Gigaton Problems Need Gigaton Solutions

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Numerous challenges have been identified as critical for sustainability, including population growth, access to energy and resources, climate change, biodiversity decreases, and widespread poverty. Governments, industry, researchers, and advocates have proposed and begun to implement a range of actions and policies designed to tackle these challenges. Many of these practices are helpful for approaching sustainability, but their contributions typically do not match the scale of the challenges they aim to tackle. For example, recently the City of Pittsburgh announced plans to spend $24 million to replace 40,000 of its existing street lights with LED lights. This project is estimated to eliminate 17,853 tons of carbon dioxide (CO_2) emissions per year (*1*), which of course is very helpful. However, this is only an approximately 0.7% reduction in the total CO_2 emitted by the City (*2*). Although replacing street lights is likely to save the City money, such a small reduction in CO_2 emissions contributes little to solving the challenge of climate change. That investment is probably better spent on educating people about how to save energy in their daily lives, such as by turning computers off when leaving their offices, which will have a larger impact at the City's scale. To meaningfully address climate change and other challenges, society needs a clear understanding of the magnitude of those challenges, and to match its actions to the scale of the problem.

The world population is now almost 7 billion, with approximately 80% living in less developed regions (*3*) and with growing aspirations. In 2007, world energy consumption was 12 billion tons of oil equivalent (Gtoe), or 504 exajoule (EJ), 81% of that from nonrenewable fossil fuels. Furthermore, the combustion of these fossil fuels emitted 29 billion tons (Gt) of CO_2, or 8 Gt of carbon (GtC) (*4*). Although there is no world-wide estimation of material use, the major players, the U.S., China, and the European Union (15 member states in particular), collectively consume 14 Gt of materials annually, only about 5% of which are renewable (*5*,*6*,*7*). Across the globe, many activities generate on the order of one ton per person per year of unwanted "products" in the developed countries and, increasingly, in developing nations. Many of these activities have significant environmental impacts, including fossil fuel use, non-fossil fuel material use, and carbon emissions, as well as other impacts such as nitrogen fertilizer use (0.1 gigatons of fertilizer nitrogen per year) and cropland soil erosion (2 gigatons per year in the U.S. alone). Some activities, energy imports in particular, have political and security dimensions: U.S. imports nearly 1 gigaton of petroleum annually, and European Union imports of natural gas total nearly 1 gigaton annually as well. These challenges are "gigaton problems," in the sense that they produce a billion tons contamination, waste, effluence, or dependence each year.

*<insert **Box 1** around here>*

In turn, "gigaton" efforts are required to tackle these problems. For example, a recent study concluded that, to avoid the most serious climate change impacts, a 70% reduction of greenhouse gas (GHG) emissions from 2000 levels is required by 2100 (*8*). The world's population is projected to increase to more than 9 billion by 2050 (3), the world's economy is expected to expand, and demand for energy can be expected to increase accordingly. If per capita energy consumption and the proportions of energy from fossil fuel, nuclear, and renewable sources remain the same, then world energy consumption in 2050 would be nearly 1 Gtoe. To achieve the 70% CO_2 emission reduction goal, 6.9 Gtoe of fossil fuels need to be replaced by nuclear or renewable sources, which is equivalent to the addition of approximately 2,300 1-GW nuclear power plants over the next fifty years or growing biomass feedstocks, such as miscanthus (*9*), on the equivalent of the entire land area of India, Argentina, and Australia combined. Given the current situation of international negotiation on climate change, building the required alternative energy capacity at the global scale necessary to avoid the most serious climate change impacts would be quite difficult.

<*insert* ***Figure 1*** *around here*>

Thus, development of new technologies will be important for addressing the gigaton problems of climate, energy, nitrogen, material, and water. For example, whereas first generation biofuels have been questioned because of their negative climate impact (*10*) and competition for land use (*11*) and water resources (*12*), algae biofuels promise high energy yield, i.e., 10 to 20 times more than cellulosic biofuel feedstocks on a per hectare per year basis (*13*). Thus, to avoid the most serious climate change impacts, the replacement of fossil fuels by growing algae for biofuels by 2050 would, in the worst scenario, only consume one tenth of the land required to grow biofuel feedstocks, or roughly no larger than Alaska for the entire world. Advanced biofuels, as well as other promising technologies that have the potential to solve the gigaton problems, require time to progress up the learning curve and move from the laboratory to the market (*14*) and become economically viable.

