 2002</td>
</tr>
<tr>
<td>GDP</td>
<td>1.26</td>
<td>EU 1999–2003</td>
</tr>
<tr>
<td>GDP</td>
<td>1.13</td>
<td>Germany 2003</td>
</tr>
<tr>
<td>Total electrical consumption</td>
<td>1.07</td>
<td>Germany 2002</td>
</tr>
<tr>
<td>Serious crimes</td>
<td>1.16</td>
<td>U.S. 2003</td>
</tr>
<tr>
<td>Total housing</td>
<td>1.00</td>
<td>U.S. 1990</td>
</tr>
<tr>
<td>Total employment</td>
<td>1.01</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Household electrical consumption</td>
<td>1.00</td>
<td>Germany 2002</td>
</tr>
<tr>
<td>Household electrical consumption</td>
<td>1.05</td>
<td>China 2002</td>
</tr>
<tr>
<td>Household water consumption</td>
<td>1.01</td>
<td>China 2002</td>
</tr>
<tr>
<td>Gasoline stations</td>
<td>0.77</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Gasoline sales</td>
<td>0.79</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Length of electrical cables</td>
<td>0.87</td>
<td>Germany 2002</td>
</tr>
<tr>
<td>Road surface</td>
<td>0.83</td>
<td>Germany 2002</td>
</tr>
</tbody>
</table>

Systems-level regularities emerge from the collective behavior of cities’ individual components, citizens, and their interactions. The specific contribution of each component and mechanisms governing their interactions remain largely unknown.

Interdependence of Different Infrastructure Components

Interrelation of different infrastructure components
Combined Heat and Power Generation

In the U.S., combined heat and power
• Accounted for 7% of U.S. electricity generation capacity as in 1999.
• Had a typical system efficiency of 68%, with some new systems exceeding 90%.
• Emitted on average $\frac{1}{10}$ of the nitrogen oxides (NO$_X$) per kWh of average utility grid electricity.

• Could potentially provide
  • 20% of U.S. electricity by 2030, &
  • reduce CO$_2$ emissions by 0.2 Gt-C annually

• EU27 produced 366 TWh of CHP electricity, i.e. 11% of the total electricity generation in 2007.

• Combined Cycle Natural Gas is 60% Efficient – Georgia power retiring 500 MW plant and building 2500 MW at McDonough.

Perkins + Will, Atlanta Office

• LEED Platinum Building:
  – Microturbines are used for heating and cooling using Adsorption Chillers
  – Radiant heating floors system
  – Microturbines also supply 40% of the total electricity

Adsorption Chiller

65 kW Microturbine

Perkins+Will Office Building
Combined Heat and Power (CHP)
GW scale: ~ 1 million homes

Credit: Valerie Thomas.
Electric Power Infrastructure of Denmark

- Exemplary Case-study on
  - Combined Heat and Power Generation
  - Distributed Power Generation
### Electric Power Infrastructure of Denmark

<table>
<thead>
<tr>
<th>Electricity Capacity</th>
<th>13409 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine Capacity - Share of Total Electricity Capacity</td>
<td>26%</td>
</tr>
<tr>
<td>CHP Production - Share of Total Thermal Electricity</td>
<td>55%</td>
</tr>
<tr>
<td>CHP Production - Share of Total District Heating Production</td>
<td>77%</td>
</tr>
</tbody>
</table>

- Today all cities and most towns in Denmark are supplied with district heating.
- As much as **55% of all electricity produced in Denmark is from CHPs**. No other EU country has such a large share.
- About **30% of the fuel is saved in CHP** compared to a situation, where heat and electricity were supplied by separate productions.
- Denmark is in the international forefront with regard to modern **CHPs with a net efficiency ratio of 90-98%**.
- 60% of the total demand for heating of buildings and supply of hot water is covered by district heating. A remarkable market share compared to other countries.
- The annual statistics document that 9 out of 10 families pay less for their district heat compared to heat from individual supply from oil or gas.
- The use of cleaner fuels also matters. The fuels have for decades been diversified ranging from coal and natural gas to waste and biomass. It is estimated that CHP and district heating has **reduced total national CO₂-emission by 8-11 Mt per year**.
Electrification of Personal Vehicles

Plug-In Hybrid Electric vehicles (PHEVs) (Source: PNNL, 2007)

- 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 usage (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%

