Buildings and Infrastructure from a Sustainability Perspective

Sustainable and Healthy Communities Program - Theme 4.1.1

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Executive Summary

The economic, societal and environmental impact of our buildings and infrastructure (B&I) is substantial. Within the United States, buildings and infrastructure comprises 16% of the gross domestic product (BEA, 2013), 41% of the primary energy consumption (EERE, 2012e), 13% freshwater withdrawals (Kenny & al., 2009), and 37% of greenhouse gas emissions (EIA, 2009). Although we spend 90% of our time within buildings (EPA, 2012), building research accounts for 0.2% of all federally funded research (USGBC, 2006). Additionally, the nation must invest about $255 billion in the next five years just to maintain its water/wastewater infrastructure (ASCE, 2009), and green infrastructure is increasingly recognized as an opportunity to decrease these costs while providing environmental, economic, and societal benefits.

Green buildings and their associated infrastructure are nascent from a research, development, and societal deployment standpoint. Buildings with a green certifications currently comprise only 1% of over 132 million residential buildings and about 1% of 4.9 million commercial buildings in the United States (EPA, 2014b; USGBC, 2013). About half of green building and infrastructure developments are attributed to government stimulus (Marcacci, 2012; McGraw-Hill, 2012). Although some cities appear to be ahead of the curve, most green infrastructure projects are sparely dispersed at the "pilot" scale level of development. Green buildings and infrastructure development needs to broadly extend into a community to make a significant effect on energy and water demands and environmental impacts.

Green facilities represent a large experimental test bed to validate the effectiveness of point-based rating systems such as LEED that are used to design buildings and infrastructure with smaller environmental footprints (Berardi, 2013; Orr, 2014). Currently, green certified buildings comprise a majority EPA and other federal agency's recently constructed facilities. As of 2011, the federal government had 519 LEED certified projects, 40 Green Globes certified buildings (Wang, Fowler, & Sullivan, 2012), and over 130 ENERGY STAR certified buildings (GSA, 2010). These federal buildings could be used to holistically evaluate traditional metrics such as water and energy consumption and also novel metrics such as human performance. This information could also provide crucial information to evaluate the interactions among the three pillars of sustainability – society, economy and the environment.

One of the primary issues surroundings full-scale adoption of green buildings and infrastructure is the uncertainty associated both with products and technologies. Researching our existing green federal buildings and associated infrastructure would provide communities with critical information on materials and technologies that will invariably have their pros, cons, and unintended consequences. This information would also serve as baseline information to supplement and create community tools to assist individuals ranging from building owners to directors of metropolitan sewer districts to make informed decisions.