There is, however, a wide range of existing technologies and approaches that, if deployed at scale, could make a significant contribution to addressing the gigaton problems. Taking the gigaton GHG problem as the example again, Pacala and Socolow (*15*) show that known technologies are sufficient to levelize global emissions of CO_2 over the next 50 years. They propose using a combination of approaches, including energy efficiency, decarbonization of power, decarbonization of fuel, and forest and agricultural management. Altogether, seven GtC "wedges" are sufficient to stabilize the emissions. Additionally, two wedges will be needed to reduce global CO_2 emissions by 30% by 2050 to avoid the most serious climate change impacts. Figure 2 illustrates the wedges needed to meet both the 2050 stabilization goal (*15*) and the goal of reducing CO_2 emission by 70% by 2100 (8). Although the period between 2050 and 2100 may not be an ideal horizon given the current pace of global change (*16*), at least possible solutions exist for solving this gigaton problem by 2050 using only existing technologies. However, statistics on global fossil fuel CO_2 emissions in 2007 indicate that the world is still in the business-as-usual (BAU) trajectory.

<*insert* ***Figure 2*** *around here*>

Solutions to gigaton problems can rely on both existing and new technologies. Either way, solutions used to target places that offer large-scale emission-reduction opportunities. Notably, approximately 50% of the world's population and 80% of the U.S. population now live in urban areas, and these percentages are expected to grow to 70% and 90%, respectively, by 2050 (*17*). Urban areas occupy only 2% of the earth's surface, but, as centers of population and economic production, they dominate resource consumption and waste generation. As Klaus Toepfer, the United Nations Environment Programme chief, stated in 2005 (*18*), "*Cities pull in huge amounts of resources, including water, food, timber, metals and people. They export large amounts of wastes, including household and industrial wastes, wastewater and the gases linked with global warming. So, the battle for sustainable development, for delivering a more environmentally stable, just and healthier world, is going to be largely won and lost in our cities.*" The urban system, as the world's primary sink of resources and source of wastes, is thus a key point to tackle the gigaton problems. A review of the carbon emissions of twelve large metropolitan areas around the world found that their carbon footprints usually were smaller than their national averages, which suggests that urban areas offer a relatively carbon-efficient lifestyle (*19*).This finding is particularly applicable to the U.S., where two-thirds of the population lives and three-quarters of economic activity takes place within the 100 largest metropolitan areas, but these areas account for a much smaller percentage of the U.S. carbon dioxide (CO_2) emissions (2). However, many of the fastest-growing metropolitan areas are also the least compact and most carbon-intensive. This is evident in the rapid growth of many sprawling southern cities, such as Phoenix, AZ, Austin, TX, Raleigh, NC, Atlanta, GA, and Nashville, TN. New development in the U.S. often occurs in locations and patterns that fail to take advantage of energy and location efficiencies, which underscores the need for improved policies and practices (2).

Dense urban areas can only exist because of complex, interdependent infrastructure systems. Urban infrastructure often lasts 50 to 100 years, and up to 90% of infrastructure-related environmental impact occurs in the use phase (e.g., *20*,*21*). With urban infrastructure expected to increase by more than 40% between 2000 and 2030 (*22*,*23*), an opportunity exists to change significantly how urban communities consume resources and produce and manage wastes, and thus to contribute to solving some of the gigaton problems. To do this, however, we need a better understanding of the complexity of urban systems and of how infrastructure systems interact with each other.

Urban systems act in many ways like organisms: they process resources (water, energy, and materials) and information, create infrastructure systems and services, and produce wastes. Individually, infrastructure systems interact with each other in complex ways, as illustrated in Figure 3. A simplified example is the nexus of water, energy, and land use: Urban development requires water and energy infrastructures, the operation of energy infrastructure needs water, the production and supply of water need energy, and the development of energy and water infrastructures alters land use patterns.

