Chapter 8
Energy and Water Interdependence, and Their Implications for Urban Areas

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Glossary

Anthroposphere	That part of the environment that is developed or adapted by humans.
Life cycle assessment (LCA)	Analysis of the impact of a product or service through all the stages of its life including raw resource acquisition, material processing, fabrication, assembly, transportation, operation, disposal, recycling, repurposing, or reusing.

This chapter was originally published as part of the Encyclopedia of Sustainability Science and Technology edited by Robert A. Meyers. DOI:10.1007/978-1-4419-0851-3.

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M.M. Begovic (ed.), *Electrical Transmission Systems and Smart Grids: Selected Entries from the Encyclopedia of Sustainability Science and Technology*,
DOI 10.1007/978-1-4614-5830-2_8,

Low-impact development (LID)	A way of managing stormwater runoff through decentralized water systems, such as green roofs and rainwater harvesting.
Material flow analysis (MFA)	Analysis of how resources move through the industrial, consumer, and ecological sectors.
Resilience	The ability for a structure to maintain its fitness and function in response to indigenous and exogenous stressors; it is characterized by four measures: Rapidity. A measure of the capacity to contain losses or prevent further degradation in a timely manner. Redundancy. A measure of the inherent substitutability. Resourcefulness. A measure of the capacity to mobilize resources to restore functionality in the event of disruption. Robustness. An ability of the system to withstand a given level of stress and/or demand.

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Sustainability	The development of an anthrosphere that exists within the means of nature. Sustainability requires that humans use no more resources than nature can renewably provide and generate only wastes that nature can assimilate in a timely manner and without overwhelming natural cycles.
Urban heat-island effect	The phenomenon where the temperature in a developed area with a high concentration of buildings, roads, and other physical infrastructure is significantly higher than in the surrounding undeveloped areas.
Urban sustainability	An assessment of the long-term viability of a place considering the physical infrastructure (such as water, sewer, transportation, and buildings), socioeconomic issues (such as human well-being, health, wealth, safety, and security), and natural environment (such as resources, wildlife, and ecosystem health).

Definition of the Subject

There are many definitions for sustainability. Mathis Wackernagel, creator of the ecological footprint concept, defined sustainability as "securing people's quality of life within the means of nature" [1]. The United Nations' World Commission on Environment and Development (the Brundtland Commission) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. Throughout this report, sustainability will be defined as the development of the anthroposphere within the means of nature. Here, the anthroposphere is the built environment or the environment that humans created for security, wealth generation, and comfort. For it to exist within the means of nature implies that the anthroposphere must use resources that nature provides, and generate only the kind and amount of waste that can be assimilated into the environment without overwhelming natural cycles. At the global scale, there are several examples that suggest that current development patterns are unsustainable. Presently worldwide, there are approximately 7 billion people using 14 Gt of materials [3]. With only 5% of the global material use being renewable, the extraction of natural resources is beyond what nature can reasonably supply. At the other end, an enormous amount of synthetic and potentially toxic materials are being introduced into the global material cycle.

To fully understand sustainability, one needs to take a whole system approach. In the traditional reductive engineering paradigm, each of the individual infrastructure components such as water, energy, and transportation are optimized separately. However, since the function of all the component elements depend on each other, a more optimal solution can occur if all the urban pieces are considered together. These interdependencies form an ecosystem of infrastructure that, if functioning properly, provides a lasting basis for human enterprise. An example of the interdependencies and the need for them to be considered together is the water energy nexus. In all but the most primitive cultures, it takes water to create useful energy and energy to create useful water. This nexus requires a comprehensive understanding not just of power generation or of water resource management, but of both and how they connect and interact at temporal and spatial scales that are both large and small. And on top of these engineering relationships, environmental, social, and economical concerns must also be integrated.

Why is sustainability, particularly urban sustainability, so important? The United Nations Environmental Program (UNEP) chief, Klaus Toepfer, stated in 2005 that "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. Thus their impacts stretch beyond their physical borders, affecting countries, regions and the planet as a whole. 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" [4]. The UNEP expects 64% of the world's population to live in urban areas by 2040, a dramatic increase from 50.5% in 2010 [5]. For the developed countries like the United States, those in the European Union, and others, the share of urban population is projected to be 87% in the same time period [5]. With such an influx of people from rural areas to urban areas, cities must be prepared for this mass in-migration. With much of this movement expected in developing countries, those that adopt sustainability as a guiding framework for development could leapfrog other countries that are financially and systemically burdened with maintaining the status quo. For the developed world, a hybrid approach in which existing centralized systems are augmented by decentralized systems could help those cities remain competitive and viable. New or old, however, each city has different demographics, cultural values, fiscal and physical constraints, climate, and topology, and any solution to the demand for urban infrastructure – sustainable or not – will have to be uniquely tailored to consider these differences.

Introduction

Transmission grids are an integral piece of urban infrastructure. Understanding how electricity is used and finding ways to decrease the use of energy will be essential for developing more sustainable urban systems. Likely the greatest opportunities for improving efficiencies and increasing sustainability lies not in a single solution, but in how all the pieces – old technology and new – interconnect and work together. Transmission grids not only transmit energy to residencies and workplaces, but also to water treatment systems, to industries, to street lights, to trains, and to the gasoline stations where cars are fueled, just to name a few. These dependencies are not unidirectional, however. Energy production and demand are also significantly dependent on these systems. Pipelines move natural gas, oil, and water to refineries and power plants, while trains and ships transport coal for use in heating, manufacturing, and power production. Adding to this is the emergence of affordable and technologically feasible renewable or decentralized energy options such as photovoltaics, wind power, and microturbines. The most productive, healthy, and sustainable cities of the future will be the ones that learn to use all these resources to build and operate wholly integrated energy systems that meet the short- and long-term economic, social, and environmental needs and aspirations of their residents and region.

Urban areas are complex interconnected systems analogous to ecological food webs. For an urban area to function properly, water, energy, and transportation systems need to be effectively designed to support the area's desired land use. Similarly, the land-use pattern also should be governed according to the capacity of the area to host development. Beginning in the nineteenth century, these systems have increasingly been designed, built, and operated as isolated systems without considering how they interact. Water purveyors have been concerned about water distribution. Power companies examined energy production, distribution, and usage. Transportation planners examined ways to move people and goods safely and efficiently. Generally, they cared about optimizing their own processes to satisfy their own needs. However, in recent years, some cities have begun to realize that they could improve efficiency by considering how these different systems interact and function together within the whole urban system, rather than as individual and independent parts. For example, energy generation requires water for steam production and cooling. The waste heat from energy production could be used to produce hot water, heat homes, or provide air-conditioning. In another example, a Pacific Northwest National Laboratory study in 2007 suggested that 73% of the United States' current light-duty vehicle fleet could be supported by the existing electric power infrastructure [6]. It is less clear, however, how the increased electricity demand required to electrify transportation would affect water demand. These are just two simple examples. Socioeconomics, policy, land use, and urban infrastructure form a complex system that makes up the city. When a holistic approach is adopted to analyze the urban infrastructure, many properties emerge that are not apparent when the components are analyzed individually. These emergent properties evolve from the economic and sociopolitical framework adopted by the stakeholders for the urban area. Hence, citizen capacity building, whereby informed citizens demand more sustainable infrastructure, is vital to driving the political agenda to improve the urban infrastructure.

A city is such a multifaceted and complex system that one cannot easily test the effect of certain decisions or actions. However, the impact of decisions can be estimated through modeling that simulates how agents change their behavior in reaction to different options. For example, a first-generation agent-based modeling analysis of urban infrastructure would include the following:

(a) A determination of the spatial and temporal demand for urban infrastructure due to development/redevelopment activities
(b) A listing of infrastructure alternatives that satisfy the needs of the development
(c) A calculation of the material and energy required for the different alternatives
(d) A determination of the vulnerability and resiliency of the urban infrastructure alternatives against exogenous or endogenous risks
(e) An assessment of the local, regional, and global impacts of the alternatives through life cycle analysis

A second-generation model would include feedback loops in which all previous decisions are reconsidered in light of outcomes revealed by the model. This is more realistic because of future decisions do depend on evolving properties. Once the model is verified, the dynamic policies and economic drivers (i.e., market forces) that will yield more sustainable and resilient urban infrastructure can be determined more accurately. More importantly, the model can be used to assess the sensitivity of outcomes to different inputs and resources can be focused on those components that will result in the greatest improvement.