EPA Fuel Economy and Environmental Comparisons

<table>
<thead>
<tr>
<th>Charge Time</th>
<th>4 hours @ 240V</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Electric</td>
<td>93 MPGe</td>
</tr>
</tbody>
</table>
- When battery is fully charged, first 35 miles only.
- 36 kWh/100 miles

| Gas Only | 37 MPG |
- When electricity is used up, runs on gas for another 344 miles.
- 2.7 gallons per 100 miles

<table>
<thead>
<tr>
<th>Range (Miles)</th>
<th>All Electric Range (battery)</th>
<th>Extended Range (gas)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>35</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>379</td>
<td>350</td>
<td>369</td>
<td>370</td>
</tr>
</tbody>
</table>

Utility cost (life-cycle): $601 vs $1,302
Plug-in Hybrid Electric Vehicles (PHEVs) and Vehicle-to-Grid (V2G) power

PHEVs can send power back to the grid when parked, and function as distributed storage for intermittent energy from renewable sources.

US demand-supply balances during maximum demand with various V2G ratios in 2045

30% V2G penetration could reduce ~100 GW or about ⅓ of the total peak demand of ~300 GW in US by 2045

Source: Modelling Load Shifting Using Electric Vehicles in a Smart Grid Environment – © OECD/IEA 2010
Energy for Water in US

Average Energy requirement for different water and wastewater treatment technologies

<table>
<thead>
<tr>
<th>Water Collection and Treatment*</th>
<th>kWh/MGal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Water Treatment</td>
<td>220</td>
</tr>
<tr>
<td>Groundwater Treatment</td>
<td>620</td>
</tr>
<tr>
<td>Brackish Groundwater Treatment</td>
<td>3,900-9,700</td>
</tr>
<tr>
<td>Seawater Desalination</td>
<td>9,700-16,500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wastewater Treatment**</th>
<th>kWh/MGal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trickling Filter</td>
<td>950</td>
</tr>
<tr>
<td>Activated Sludge</td>
<td>1,300</td>
</tr>
<tr>
<td>Advanced Treatment without Nitrification</td>
<td>1,500</td>
</tr>
<tr>
<td>Advanced Treatment without Nitrification</td>
<td>1,900</td>
</tr>
</tbody>
</table>

Energy consumption by Public Water and Wastewater Utilities (in Billion kWh)

- About 4% of the total electricity consumption in US is for water and wastewater sector.
- About 19% of the total electricity consumption in California is for water and wastewater sector (average).

*Includes collection but does not include distribution
**More advanced treatment require more energy

1 EPRI, Water & Sustainability, Volume 4, 2002
Energy Saving Potential

<table>
<thead>
<tr>
<th>unit</th>
<th>Water Supply</th>
<th>Wastewater Collection and Treatment</th>
<th>Stormwater Collection and Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWh/kgal</td>
<td>1.7</td>
<td>1.83</td>
<td>1.464</td>
</tr>
</tbody>
</table>

**Per house unit land use**

- energy saving from land use and stormwater management

- Water saving from energy saving (1.65 gal/kwh based on Atlanta’s energy mix)

<table>
<thead>
<tr>
<th>unit</th>
<th>BAU</th>
<th>BAU + Rooftop rain harvesting</th>
<th>Compact growth</th>
<th>Compact growth + Rooftop rain harvesting</th>
<th>Compact growth + Rooftop &amp; Rain garden harvesting</th>
</tr>
</thead>
<tbody>
<tr>
<td>kgal</td>
<td>0</td>
<td>0.4</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Water for Energy in US (gal/kW-hr)

- Western Interconnect
- Eastern Interconnect
- Texas Interconnect
- Arizona
- Georgia
- US Aggregate

Thermoelectric
Hydro
Weighted Average

<table>
<thead>
<tr>
<th>Region</th>
<th>Thermoelectric</th>
<th>Hydro</th>
<th>Weighted Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Interconnect</td>
<td>0.38</td>
<td>12.40</td>
<td>4.42</td>
</tr>
<tr>
<td>Eastern Interconnect</td>
<td>0.49</td>
<td>55.10</td>
<td>2.33</td>
</tr>
<tr>
<td>Texas Interconnect</td>
<td>0.44</td>
<td>4.42</td>
<td>0.43</td>
</tr>
<tr>
<td>Arizona</td>
<td>0.32</td>
<td>64.85</td>
<td>7.85</td>
</tr>
<tr>
<td>Georgia</td>
<td>0.60</td>
<td>47.42</td>
<td>1.65</td>
</tr>
<tr>
<td>US Aggregate</td>
<td>0.47</td>
<td>18.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>
Daily Water Saving by PV Penetration - ATL