<*insert* ***Figure 3*** *around here*>

The links between different infrastructure systems are heterogeneous: Some infrastructures are highly coupled, e.g., water systems and power systems, whereas others are relatively loosely connected, e.g., transportation systems and power systems. While changing those linkages may not always have the desired effect (e.g., *24*), sometimes it can provide surprisingly promising outcome for addressing some of the gigaton problems. For example, two large producers of CO_2 emissions, transportation systems and power systems, which are now only loosely connected, can be dramatically transformed if coupled together. Although location matters at the metropolitan level (*25*) and the trade-off of energy use related to batteries is not considered, it has been estimated that, at the national scale, the existing U.S. electric power infrastructure could electrify 73% of the U.S. light duty vehicle fleet using plug-in hybrid technology (*26*). The life-cycle benefit is equivalent to eliminating 52% of the nation's oil imports and reducing the nation's annual GHG emissions by 27%. By 2050, the full deployment of plug-in hybrid technology throughout the U.S. light duty vehicle fleet would stabilize CO_2 emissions from the transportation system at the current rate (*27*). The preliminary nature of these estimates notwithstanding, they do show the potential benefits of combining transportation and electrical energy production.

<*insert* ***Box 2*** *around here*>

Reorganizing the linkage among individual infrastructure systems is like changing food chains in ecology, if analogizing infrastructures as species and the urban system as an ecosystem. This **infrastructure ecology** has a high potential to significantly contribute to solving the gigaton problems. Given its role in creating and maintaining urban infrastructures, 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. Specifically, we present these challenges to the engineering community:

- Recover nutrients from wastewater and urban waste systems. Minimize dissipation of nitrogen, phosphorus, and carbon.
- Recover and use heat from all electricity generation. Currently the heat generated from nuclear power production and coal-fired power plants is essentially entirely or mostly dissipated (*28*). Natural gas power plants generally use combined cycles for more efficient generation.

- Use natural gas for combined electricity and heat, not just for heat. Currently natural gas is used as a direct source of heat in many residential, industrial, and commercial settings.
- Recycle residential food waste, paper, plastics, and metals. Reduce landfills to a minimum.
- Identify and anticipate cross-system interactions. For instance, tackling transportation and energy problems with corn-based ethanol brings predictable increases in fertilizer use, agricultural land use, run-off and erosion, and food prices. Reducing air pollution can raise water pollution (*29*).

Integration of urban infrastructures cannot address all of the gigaton problems. A substantial fraction of the nitrogen, soil-loss, and water gigaton problems derives from the structure and operation of agricultural systems located far from urban centers, and a substantial fraction of the energy, GHG emissions, water contamination, and material consumption gigaton problems derives from the structure of industrial systems that are not integrated into urban centers. Yet a substantial fraction of the gigaton problems derives directly from the structure and operation of urban infrastructures. Current efforts to address these issues in urban systems have not yet been at the scale required to make a significant difference. However, Walmart Corporation and multinationals have illustrated the influence that up-stream buyers can exert on the downstream supply chains. The leadership of urban centers can play a similar role in the greening of rural enterprises. Furthermore, to stimulate the development of gigaton solutions, we should create market incentives or stipulate mandates that get gigaton-investors and gigaton-entrepreneurs on task.