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Abbreviations and Acronyms

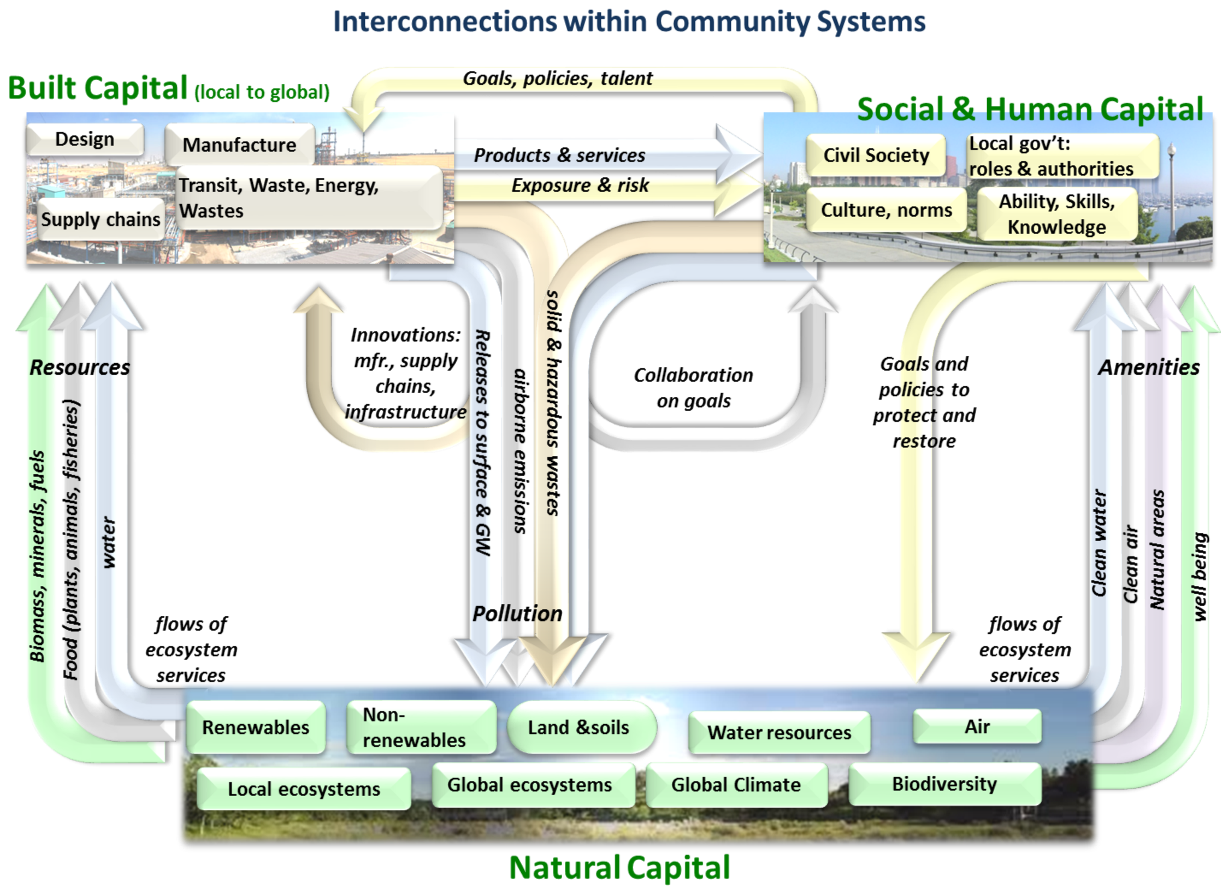
ACEEE	American Council for an Energy-Efficient Economy
ACGIH	American Conference of Industrial Hygienists
ALA	American Library Association
AOA	Administration on Aging
ARM	Adjustable rate mortgage
ARRA	American Recovery and Reinvestment Act
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
B&I	Buildings and infrastructure
BEA	Bureau of Economic Analysis
C&D	Construction and demolition
CAS	Chemical Abstracts Service
CBECS	Commercial buildings energy consumption survey
CDC	Centers for Disease Control and Prevention
CEAE	Civil, Environmental and Architectural Engineering at the University of Colorado
CHP	Combined heat and power
CO_2	Carbon dioxide
CSOs	Combined sewer overflows
DBG	Deutsche Bank Group
DDT	Dichloro-diphenyl-trichloroethane
DOD	Department of Defense
DOE	Department of Energy
DHS	Department of Homeland Security
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group, Inc.
FCIC	Financial Crisis Inquiry Commission at Standard Law School
GDP	Gross domestic product
GHGs	Greenhouse gases
gpd	gallons per day
gpf	gallons per flush
GSA	General Services Administration
HELCOM	Helsinki Commission, Baltic Marine Environment Protection Commission
HHS	Department of Human and Health Services
HVAC	Heating, ventilation, and air conditioning
IRIS	Integrated Risk Information System
JCHS	Joint Center for Housing Studies of Harvard University
kWh	Kilowatt-hour
LEED	Leadership in energy and environmental design
MCTF	Middle Class Task Force of White House Council on Environmental Quality
$MMTCO_2e$	Metric tons of CO_2 equivalents
MSW	Municipal solid waste
NSF	National Science Foundation
NRDC	Natural Resources Defense Council
NEBRA	North East Biosolids and Residuals Association