Methodologies

There are many methods for evaluating sustainability. As with all methods, each has strengths and limitations. Some of the methods used to evaluate the sustainability of urban environments are discussed below.

Resiliency

Resiliency is the ability of a structure to maintain its functionality despite exogenous or endogenous stressors. Resilient systems are flexible and adaptable and typically provide a better return on material investments in the long term. There are four important attributes that compose resiliency: robustness, redundancy, resourcefulness, and rapidity. Robustness is the ability of the system to withstand a given level of stress or demand. Redundancy is a measure of the inherent substitutability, or the ease with which a component or a whole system, or the function that they provide, could be replaced in case of a failure. Resourcefulness is a measure of the capacity to mobilize resources in the event of disruption. Rapidity is a measure of the capacity to contain losses or prevent further degradation in a timely manner. These 4 “R’s” can be used as metrics in determining the sustainability of a system or infrastructure [7]. Urban infrastructure that is designed to minimize material and energy investments may not in fact be sustainable in the long term if the reductions result in low resiliency and the functioning of the infrastructure is jeopardized. Resiliency serves as a check against short-sighted, but well intentioned, actions that do not contribute to longer-term sustainability.

Life Cycle Assessment

Life cycle assessment (LCA) is the analysis of the impact of one particular product across all phases of the product's "life." Life can be defined in multiple ways. The most common way an LCA is performed is from cradle-to-grave. This considers raw material extraction, manufacturing, use, and disposal. While a great deal of attention is often paid to a product's manufacturing phase, the use phase is often the most important phase based on a product's impact. For example, a car uses a great deal more energy and resources in the use phase than in the manufacturing phase.

If a product is recycled or reused instead of being disposed of, it is cradle-to-cradle, and the life of the product is extended. For example, plastic soda bottles made of polyethylene terephthalate (PET, recycling symbol number 1) can be recycled to make new plastic bottles or a variety of other products, like T-shirts and carpeting. Cradle-to-cradle aims to reduce waste and decrease the amount of virgin resources that are used in a product.

Other methods may shorten the view of an LCA, such as cradle-to-gate and gate-to-gate. Cradle-to-gate looks at the product from raw resources all the way through manufacture, but ends there. This might be useful particularly to a manufacturing plant or for products that have negligible effect in their use and disposal phase. Manufacturing also might look at a gate-to-gate LCA. This kind of LCA looks only at the production chain. This could be useful in comparing the efficiencies of different manufacturing methods and tools.

Two additional LCA methods that may be employed are the Economic Input-Output LCA (EIO-LCA) and the Ecologically based LCA (Eco-LCA). The EIO-LCA was developed at Carnegie Mellon, and is used to measure the economic effects of the materials and energy used to make a product [8]. Ohio State University developed the Eco-LCA [9]. This tool adds to the traditional cradle-to-grave LCA by emphasizing more analysis on the direct and indirect effects of a product on pollutant emissions and economic flows.

Life cycle assessment is a useful tool when looking at sustainability; however, it does have a number of limitations. Not all factors can be tracked or easily given a numerical value. For example, it is difficult to put a numerical value on the health effects of a product because toxicity and the transport and exposure routes may not be that easy to quantify.

One other limitation of LCA is the cutoff problem. For any product or process there are a large number of product stages or processes upstream and it is never possible to include all of them. Consider, for example, automobile manufacturing. An automobile needs parts for its manufacturing. The parts need a suite of metals. Mining equipment is required to obtain the required metals. But the metal needed for the mining equipment also required machines to obtain it. And so the chain continues.

In LCA, the chain needs to be truncated somewhere resulting in errors of omission. Additionally, the different LCA methods and commercially available software, like SimaPro, that are widely used to conduct LCA may use different assumptions and data resulting in a variation of results that must be reconciled.

Material Flow Analysis

A material flow analysis (MFA) is a process used to assess the flow of mass and energy within a defined system. It can be conducted at national scales, at the scale of a product, or at any scale in between. Urban metabolism is a specific MFA tool looking at a defined urban area. This method tends to look at the city as a “black box.” It considers the flows moving in or coming out of the city, but does not necessarily look at the mechanisms inside the city that cause these fluxes to occur. It does give a view of the amount of goods and energy needed to support a city, and how much waste the city produces. However, one constraint is the need for extensive input and output information for a huge number of materials. Some of these numbers are tracked at the national level, or are easy to track within one industry, but may be difficult to find or track for less controlled regions like states or cities. This approach works well for islands because all inputs are brought in by boats and recorded, and outputs also must go out on boat or stay on the island. With better data collection, this method will become increasingly useful. An improvement on urban metabolism would be to track the inflows of resources, the outflows of wastes, and the creation of infrastructure that creates wealth and comfort. The guiding principles would be to use fewer resources to create and operate the infrastructure needed per capita. In practice, it can be difficult to compare one city to another because cities can be in different states of build-out of its infrastructure (e.g., a greenfield city as compared to a more mature city) and its climate, demographics, and topology can impose significant confounding effects.

Industrial Ecology

Industrial ecology can be defined as a multidisciplinary system-level study focusing on the interconnections between the industry, economics, and the natural environment. Industrial ecology utilizes a suite of different tools to analyze these interdependencies. Among these tools are life cycle assessment and material flow analysis, along with designing and manufacturing for the environment and ecological efficiency within the industry. The waste or by-products of one industry might be a resource for another industry, and if the two industries are located close enough for logistical viability, then the waste/by-product can be utilized by the other industry. For example, a cement manufacturer located near a power production facility may be able to use residual fly-ash from the power plant for its cement mix. And if a drywall production facility is also in the vicinity, it might be able to use the $CaSO_4$ from the cement plant as its raw material. Thus the net waste generation from these industries is reduced and their proximity saves significant fuel from the reduced need for transportation. This multitude of tools used in an industrial ecology assessment allows an industry or city to look at various designs and see how they affect inputs, outputs, and the overall effect on the economy.

Urban Sustainability

Urban sustainability is a systems-level holistic analysis of the sustainability of an urban system, particularly in regard to its infrastructure. Urban infrastructure is an intricate network of six major components: (1) private residences, (2) commercial establishments (including churches, schools, etc.), (3) water and wastewater, (4) energy, (5) transportation, and (6) land use. Urban sustainability also includes socioeconomic impacts and the policy drivers that cause the emergent properties of urban systems. With the demand for basic infrastructure growing with population, cities need to plan their infrastructures accordingly. Traditionally, urban areas were built with the "big-pipe concept," where the natural ecology was replaced with *hardscape* to provide for the urban infrastructure. *Nature* was restricted to curbside trees, and manicured parks and lawns filled with nonnative plants which require significantly more water and nutrients to thrive than the indigenous varieties. More recently, however, the importance of ecosystem services and preservation of natural ecology has been realized and natural alternatives, such as blue-belts for stormwater management, are increasingly being used in place of hardscapes. With this method, models are being developed to evaluate different options and to determine what social and economic decisions are needed to make them happen.

Current Infrastructure

Although current infrastructure may not be optimal, a large amount of capital has been invested in it and people still depend on it. One option for increasing sustainability is to develop a hybrid system of centralized and decentralized infrastructure, which increases redundancy without increasing the amount of requisite resources. Future planning also should guide how systems interact, and plan accordingly to save resources. Such interactions will now be described.

Water and Energy Nexus

Potable drinking water treatment provides clean drinking water, and wastewater treatment sanitizes sewage. Both use a great deal of energy in acquisition, treatment, and distribution. In 2000, the United States used more than 50 billion kWh of energy to attain, treat, and distribute drinking water and wastewater [10]. This is a huge demand for energy that is expected to continue to grow through 2050. The Electric Power Research Institute's (EPRI's) report on *Water and Sustainability* expects that by the year 2050, this number will reach over 75 billion kWh (Fig. 8.1). Already, water accounts for about 4% of the total energy sold in the United States. In California, it represents 18% of energy needs. And as water demand increases and good quality raw water becomes more difficult to find, these shares are likely to rise as advanced treatment technologies for reclaiming water or desalinating water are much more energy intensive. With this in mind, when a city is considering their water infrastructure, it also may want to keep in mind the amount of energy needed for various treatments for water and wastewater.