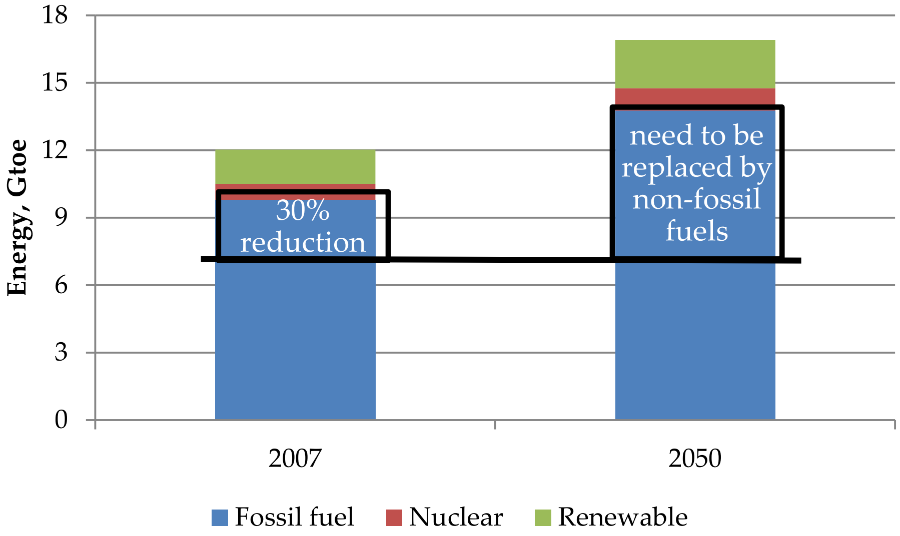

Figure 1. Projected world energy consumption and sources in 2050 based on a population projection (**3**) with constant per capita energy consumption and the same distribution of energy sources as in 2007. The horizontal link represents the maximum annual fossil fuel consumption permitted to be on track to meet a 70% CO_2 emissions reduction goal by 2100 (**8**).

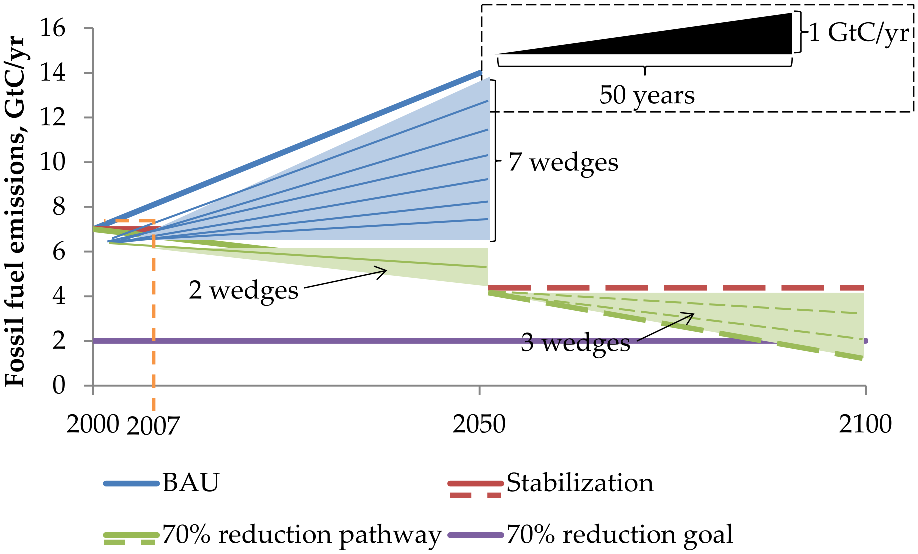

Figure 2. Stabilization wedges needed to mitigate fossil fuel CO_2 emissions from a business-as-usual (BAU) scenario to the 2000 rate (*15*) and to a goal of 70% reduction by 2100 (**8**).

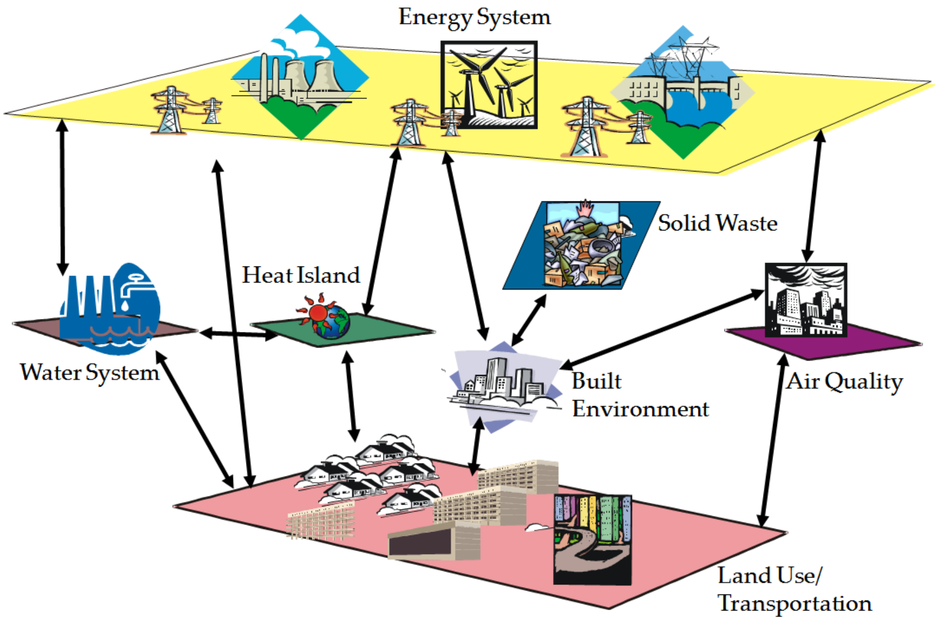

Figure 3. Interactions of current urban infrastructure systems.