O&M	Operation and maintenance
ORD	Office of Research and Development
OSHA	Occupational Safety & Health Administration
PBDEs	Polybrominated diphenyl ethers
PCBs	polychlorinated biphenyls
Quad Btus	10^{15} British Thermal Units
R&D	Research and development
RECS	Residential Energy Consumption Survey
REIC	Real Estate Inspection Company
RFC	Raftelis Financial Consultants, Inc.
RDC	Resource Dynamics Corporation
SMR	SMR Research Corporation
SSOs	Sanitary sewer overflows
TBG	Terrapin Bright Green LLC
TRIO	Total Resource Impacts and Outcomes
TSCA	Toxic Substances Control Act
USCB	United States Census Bureau
USGS	United States Geological Survey
USGBC	U.S. Green Building Council
WBDG	Whole Building Design Guide

Introduction – Viewing buildings and infrastructure (B&I) through the lens of sustainability

According to the U.S. Environmental Protection Agency, U.S. citizens spent about 90% of their time in residential and commercial buildings (EPA, 2012). Therefore, the buildings we use and the infrastructure that services it is instrumentally important from a sustainability perspective. This report focuses upon buildings and infrastructure from a systems framework (Figure 1). This framework visualizes community interactions from a triple bottom line or "three pillars" sustainability perspective - Society, Economy, and the Environment. From this perspective, emphasis will be placed on the identifying the research and development (R&D) needs to support sustainable community decisions.

Figure 1. Sustainability in a systems framework & interconnections among the three pillars



(Source: J.Fiksel, "A systems view of sustainability: the triple value model," Environmental Development, June 2012)

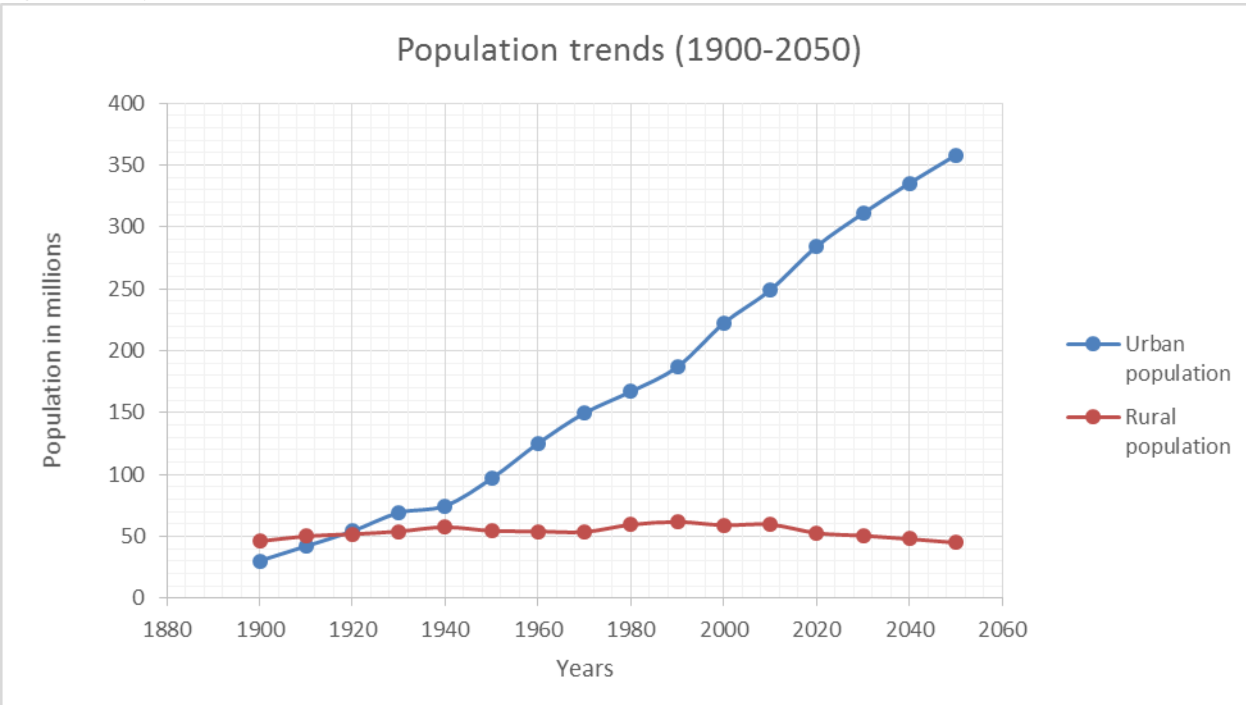
Many past building and infrastructure examples exist where actions in one of the three sustainability pillars resulted in unintended consequences in another pillar. A key example occurred during the energy crisis of the 1970's (economic pillar). To reduce their demand on costly energy, building owners took measures to prevent drafts and reduce the amount of unconditioned (i.e., outside) air within their buildings. With less outside air coming in, indoor contaminants increased resulting in "sick building syndrome" (societal pillar). At the height of the crisis, the World Health Organization estimated that up to 30% of the new and remodeled buildings may have been linked to "sick building syndrome" (SBS) (EPA, 1991).