French Nuclear Power

In 2003, France experienced what was then their hottest summer on record [15]. The higher temperatures increased the demand for air-conditioning and refrigeration, which translated into an increased demand for electricity. In turn, increased energy production created more waste heat, which required more water for cooling purposes. Though France had plenty of capacity to produce electricity – the nation obtains ~80% of its electricity from nuclear power – the heat wave and drought limited the amount of water available for operation of the nuclear power plants, and the country was forced to turn off or reduce production at 17 of its nuclear reactors. As a result, France could no longer export electricity, which had been sold at €95 per MW-h to other EU countries, but needed instead to import electricity at a cost of ~€1,000 per MW-h.

Water can be treated using different methods, and with methodology differences there also are differences in energy dependency. Surface water tends to be cleanest, and as such requires the least amount of energy to collect and treat (Table 8.1). Surface water is not available in all areas though. Groundwater requires slightly more energy to treat and seawater desalination can use up to 75 times the amount of energy as surface water.

For treating wastewater, methods include a trickling filter, activated sludge, advanced treatment without nitrification, and advanced treatment with nitrification. The energy demand, shown in Table 8.2, is lowest for the trickling filter and highest for advanced treatment with nitrification. The simplest treatments consume the least

Fig. 8.1 Energy needed for drinking water and wastewater processes in the United States with data from the year 2000 and predictions of use until 2050 [10]

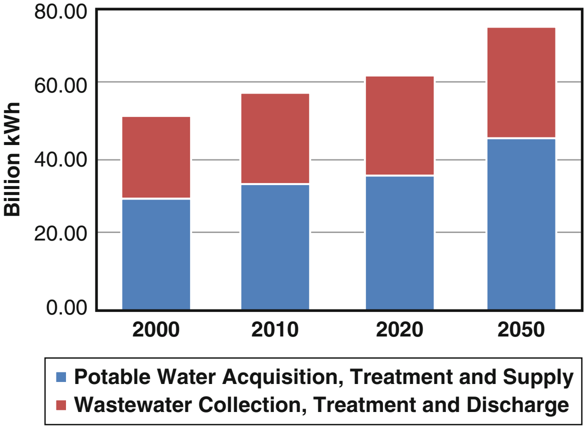

Table 8.1 National average energy demand by various water treatment systems [10, 11]

Water treatment and collection	kWh/MGal
Surface water treatment [11]	1,422
Groundwater treatment [10]	1,824
Brackish groundwater desalination [11]	3,900–9,750
Seawater desalination [11]	9,780–16,500

Table 8.2 National average energy demand by various wastewater treatment systems [10]

Wastewater treatment and collection	kWh/MGal
Trickling filter	955
Activated sludge	1,322
Advanced treatment without nitrification	1,541
Advanced treatment with nitrification	1,911

amount of energy, but they may not always be the most viable option given the quality of the water being treated and the requirements for the processed water. The gap in energy demand for the various approaches is much smaller in the case of wastewater than it is for water treatment.

Finally, power is also needed to distribute water. Logically, the farther that water needs to travel and the more difficult the water is to access, the more the energy that will be required to move it. Distributing water from lakes and rivers is the least energy intensive. It requires about 1,400 kWh/MGal to deliver [12]. Not all cities have lakes and rivers available to tap, however. For them, groundwater is more difficult to attain and requires slightly more energy. Lastly, discharging wastewater requires between 2,350 and 3,300 kWh/MGal on average.

The converse of energy being needed to provide, treat, and distribute water is that water is needed to produce, convert, and store energy. Water use in energy production varies depending on the source of energy. In the case of thermoelectric power generation, water is required for cooling purposes, while in case of

Table 8.3 The evaporative loss of water by different energy sources in the United States [14]

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

hydroelectricity, water is used as the source of power. Water is also required for petroleum fuel processing, the primary energy source for transportation. Thus all forms of energy require water, which varies in the amount and purpose of its use depending on the energy source. Thermoelectric power accounts for 39% of freshwater withdrawals and 52% of our fresh surface water withdrawals [13].

The consumptive use of water for power generation is from evaporative losses. Every day thermoelectric power loses an average of 3.3 billion gallons of water to evaporation [13]. As one may suspect, certain kinds of power generation consume more water than others (Table 8.3). Accounting for the amount of energy produced and the water loss associated with each source, approximately 2 gal of water per kilowatt hour is lost to evaporation in the United States. Hydropower has an evaporative loss of 18.27 gal per kilowatt hour, which is more than 35 times the evaporative loss of water from coal-based thermal power. This implies that hydropower is feasible only in areas with an abundance of water. In contrast, photovoltaics and wind consume much less water.

Example: Water and Energy Demand: A Tale of Two Cities

Atlanta and Phoenix are two cities with rapidly growing populations. As such, the demand on water and energy are rapidly growing. Being that they are in different regions, they have different demands for water. Table 8.4 describes how these cities are very different in terms of demand. For example, Atlanta uses more water indoors, but Phoenix uses a significant amount more outdoors. With long commutes and poor public transportation, Atlanta uses significantly more fuel per person per day than Phoenix. Some of the more important differences are due largely to Phoenix being a city in an arid region, very hot and dry, whereas Atlanta is more humid and wet generally. The water consumption for electricity production in Phoenix is more than four times that of Georgia. The electricity consumption for water supply and treatment also is around five times more in Phoenix than Georgia. With it being considerably more difficult to get water to Phoenix, these numbers are bound to become higher. The dependence of water on energy and energy on water in Phoenix are even greater than in Atlanta. Yet Atlanta has experienced a great deal of turmoil with its water resources, as described in the previous paragraph. So a strain on the Colorado River is subject to cause more damage, all things being the same. This table also shows that cities are not the same. No solution is right for all cities.

Table 8.4 The relationship between water use and electricity use for the cities of Phoenix and Atlanta

		The City of Phoenix		The City of Atlanta	
Residential water demand	Indoor (gpcd)	48[a]	1999 data in Chap. 4 of The Water Environment of Cities [37]	71	2001 data in The World's Water 2008–2009: The Biennial Report on Freshwater Resources
	Outdoor (gpcd)	110[a]		20	
Power use	Residential electricity, kWh/person-day	36	2005 data [38]	41	2005 data Brown et al. (2008)
	Fuel, kWh/person-day	5.5		12.3	
Water consumption for electricity production	gal/kWh	7.85 (Arizona)	National Renewable Energy Laboratory (2003)	1.65 (Georgia)	Torcellini et al. (2003)
Electricity consumption for water supply and treatment	Water, kWh/MG	8,600	[39] Conveyance, 4600 Pumping, 2600 Water treatment, 100 Water distribution, 1300	1,700[b]	City of Atlanta Watershed Management, [13, 36]
	Wastewater, kWh/MG	10,700	[39] Wastewater collection and treatment, 1500 Reclaimed water, 9200	1,830[b]	

These data demonstrate the difference in use for the two different regions. Information of this sort must be considered when making energy and water plans for each city

[a] The numbers are modified assuming four people for one household

[b] The numbers are estimated based on the water and wastewater production of the City of Atlanta, the electricity use of the Atlanta Watershed Management Department (Thomas 2007), and the electricity demand for water supply and wastewater treatment of the South Atlantic Region (DOE [13])

Beyond the Water and Energy Nexus

While water and energy are inherently connected, there are other connections that are equally important in the context of urban infrastructure (Fig. 8.2). Transportation needs energy to fuel vehicles, and the amount of energy available affects modes of transportation. Land use affects the amount of transportation activity in an area, and transportation is needed to made land accessible. The availability of water affects how land is used, and the way land is used affects the demand on water and the ways water can be treated. Likewise, the availability of energy affects land and water use, and the way the land is used affects the energy demands and the kind of energy that can be created. Additionally, water is also used for extracting fuels and growing biofuels, which affects the transportation sector.