- Household peak demand
  4 kW

- PV penetration
  10%(0.4 kW) and 30%(1.2 kW)

- Load factor
  0.4
  \[
  \frac{\text{Energy Consumption}}{\text{Energy Availability}}
  \]

- Average water consumption for energy
  1.65 gal/kWh
  based on Georgia Energy Mix
  Coal 70 %
  Natural Gas 15%
  Nuclear 14 %
  Hydroelectric 1 %

- Domestic water consumption
  Evapo-transpiration is around 80 % of outdoor water use
TEST BEDS

- The Springs community, located in Chandler, AZ, was first selected and used as a test bed to research microgrid design methods.
SIMULATION – 65 kW Microturbines and PV Arrays. Enough Gas, 50% of Water, Cost $.336/kWhr
Optimal Microgrid Configuration

- **Optimal Configuration** of microgrid system
  - PV capacity: 157 kW
  - Microturbine capacity: 270 kW for total five units

- COE (cost of electricity)
  - $0.336 per kWh

- Natural gas demand
  - 3830 SCFH (cubic feet per hour) for microturbines
  - About 0.005% of Natural gas capacity, 69.699 ~ 101.23 x 10^6 CFH

**Water Demand and Supply Capacity**

- Domestics Water for 81 Homes: 24.5 gpm
- Water for Central Energy Supply: 17 gpm
- Water for 270 kW Microturbine: 200 gpm
- Water Main: 414 gpm

**Total water demand occupies 54% of supply**
Energy for Transportation: Atlanta

**Preliminary Energy & CO₂ Results, Atlanta (Base Case)**

- Poor environmental performance of electric vehicles, all sizes, due to coal fired power plants
  - Georgia Power’s Plant Bowen emits about 0.9kg CO₂/kWh
- MARTA rail & bus performance bad due to low ridership
Water for Transportation in US

Life Cycle consumptive water use by different transportation fuel alternatives

(Source: Harto, C; et al., Life cycle water use of low-carbon transport fuels, Energy Policy, 2010)
Water for Mobility Network: 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
Case Study: Storm Water Treatment for Vancouver

- It was estimated that there was a $4 billion expense to separate stormwater systems from wastewater. However, when they opted for LID technique implementation there was an estimated $400 million income from increased property value and associated tax revenue.

- The new concept was aptly titled “From Pipe Dreams to Healthy Streams: A Vision for the Still Creek Watershed“
Outline

• What is Sustainability and the Gigaton Problem?
• Infrastructure Ecology
• Low Impact Development
• Complexity and Urban Development Simulation
• Material Flow Analysis
• Air Quality, Heat Island, Noise, Carbon Foot Print Simulations
• Conclusions
LID Techniques for SW Management

- Bioretention
- Cistern
- Constructed Wetland
- Dry Pond
- Grassed Swale
- Green Roof
- Infiltration Basin
- Infiltration Trench
- Porous Pavement
- Rain Barrel
- Sand Filter
- Vegetated Filterstrip
- Wet Pond

Potential effects of LID technique implementation in urbanized areas of Southern California and San Francisco Bay region:

<table>
<thead>
<tr>
<th></th>
<th>Water Savings (acre-ft/yr)</th>
<th>Energy Savings (MWh/yr)</th>
<th>CO₂ Savings (Mt CO₂-equiv.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>229,000</td>
<td>573,000</td>
<td>250,500</td>
</tr>
<tr>
<td>Medium</td>
<td>314,500</td>
<td>867,000</td>
<td>379,000</td>
</tr>
<tr>
<td>High</td>
<td>405,000</td>
<td>1,225,500</td>
<td>535,500</td>
</tr>
</tbody>
</table>

Bioretention Basins  | Rain Barrel and Green Roof, Atlanta (Southface)  | Pervious Pavement  | Vegetated Swale, Vancouver (Crown Street)
Alternatives and Case Studies

Rainwater Harvesting
Green space & Onsite WW reclamation
Sewer Mining and Onsite WW reclamation

Energy Recovery
Nutrient Recovery
Smart Irrigator
Small Water Fixture
Wastewater as Energy/Nutrient Resource