Text Box 1

Some other gigaton problems

- The substantial improvements in food production over the past century have been made possible through a range of advances, among them the production of large amounts of nitrogen-containing fertilizers. These fertilizers underpins much of the world's food production systems, but after application the nitrogen remains active in the environment, causing substantial changes to aquatic (e.g. dead zones in coastal areas) and terrestrial ecosystems and making contributions to climate forcing in the form of nitrous oxide (N_2O) (*30*,*31*).
- Large-scale contamination of rivers and other water bodies and the massive water demand of cities has resulted in a nested set of water scarcity and water contamination problems throughout the developed and developing world (*32*). 2.5 billion people are without access to hygienic sanitation, and this number is growing (*33*).
- Solid waste disposal (and recycling) continues to pose challenges on a gigaton scale. A worrying proportion of the trash never makes it to the landfill or recycling centers, and end up dumped into the ocean. Every year, 1.4 billion barrels of oil are transformed into 500 billion plastic bags, millions of which are washed up on beaches and coastlines (*34*).
- Food production poses gigaton problems, with world supply in multiple gigatons of edible matter annually. Scarcity of arable land, transportation of safe and sustainably grown foods, and other factors (that often occur outside of urban systems but directly "feed" into them) remain gigaton problems.
- Global population continues to grow, adding several gigatons of hungry consumers to Earth's systems every year. The population growth in urban areas is likely to be even more dramatic.
- Annual generation of construction and demolition (C&D) waste is 0.35 Gt in the U.S. alone (*35*). These large quantities have led to increasingly strict management and recycling requirements. As infrastructure ages and is replaced, the task of C&D waste management will grow.
- Annual generation of municipal solid waste is 0.25 Gt in the U.S., of which about one third is recycled (*36*). Landfilling is dominant; recycling is typically far from urban centers. There may be substantial opportunities to integrate recycling into urban areas (*37*) as well as to increase the efficiency of material use.

Text Box 2

Other methods for reorganizing linkages among infrastructure systems also have the potential to significantly change the overall performance of urban systems.

- Waste heat from electricity production is currently dissipated through use of large amounts of cooling water. This waste heat could be utilized as heat through use of district heating systems or through application to food production systems or industrial processes (*38*). Generation of electricity within urban areas rather than at large distances can make more efficient use of the electricity and heat. Combined heat and power systems in large buildings can cost-effectively provide electricity and heat (*39*). 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 (*28*).
- Use of biomass to produce combined heat and power is more efficient than use of biomass to provide electricity or heat alone (*40*). Some utilities are converting old coal-fired power plants to biomass. Although replacing coal with biomass will reduce GHG emissions, these old electricity-only power plants will be just as inefficient as they always have been. Utilization of biomass in or near urban areas or industrial sites will allow combined generation of heat and power, reduce water needs, and at least double the efficiency of biomass utilization.
- Energy use in buildings represents a substantial fraction of the total energy use in the U.S. and worldwide. Standards for building energy efficiency are generally set at the state or city level. In some areas standards are weak; in other areas standards are strong but enforcement is weak (*41*,*42*).
- The emission of nitrogen into the environment is resulting in widespread contamination and alteration of aquatic and terrestrial ecosystems (*30*,*31*). Most of the nitrogen and other nutrients that enter current urban wastewater systems are largely flushed into water bodies. Recovery and reuse of nutrients from urban wastewater can contribute to reducing long-term water contamination problems (*43*,*44*), and can simultaneously reduce water consumption. Reducing nitrogen emissions in the first place, through agricultural innovations like biotech crops, could bring major reductions in fertilizer and insecticide applications and productivity gains that reduce the demand on arable land of bring (giga)tons more food to market (*45*).
- 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.

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