Energy for Transportation

Energy is needed to power a variety of transport vehicles including airplanes, trains, boats, trucks, and automobiles. The fuel used in these vehicles may be equally diverse and may include gasoline, diesel (both petro and bio based), ethanol, methanol, natural gas, electricity, hydrogen, solar, and even coal and wood (though these latter two are nearly negligible in the modern vehicle mix). The latest trend is to create hybrid vehicles that can utilize two or more fuel sources (e.g., gasoline and electricity). As of 2009, the transportation sector accounts for ~28% of the of total

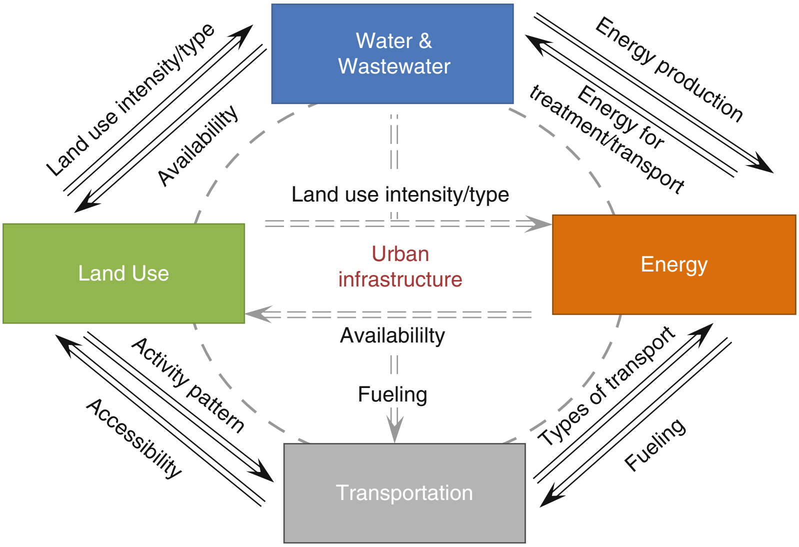

Fig. 8.2 Water, energy, transportation, and land-use systems are interconnected in urban regions

energy consumption in the United States and 72% of the nation's petroleum consumption [16]. Transportation also accounted for 3% of natural gas consumption and 12% of renewable energy use, mostly in the form of ethanol. Given these significant shares, the effect of transportation on energy needs to be considered when planning cities or city improvements.

Transportation, Land Use, and Energy

As the need for mobility increases, improving existing vehicle efficiency will lead to marginal reductions in the environmental impacts of transportation. Greater improvements, however, may be possible if switching to other modes of transportation is considered. In a 2007 study of plug-in hybrid electric vehicles, the Pacific Northwest National Lab [6] found that the current US electric power infrastructure could support the energy needs of 43–73% of the current light-duty vehicle fleet – the lower range resulting from the limiting of vehicle charging only to the 6 PM to 6 AM period. The study further estimated that if 73% of the US fleet was converted to electric vehicles, the United States would no longer need to import oil, and greenhouse emissions could be reduced by 27% (even if all electricity were generated by coal-fired power plants). While such broad-scale analyses are informative, it is important to note that complex local relationships underlie these bigger developments.

Bras recently completed an assessment of the energy and carbon dioxide emissions from different modes of transportation in Atlanta. Many kinds of vehicles and fuels were included in the study: conventional gasoline, diesel, compressed natural gas (CNG), ethanol 85 flexible-fuel vehicles (E85 FFV), spark-ignition (SI) gasoline hybrid electric vehicle (HEV), diesel HEV, SI plug-in hybrid electric vehicle (PHEV), diesel PHEV, electric vehicle, diesel vehicle, MARTA Clean Diesel bus, MARTA CNG bus, and MARTA rail. (MARTA is the Metropolitan Atlanta Rapid Transit Authority, which is the primary form of public transportation in Atlanta.) All of these transportation methods were evaluated on a Well-To-PUMP (WTP) and Pump-To-Wheels (PTW) basis for energy use and carbon dioxide emissions (see Figs. 8.3 and 8.4). Due to low ridership, MARTA's buses and rail are among the worst for both carbon dioxide emissions per passenger distance and for energy use per passenger distance. Increasing ridership would greatly improve these metrics. Other results suggest that electric vehicles do not fare much better than conventional gasoline and diesel. This is due, in part, to Georgia's dependence on older inefficient coal-fired power plants for energy. Overall, plug-in hybrid electric vehicles used the least energy and emitted the least carbon dioxide per passenger distance.

The implications of the effect of ridership on energy use and carbon dioxide emissions from various transportation modes in Atlanta suggest that other variables beyond just vehicles and fuel are also important. Planning and developing cities for growth with compact land use and transportation could significantly improve their sustainability and lower their dependence on energy. The way land is used affects the modes of transportation available and their efficiencies. For example, a compact

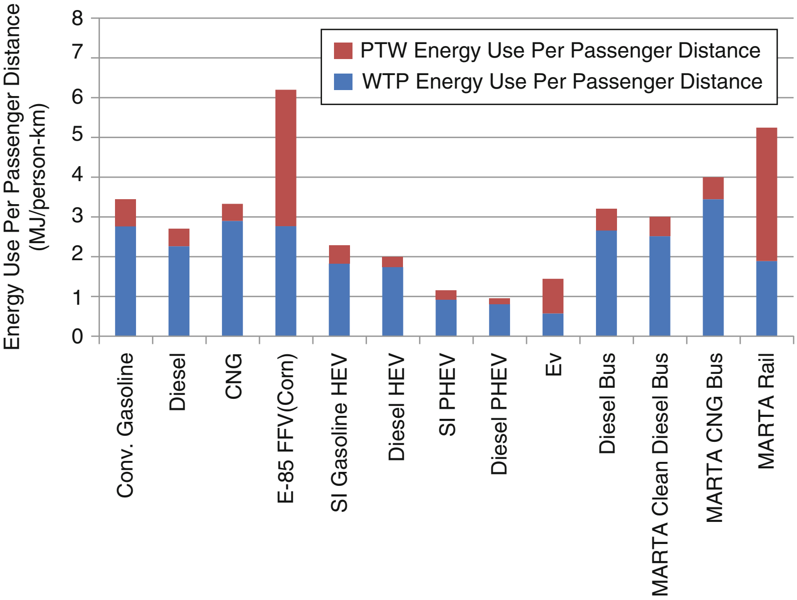

Fig. 8.3 The energy use per passenger distance for various transportation modes in Atlanta, GA

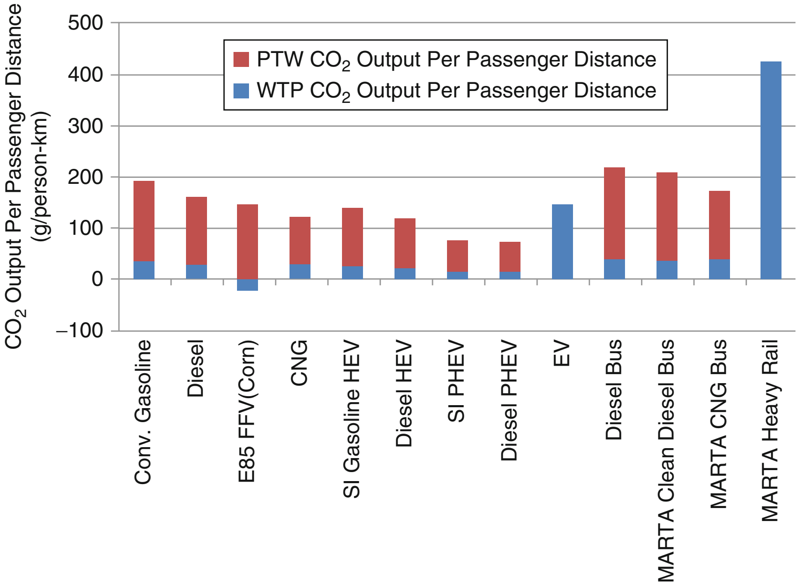

Fig. 8.4 Carbon dioxide emissions per passenger distance for various transportation modes in Atlanta, GA

Table 8.5 The dependence of various transportation fuels on water

Unit: Gal/kWh	Low	High	
Coal [13]	0.007	0.027	Mining+washing
Petroleum/oil [13]	0.03	0.076	Extraction+refining
Natural gas [13]	0.01	0.01	Extraction+processing
Corn-ethanol [17]	1.26	19	Assuming 15% irrigation for USA
Cellulosic ethanol [17]	0.13	0.431	No irrigation
Cellulosic ethanol [17]	16	19	Irrigation
Soy-biodiesel [17]	0.392	8.98	Assuming 4% irrigation for USA
Algae biodiesel [17]	0.839	1.762	Enclosed
Algae biodiesel [17]	0.895	18.351	Open

city favors walking, heavy rail, and other modes of efficient public transportation. New York City is a good example of this kind of city, where parking fees, gas expenses, and traffic lead the majority of the population to walk, take the subway, or ride the bus. An opposing example might be Atlanta, where the city is not compact enough to offer many people the option to walk or use public transportation.