Societal pillar of B&I

Demographics

Population dynamics is a key driver of how society develops, deploys and modifies their buildings and infrastructure, which then influences the economic and environmental pillars of sustainability. For over a century, the population of the United States has steadily increased to over 300 million people. As demonstrated in Figure 2, the population has overwhelmingly grown in urban environments with a steady but slow decrease in rural environments relative to urban populations.

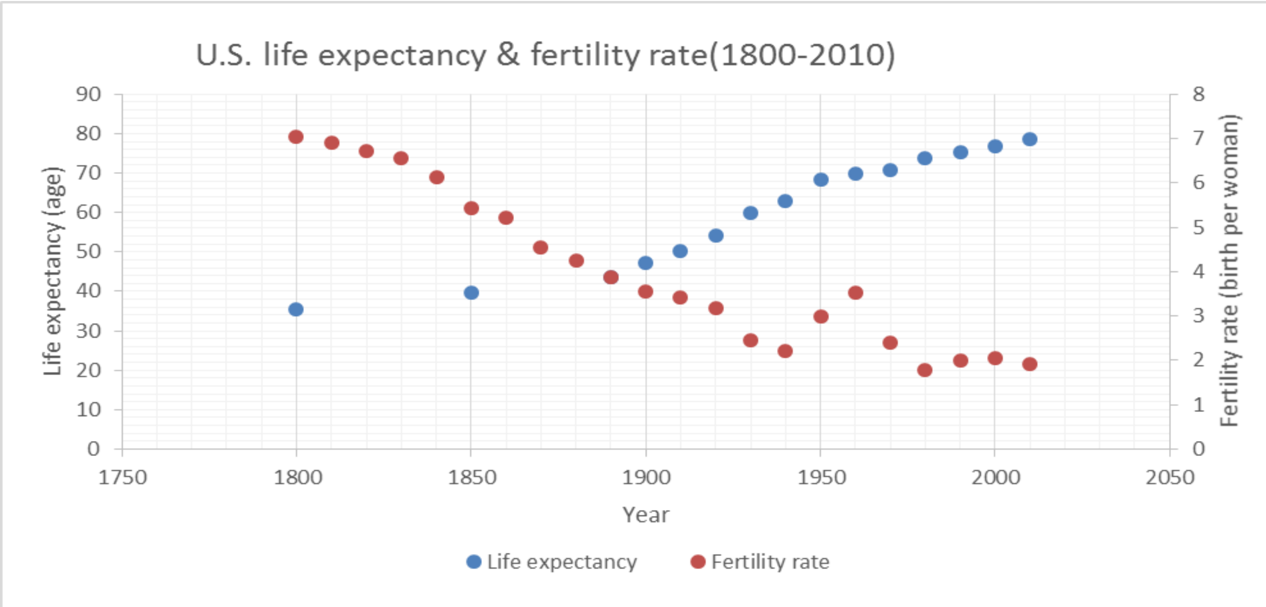
Figure 2. Population trends in the U.S.