- **Nutrient Recovery**
  Global phosphorus reserves may be depleted in 50 ~ 100 years (Gunther, 2005)
  Phosphorus available from *feces and urine*
  : 22% of total global phosphorus demand (Mihelcic, 2011)
  Phosphorus available from *manure*
  : 42% of all P applications to crops in US (Council for Agricultural Science and Technology, 1996)

- **Energy Use for NH$_3$-N Removal and Fixation**

<table>
<thead>
<tr>
<th>NH$_3$-N Removal from Wastewater</th>
<th>HABER-BOSCH process for Ammonia Fixation</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 MJ (5 kWh)/kg as NH$_3$-N</td>
<td>32 MJ (9 kWh)/kg as NH$_3$-N</td>
</tr>
</tbody>
</table>

- **Energy Recovery with Anaerobic Digester Biogas (CH$_4$ and H$_2$)**
  Wastewater Organics (potential)  6.8 MJ (1.9 kWh)/m$^3$, 13 MJ (3.6 kWh)/kg-COD (potential)
  King County South Treatment Plant (WA)  1.1 MJ (0.3 kWh)/m$^3$, 2.5 MJ (0.7 kWh)/kg-COD
  for CHP by carbonate fuel cell
Modeling a System of Systems

Natural Environment Systems
- Natural Hazards
- Technological Hazards
- Climate Change

Social and Economic Systems
- Income
- Equity
- Social Structure
- Policy Framework
- Health

System Integration Software
- Water Supply
- Energy Supply
- Transportation
- Urban Growth
- Waste Water
- Solid Waste

Facility Aging
Demographic Changes
Fiscal Constraints
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

- 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

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

Floodplain
Highway Buffers
Sewer Service
Employment Centers
Lake Buffers
Public lands
Parks
Ramp Buffers
Growth Scenarios in Atlanta:

Comparison of two different growth scenarios for Atlanta in 2030 using *What-If* urban modeling tool

Courtesy: French, S; GT
Water Use by Location
Business as Usual

- Rain harvesting has a potential to supply around 57% of water demand
Water Use by Location
Business as Usual

- Rain harvesting has a potential to supply around 57% of water demand
Water Use by Location
Business as Usual

• Rain harvesting has a potential to supply around 57% of water demand
Water Use by Location
Business as Usual

- Rain harvesting has a potential to supply around 57% of water demand

Unit: 1 dot = 250,000 gallon per day (gpd)

Year 2025
Water Use by Location
Business as Usual

• Rain harvesting has a potential to supply around 57% of water demand

Year 2030

Unit: 1 dot = 250,000 gallon per day (gpd)
Water Use by Location Business as Usual

• Rain harvesting has a potential to supply around 57% of water demand
Projected Residential Material Consumption (BAU)

Material Demand (1000 tons)

- Steel
- Gravel
- Concrete
- Wood

Year:
- 2010
- 2015
- 2020
- 2025
- 2030
Projected Residential Electricity Consumption (BAU)
Emergent Property: Ozone in ATL

Credit: Ted Russel
Planning in Atlanta Metro

Evaluated 2305 policy statements from 30 plans for plan quality and commitment to sustainable development

- Most plans focus on land use and community services (police, fire, schools).
- Only one policy statement in one plan focused on energy

Plan Quality
- Mean plan quality score: 2.3 out of 4 (range – 1.3 to 3.2)
- 471 of statements (20%) were high quality – strongly worded, measurable, and specific
- 644 statements (28%) received no quality points

Commitment to Sustainable Development
- Average plan 40% statements SD,
  - Min 9% - Max 80%
- Plan policy statement commitment to SD

Correlated with high quality
Genuine Progress Indicator (GPI)

Sum of 24 measures grouped into 4 dimensions of sustainability

• Economic (5): income – adjusted for equality, underemployment, non-market labor
• Social (5): social cohesion – including family, leisure, and crime
• Environment (5): cost of pollution (air, water, noise, waste)
• Resources (9): natural and man-made capital
Development in Atlanta

- Development measured as change in welfare
- Welfare measured by GPI

Graph shows average of 28 county results for MSA

FROM IT, WE CAN SAY:
- GPI increased 1980-2000
- Only Economic dimension positive
- Social, Environment, Resources dimensions reduce overall welfare by about half of Economic welfare
- Gains in Economic dimension somewhat at the expense of Social and Resource welfare decline