Water for Transportation

Along with energy and land use, water is also intertwined with transportation. Department of Energy data [13], along with data from Harto's LCA of low carbon fuels [17], shows that oil consumes between 0.03 and 0.08 gal of water per kilowatt hour of energy [13] (see Table 8.5). Natural gas production uses a similar amount. Water needed to produce biodiesel from irrigated soy, though, is in the range of 0.39–9 gal of water per kilowatt hour. Corn-ethanol needs up to 19 gal of water per kilowatt hour, or ~500 times more than that for oil. From another perspective, Webber [12] found that a traditional gasoline car consumes around 7–14 gal of water per 100 miles traveled, PHEVs consume ~24 gal per 100 miles, and ethanol fueled vehicles require 130–6,200 gal per 100 miles.

The Compounding Power of Density

Urban density reaps a great many sustainable benefits. Public transportation is more accessible and commuting distances are generally shorter. Compact living also means that buildings can be closer to the infrastructures that provide them water and energy, which means less energy and materials are needed for distribution. It is also often the case that the more complex power and water networks that serve dense urban areas have built in redundancies that can compensate for component failures within the system. Finally, density affords other cross-pollinating opportunities such as combined heat and power, and low-impact development water infrastructure that also provides green space for recreation.

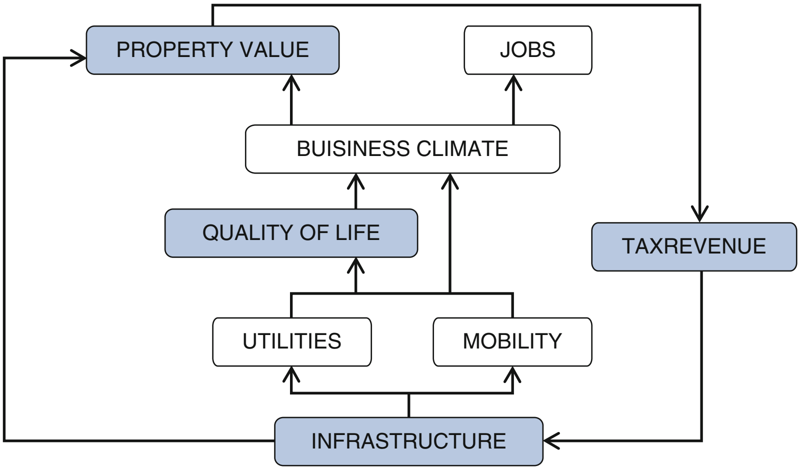

Fig. 8.5 The relationship between improved infrastructure and an improved socioeconomic environment

Jobs, Quality of Life, and Tax Revenue

The nexus of infrastructure extends beyond the interconnection of the physical, functional, and environmental constituent pieces. It also has implications for a place’s social and economic well-being. Consider again, for example, the benefits of compact urban design. Land consumed by large private residential lots cannot be used by the collective community. Small private lots, on the other hand, preserve the opportunity to leave larger tracts available for recreation, wildlife habitat, and other amenities that are not possible when the land is fragmented. These public conveniences and desired attributes improve the quality of life for everyone, create a more favorable, stable, and job-producing business climate, and raise property values. And when the resultant increase in tax revenues is reinvested in the infrastructure, an engine of prosperity is created (see Fig. 8.5).

Steps Toward a More Sustainable Future

Water

Rain water is a source of clean water that does not need much treatment. However, most cities currently do not handle this resource efficiently. In most cases, stormwater becomes contaminated when it falls onto urban or agricultural surfaces, or is shunted into the wastewater system. Collection and treatment of stormwater using low-impact development (LID) techniques offers a myriad of benefits. The first step is to separate the collection of stormwater from wastewater.

One immediate benefit is that with less water to be treated, less energy is needed in the water treatment process. Reduced flow into the wastewater stream also reduces the risk of sewage overflow into surface waters. The stormwater that is collected can be used to create green spaces, to flush toilets, for cooling, or for fire fighting. Below is a sample of LID techniques that can be used.

Vancouver

The City of Vancouver was concerned about the stormwater and sewage that was being discharged into its salmon-bearing rivers [18]. The city considered traditional separation and decentralized treatment, but after discovering that putting in a centralized stormwater treatment facility would cost the city an estimated $4 billion, it decided to look into different options. One approach that employed low-impact development and decentralized treatment satisfied the water treatment needs while also creating green space which increased property values and led to an estimated increase of $400 million in tax revenue. It also resolved the environmental problem for their salmon-bearing rivers, improved conditions for other wildlife, and reduced the urban heat-island effect.

Best Management Practices for Pollution Control

Best Management Practices (BMPs) are techniques used in controlling water pollution and the flow of water. They are put in place to control pesticides, herbicides, nutrients, other existing pollutants, and emerging contaminants like pharmaceuticals and personal care products from moving from the land to the water. Some of these techniques may simply reduce the amount of toxins used in a process or pesticides used for farming. Some structural techniques include detention basins, which are used to prevent flooding in storms, and pervious pavement, which allows water to flow through its pores while holding a number of pollutants in the soil. These techniques help manage the flow of stormwater so that wastewater systems are less likely to be overwhelmed. They often rely on natural techniques, such as bioremediation or wet land treatment, to clean the water and are often less expensive and less energy intensive alternatives.

New York

The Safe Drinking Water Act required New York City to build new water filtration plants at a cost of ~$8 billion. Balking at the cost, the city instead acquired undeveloped lands to buffer the watershed, initiated a host of Best Management Practices (BMPs), worked with the farming community to develop a Whole Farm Plan to reduce runoff pollution, used LID techniques to reduce stormwater flow, and made a few upgrades to existing sewer and septic systems in the region. In the end, these actions, in lieu of the $8 billion cost of new filtration plants, enhanced the economic productivity of the land from recreation, farming, and the protection of the watershed from runoff [19].

Green Roofs

Green roofs are roofs that are partially or wholly covered with vegetation. They increase urban green space, reduce stormwater runoff, sequester carbon dioxide directly, and reduce building energy consumption. They can be added to buildings in two ways, intensive or extensive. An intensive roof is normally between 8 and 12 in. thick and weighs 80–120 lb per square foot [20]. Extensive roofs are thinner and much lighter (10–50 lb per square foot). Intensive roofs are often built as gardens, but must be well supported due to the increased weight. Extensive roofs are not necessarily meant to be visited, but may be used for some of the same benefits, but at a lower cost.

Indigenous Plants

Plants that are native to a region require less water, fertilizers, and pesticides than exotic plants. Indigenous plants have adapted to local conditions. Less effort is needed to maintain these plants, and they live longer than other plants would in their environment. Alternatively, plants with superior carbon sequestration qualities like yellow poplar and American sweet gums more effectively reduce the carbon footprint of a city relative to slower growing hardwood trees.

Pervious Pavement

Pervious pavement allows water to pass through the pavement for groundwater recharge and thereby decreases the amount of rainfall that enters the wastewater system. Pervious pavement is ideal for large, low traffic uses like parking lots, driveways, bike paths, and sidewalks. Not only does pervious pavement reduce the load of stormwater on wastewater treatment systems, but it also reduces nutrient and metal loads from runoff (by 80% and 90%, respectively) [21].

LID techniques should be accessed city by city and based on a cost-to-benefit analysis, as not all techniques are proper for each city circumstance. But while most LID techniques are beneficial even within traditional centralized water systems, decentralized systems may offer additional benefits. With conveyance and distribution responsible for 80% of the energy demand in the water sector [10], decentralized systems can offer significant savings. In addition, due to the lower residence time of the water in the distribution system, the final water quality at the tap is less compromised. Decentralized systems also add resilience to the system due to higher redundancies than in centralized systems. That is, if a centralized system fails, all the customers that it serves are at risk of being disconnected from their water supply. When a decentralized system fails, another nearby station can supply the water needed until the damaged plant is fixed.

While newly developing areas may implement decentralized water systems, other cities with existing centralized water treatment systems should not look to totally disassemble their infrastructure. Instead they should consider developing a hybrid centralized/decentralized model. This might be as simple as adding a decentralized plant in a quickly growing area instead of expanding the centralized plant. And because LID techniques such as rainwater harvesting and low flow toilets reduce the output needed from a water treatment plant, LID techniques and decentralization simultaneously work to enable and enhance each other.