(Sources: 1. data of 1900-1990 from U.S. Census Bureau, urban and rural populations, table 4. Population: 1790 to 1990; 2. 2000 and 2010 from urban, urbanized area, urban cluster, and rural population, 2010 and 2000: United States; 3. 2020-2050 from U.N. Department of Economic and Social Affairs' Population Division, urban, rural, total population data from 1950-2050)

Interestingly, life expectancy and fertility rates have traded off for the U.S. population (Figure 3). Since 2007, the U.S. fertility rate has fallen below 2.1, a value typically associated with a societal "replacement rate," although factors such as immigration have resulted in a yearly average increase of 695,000 new U.S. citizens from 2000 through 2010 (DHS, 2012). The most current estimate from 2010 is a fertility rate of 1.9 births per woman. In contrast, life expectancy has steadily increased from the beginning of the 20th century to present. In 1900, 4% of the population was over 65 compared to approximately 13% today (AOA, 2014). Approximately 20% of the population is expected to be over 65 by 2030 (AOA, 2014). Most of the elderly own their own homes (81%) (Lipman, Lubell, & Salomon, 2012) and wish to remain in their homes (89%) during their retirement years (Dietz, 2013). Many factors influence this significant change including medical prevention and treatment advances, population related anomalies such as the baby boomer generation, and public education and awareness about healthy lifestyle habits. As these demographics shift to an older population primarily living in an urban environment, the buildings and infrastructure needs to support them will concurrently change.

Figure 3. Life expectancy and fertility rate



(Sources: 1. life expectancy of 1800, 1850 & 1890 from Historical Statistics of the United States 1789-1945, the average of male and female life expectation in Series C 6-21—Vital Statistics—complete expectation of life: 1989 to 1949; 2. 1900-1990 life expectancy from UC Berkeley Department of Demography, life expectancy in the USA, 1900-98; 3. 2000 and 2010 life expectancy from Centers for Disease Control and Prevention's Table 18 (page 1 of 2). Life expectancy at birth, at age 65, and at age 75, by sex, race, and Hispanic origin: United States, selected years 1900–2010; 4. Fertility rate 1800-2000 from Haines, Michael. Fertility and Mortality in the United State, EH.Net Encyclopedia)

Health

Indoor levels of pollutants may be 2-5 times higher, and occasionally more than 100 times higher, than outdoor levels (EPA, 2012). Given that 90% of our time is spent in buildings, several factors are important in reducing indoor contamination including: (1) the building envelop, (2) the operation and maintenance of the building's HVAC (heating, ventilating, and air conditioning) system and (3) the materials used within a building, both in its construction and operations and maintenance (e.g., cleaning supplies). Off-gassing from furniture and other consumer products is also a factor for indoor air quality; however, that is not considered here since that is not part of the building and infrastructure itself.

There are a large number of indoor air quality studies that report health effects from a wide range of building conditions. Indoor pollutants such as man-made chemical mixtures, gases, mold, and bacteria can cause illness such as dizziness, headaches, asthma, lung cancer, and other respiratory diseases (EPA, 2012). Several examples include:

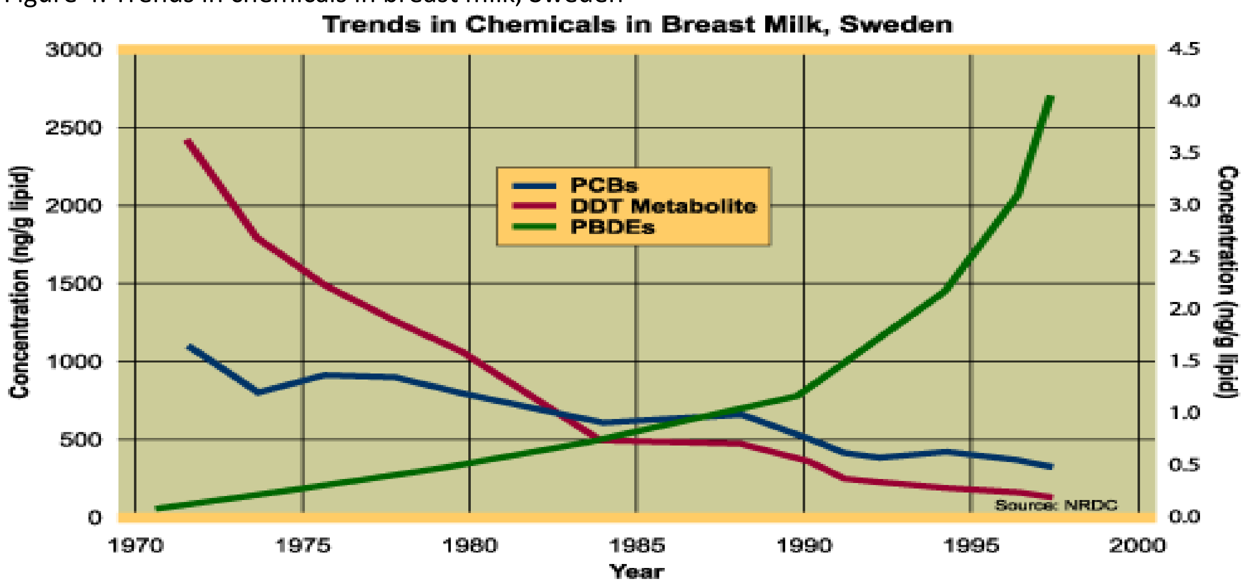
- *Building envelope creating conditions for bioaerosol contamination*. Water infiltration into a building combined with nutrient rich building materials create conditions favorable for microbiological growth (i.e. mold and bacteria formation) (WBDG, 2009). The microbial growth can create bioaerosols that can cause occupant respiratory symptoms, skin irritation and lung function impairment (Douwes, Thorne, Pearce, & Heederik, 2003).