Energy

Fossil fuels are a limited resource. As such, their use needs to be judicious and efficient. Improving the efficiency of vehicles, lighting, appliances, electronics, heating, ventilation, and cooling is one strategy. Another strategy may be redesigning the energy system by distributing power and incorporating renewables, and truly integrating multiple resource planning. Below are described a sample of opportunities.

Combined Heat and Power

A large amount of energy is lost in creating electric power; only about 30% of the energy input results in electricity delivered to the customer [23]. Seventy percent of the energy is lost in converting the primary fuel into electricity and distributing through the power grid. For that same amount of input energy, a combined heat and power system could utilize ~85% of the input energy (see Fig. 8.6). Combined heat and power has the potential to provide the United States 20% of the electricity by 2030, which could reduce an estimated 0.2 gigatons of carbon annually. This system also emits, on average, 1/10th of the nitrogen oxides (NO_x) per kWh as compared to the average grid electricity [24]. Helsinki Energy in Finland used combined heat and power, and has experienced great results [24]. Sulfur dioxide emissions from district heating were reduced around 90% from 1980 to 2004. This scheme also saved Finland six million tons of carbon emissions in 2004. Using less energy means fewer greenhouse gases are created, and with the climate changing so quickly, emission reduction is needed. Systems like these generate electricity and use the waste heat for a variety of processes like chemical manufacturing, heating buildings, or producing hot water, and thereby eliminate or reduce the energy and consequent environmental impacts needed for those demands [23, 24].

Energy Efficient Products

In most existing applications, simply upgrading or modernizing energy demanding products will result in improved efficiencies and higher performance. Even low-end refrigerators produced today may be several times more efficient than refrigerators

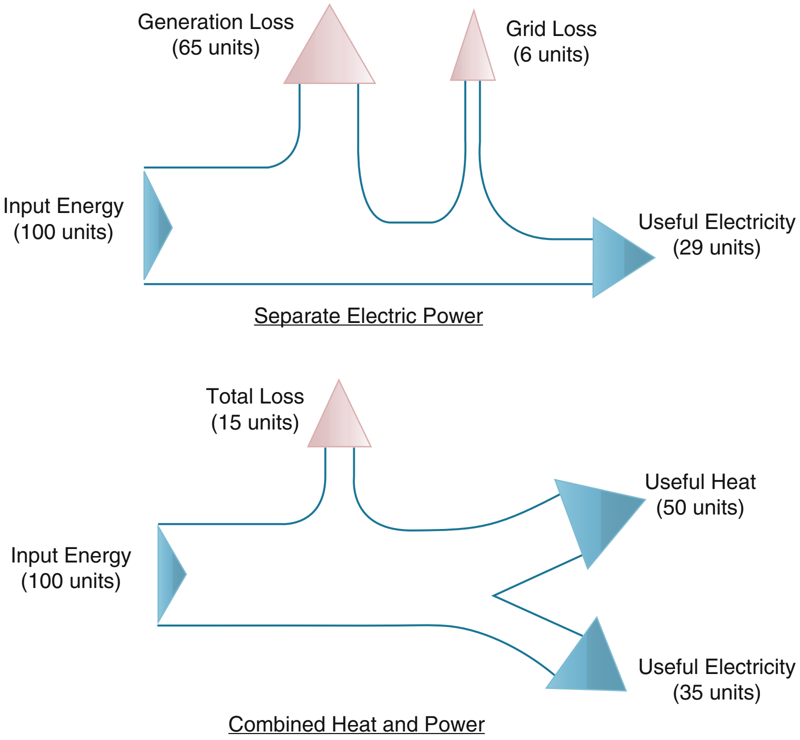

Fig. 8.6 Utilization of energy for separate electric power and combined heat and power. The amount of energy lost is much higher in the separate system due to the recycling of heat to make more energy (Amended from [22])

produced 20, 30, and 40 years ago, while also providing more features and functionality along with a relatively short payback period. When choosing new or replacement products, however, certified Energy Star products use 20–30% less energy than the federal standards require [25]. Eligible products include appliances, electronics, heating and cooling systems, lighting, fans, plumbing fixtures, and building products like insulation and roofing.

Photovoltaics and Other Renewable Energy Sources

Every day the sun provides more than enough energy to meet all the demands of humans and nature. But while nature has evolved to efficiently harvest this free energy, human made systems are only now becoming cost-effective (see Fig. 8.7). Comparing photovoltaic power generation to coal generation, Table 8.6 shows for each source the ratio of energy output to energy invested water use, land use, cost of power, and jobs. While the lower overnight cost of power still favors coal, the other attributes indicate that PV is already a competitive alternative. With costs

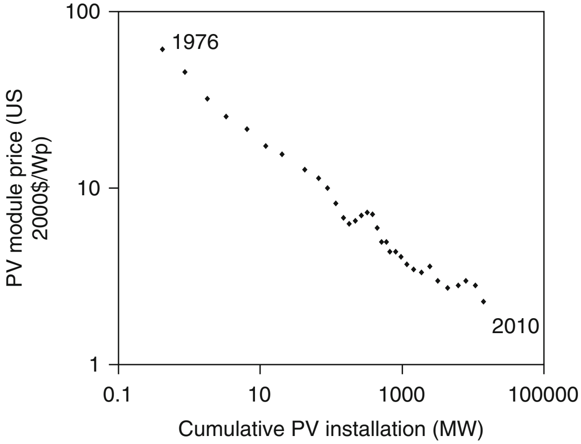

Fig. 8.7 Price of a PV module per Watt peak (constant year 2000 US dollars) as a function of cumulative installation of PV in megawatts for the period 1976–2010 [27]

Table 8.6 A comparison of power generation from photovoltaic and coal energy sources

Energy Source	Photovoltaic	Coal
$\frac{\text{Energy output}}{\text{Energy invested}}$ [28]	9.0	5.0
Water use [29]	0.001 Gal/kWh	0.49 Gal/kWh
Land use	0.51 kWh/acre (RET Screen Simulation)	690 kWh/acre [30–33]
Overnight cost [34]	$4.75/kWh	$2.84/kWh
Total job-years/GW h (avg) [32]	0.87	0.11

continuing to drop, however, PV could soon become the preferred power source with coal becoming the less attractive alternative.

Wind, geothermal, biomass, and hydroelectricity are some of the other renewable energies that are growing in importance. For example, a recent working report suggested that there is an unrealized potential of 29,400 MW of hydroelectricity that could be developed in the United States [26]. One problem with renewable resources, though, is their inherent intermittency. In order for many renewables to become practical, large-scale inexpensive energy storage methods need to be developed. These methods may include various types or combinations of electrochemical batteries, flywheels, compressed air, superconductive magnetic storage, and the oldest, the least capacity-constrained and most popular when available, pumped hydro-storage.

Decentralizing Distribution

Apart from the manner in which power is generated, system resiliency can be increased by changing how the power is distributed. The smaller scales inherent to renewable generators, such as PV, mean that these generators can more readily be

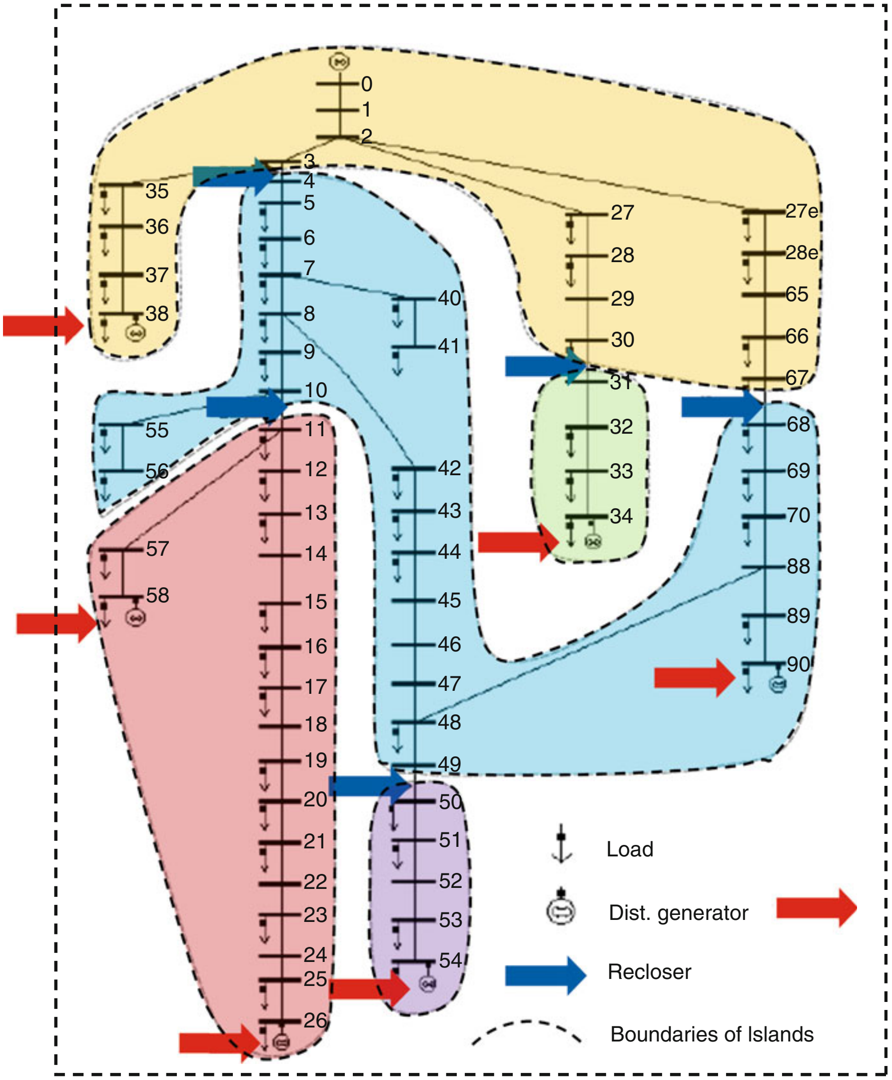

Fig. 8.8 A depiction of an islanded distribution network. This system is split into multiple zones with balanced distributed generation and loads (as shown by the *dotted lines* and *multiple colors*). There are multiple distributed generators, and each island has a recloser at the boundaries with other zones. This allows the islands to cut off from each other in case of a disturbance, keeping the larger portion of the network supplied with energy. Once the problem is fixed, the islanded system can then automatically be reconnected to the grid (transmission network)

located in various locations across the distribution feeder. Microgrids can be created by separating the distribution feeders into zones of balanced generation and load can by placing reclosers at the zone boundaries (reclosers are similar to circuit breakers, but do not have the capability to interrupt the fault current; see Fig. 8.8, e.g.).

In the case of a feeder separated from one of its supply substations by a fault location, such a network may allow the feeder still to be energized and supplied by other generators while the faults are being mitigated. That would improve reliability as measured by indices such as SAIFI and SAIDI (system average interruption frequency and duration index), CAIFI and CAIDI (customer average interruption frequency and duration index), and ASUI and ASAI (average service (un)availability index). Improvements in such indices (or composite indices) usually mean better customer satisfaction and diminished losses associated with repetitive outages, that is, increased resiliency.

Example: Distributed Renewable PV Generation

Distributed generation consists of small-scale and decentralized electric energy systems. Capacities vary, typically in the range of several kW to hundreds of MW. Accurate and efficient system analysis algorithms are needed in order to analyze the impact of PV systems on various types of microgrids and distribution networks. The influence of uncertainties can be modeled via suitably optimized Monte Carlo techniques.

Commercial PV power industries started developing in the 1970s. In spite of a 70% reduction of the real price of PV modules over 40 years, energy from PV remains too expensive to compete with conventional sources. Political changes in the United States in the early 1980s ended substantial funding for solar energy research and, since the nation represented nearly 80% of the global market for solar energy at that time, virtually halted solar energy development around the world. In 2004, renewable energy sources accounted for 9.6% of the electricity generated in the United States and 18.6% worldwide. China was the leading nation by renewable generation capacity in 2008 (598 TW h of renewable energy produced that year). A total of 3,584 TW h of renewable energy was produced in the world in 2008, of that only 12 TW h was from solar photovoltaic generators while, for example, 16% (3,288 TW h) of world electric energy was produced from hydroelectric plants. However, PV has become one of the most rapidly growing energy generation technologies. PV module shipments have grown at an average annual rate of 40% since 1996, up from 13% in the previous decade. The potential growth may transform PV into a $100 billion industry [35].

On the technical side of PV proliferation, electric power utilities are not motivated to allow interconnections of customer-owned generators (such as many PV installations would be) to their distribution networks (mostly for operational reasons). Utilities tend to put nonutility generation under the extensive technical analysis. Conversely, the regulating authorities tend to act in favor of DG owners and support that the interconnection be as easy and transparent as possible.

The main objective of PV installation is to boost the energy savings. Figure 8.9 shows annual estimated monthly PV generation output of an assumed PV system in the Atlanta area in the United States. Figure 8.10

(continued)

Example (continued)

presents how the total load demand is decreased due to the PV generation with capacity ranging 10–40% of the annual peak load at the same feeder. The figure represents the system performance on the 244th day of the year. If the distributed generator (DG) is owned by the customer, the actual benefit is cost saving in the electric bill. If the DG is owned by the utility, the benefit is avoided energy production from the less desirable or more expensive sources and reduction in transmission and distribution losses. This benefit means energy saving in both cases.

The second impact of solar electricity generation is the ecological impact. The PV output energy savings provide the opportunity to create the avoided carbon footprint by not using the more ecologically impactful technologies (coal, natural gas, etc.). In addition to reducing the effective feeder load in the distribution networks where it is installed (thus also reducing the transmission and distribution losses), PV generation can also bring about CO_2 reduction. It can also cause water footprint reduction through avoided thermoelectric and hydroelectric generation, and fuel reduction, such as coal, petroleum, and natural gas in the thermal power generation as in Table 8.6. The example assumes that the PV system is optimally oriented to maximize energy production. (If shaving of peak load levels is the main objective, it is possible to orient the PV system more westward, thereby boosting the PV output at the peak load times.)

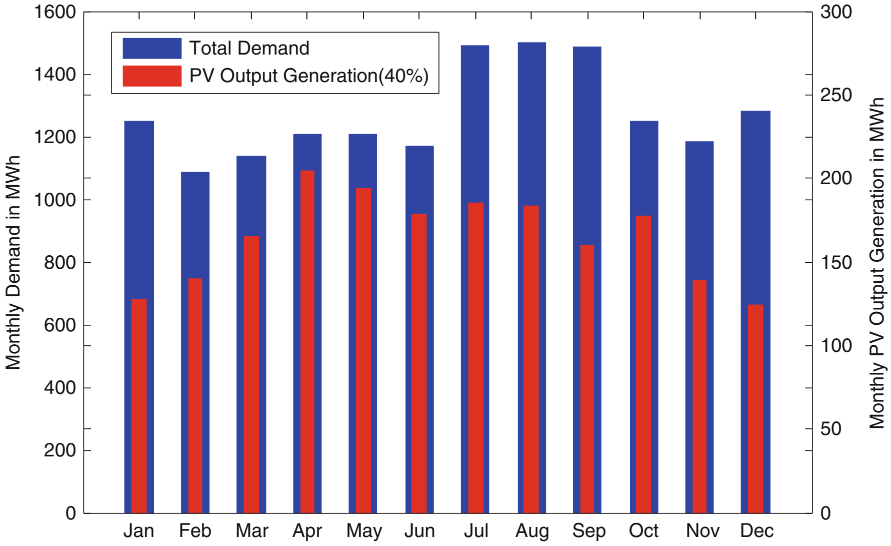

Fig. 8.9 Annual PV generation and load demand on a typical distribution feeder. It is assumed that the total PV capacity is equal to 40% of the peak load demand

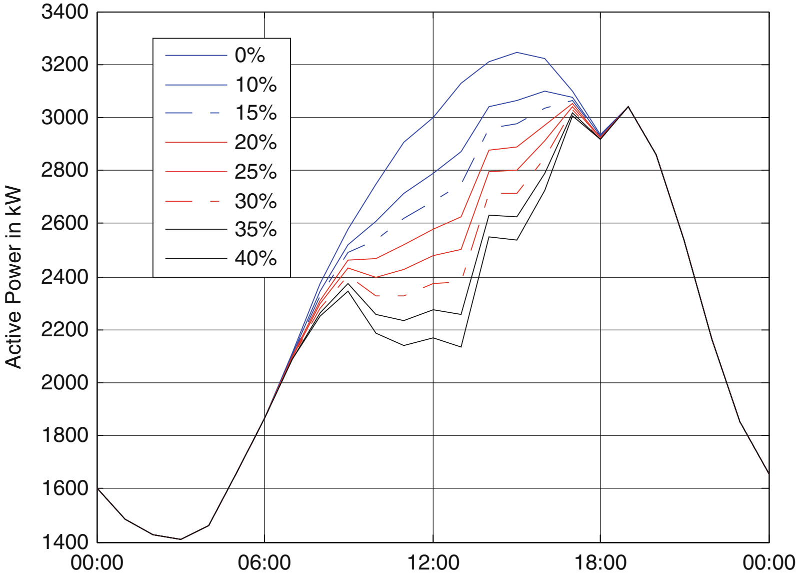

Fig. 8.10 The effect of PV generation on a typical day of the year (horizontal axis represents time of the day). Assumed PV capacity is 40% of the annual peak load

Understanding Aggregate Demand

A number of factors need to be considered in every city when making decisions to improve sustainability. Inputting all the data necessary to run a good model of a city is a massive undertaking, but the model could be a very useful tool.

For the modeling of Atlanta, Geographic Information System (GIS) tools were used to input infrastructure data. The What if?^{TM} system was used to model Atlanta. This software was used to show the suitability of various infrastructures for an area. Figure 8.11 shows the suitability for eight different land-use types. As Atlanta continues to develop, this can be used as a tool to plan infrastructures for areas that are more suitable. Along with suitability factors, this program was used to predict the land use of Atlanta as it grows. Figure 8.12 shows Atlanta's use of land in 2010 and the prediction for land use in 2030, using the Business as Usual scenario. This scenario looks to grow the city in the traditional urban sprawl way, and the figure shows much of the land use going to residential use and employment centers expanding outward from the city center. Figure 8.13 offers a different comparison, this one of two different growth scenarios: Business as Usual and Compact Growth as predicted for 2030. This comparison shows the difference in how Atlanta can grow, with more compact living and more undeveloped area, or with continued urban sprawl.

Programs such as What if?^{TM} and UrbanSim give a rough prediction of the future, but the scenarios in these programs are not easily edited by the user.

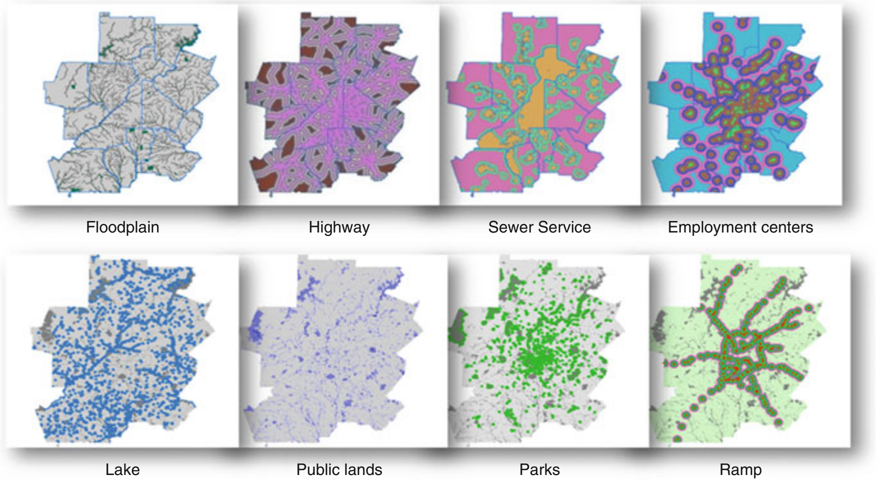

Fig. 8.11 The maps show the 13 county metropolitan Atlanta area. Based on the land, the program What if?^{TM} developed the suitability for different kinds of infrastructure and land use

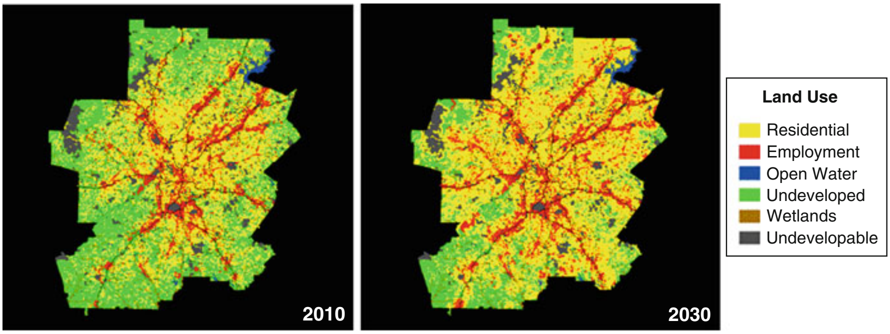

Fig. 8.12 The 13 county metropolitan Atlanta area's land use. This shows the prospective land use using the Business as Usual scenario from the What if?^{TM} software. Employment centers and residential areas expand outward over the 20 years, leaving very little area undeveloped

To date, infrastructure planning has been an exercise in developing a few different scenarios that fit the general tendencies of the agents and groups of agents that the infrastructure intends to serve. This approach, though, fails to account for a number of factors that affect the decision making of agents. Looking beyond a set of scenarios, agent-based modeling creates equations for how people react to different constraints and opportunities. For example, surveys and behavioral analyses can be used to develop algorithms that describe how people react to policy decisions or to gauge consumer awareness. These reactions though are

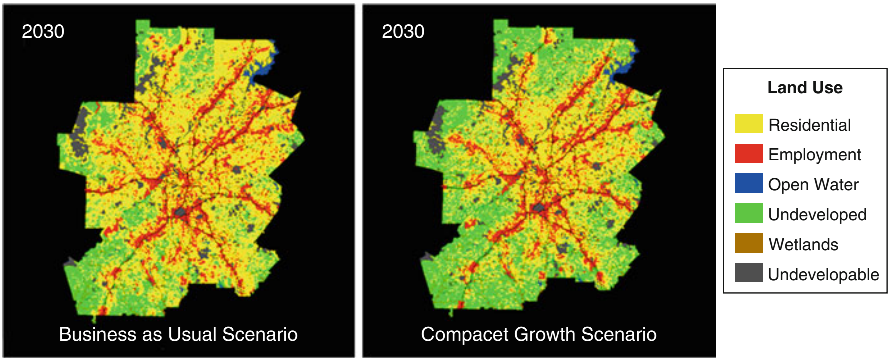

Fig. 8.13 The 13 county metropolitan Atlanta area's prospective land use in 2030. This is according to the simulation run with the What if?™ software. These show the comparison of development based on two different scenarios, Business as Usual and Compact Growth. Compact Growth shows that much more land is left undeveloped and residences remain near the city, whereas Business as Usual shows an increase in urban sprawl

tempered by the context of many other variables though such as economic feasibility, the state of current infrastructure, or the availability of technology. Modeling could provide a number of answers to questions concerning a city's sustainability. Some of the questions it could help address are as follows:

- What price are people willing to pay for renewable energies, and what kind of policies may be needed to encourage this choice?
- How can the transportation network be better planned in order to make public transportation efficient, and at what price will people pay to choose more sustainable forms of transportation?
- What incentives are needed for people to live in more compact spaces?
- How can consumption of nonrenewable resources be reduced?

Agent-based modeling, in combination with other modeling tools, is needed to predict the demand for urban infrastructure, how it should be built and designed, and what materials should be used.

Future Directions

For the future, there is a need to redesign our anthroposphere (the place where we live), so that it can exist within the means of nature: using only the renewable resources that nature can sustainably provide, while generating only wastes that nature can sustainably assimilate.

Future goals include:

- Monitor, model, visualize, and predict the emergent properties of urban infrastructure systems and their resilience to stressors.
- Understand the flow of resources and information as they move through the urban system with urban metabolism.
- Develop a pedagogy for the design of complex systems for sustainability within the context of urban systems.
- Integrate the human perspective into urban infrastructure so that socially sustainable policies and outcomes are produced.
- Research and develop sustainable alternative technologies for water treatment, and materials and energy production.

Acknowledgments The authors would like to thank Brook Byers Institute for Sustainable Systems, High Tower Chair, and Georgia Research Alliance for their financial supports.
Funding for this research was provided by the US NSF grant 0836046: EFRI – RESIN Project: Sustainable Infrastructures for Energy and Water Supply (SINEWS). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the view of the supporting organizations.

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