- *Building HVAC system creating conditions for Sick Building Syndrome (SBS)*. There are several building factors associated with climate control and ventilation that increase SBS prevalence (i.e. eye, nose, or throat irritation, and headache), such as high indoor temperature, poor fresh air ventilation rates, and inadequate humidity (Gomzi & Bobic, 2009). 30 to 70 million workers in the U.S were estimated to exhibit SBS related symptoms (Pendleton, 2002). According to a Lawrence Berkeley National Laboratory study, SBS symptoms can be reduced by increasing outdoor air exchange. As an example, a twofold decrease in ventilation rate increased SBS symptoms by 23%.
- *Building materials creating conditions for asthma*. The Healthy Building Network's report identified 20 top-priority asthmagens used in building materials such as insulation, paints, adhesives, floors and carpets, and other interior materials with which building occupants routinely come into contact by touch or inhalation (Lott & Vallette, 2013). Asthma prevalence rate increased about 16% from 2001 through 2010, reflecting 14.4 million lost school days in children and 14.2 million lost work days in adults (ALA, 2012). In particular, the greatest rise in asthma rates during the same period was a 48% increase among African American children (ALA, 2012).
- *Building infrastructure introducing contaminants via the public water system*. Legacy materials such as lead were widely used in potable water plumbing in the past and still exist in much of our aging water infrastructure. In Washington, DC, an unintended consequence of a change in the disinfection of the public water supply was to spike the concentration of lead in drinking water from 2000 through 2004. The incidence of elevated blood lead (blood lead ≥ 10μg/dL) in young children increased 4 times compared to before the disinfection change (Edwards, Triantafyllidou, & Best, 2009). Lead is considered an embryo-fetal poison for pregnant women, which at high levels has been historically associated with instantaneous abortion, stillbirth, infant mortality (Triantafyllidou & Edwards, 2012). Fetal death rate in Washington, DC peaked in 2001 where water lead levels increased 32%-63% compared to prior years (Edwards, 2014).

The number of chemicals that are discovered and used by society has been increasing at an exponential rate (Binetti, Costamagna, & Marcello, 2008). While these chemicals provide extensive innovative and practical uses, some also introduce the potential for human exposures. As an example, a Swedish study of women's breast milk showed historical trends for three significant chemicals, polychlorinated biphenyls (PCBs), Dichloro-diphenyl-trichloroethane (DDT) metabolite, and Polybrominated diphenyl ethers (PBDEs) (Figure 4) (Meironyte, Noren, & Bergman, 1999; Noren & Meironyte, 2000). The fire retardant PBDE levels in Swedish women's breast milk increased 60 fold between 1972 and 1997 once it was commercially adopted (Oecotextiles, 2010), but PCBs and DDT decreased concurrently with the ban on their use due to their adverse health effects (HELCOM, 2011; Noren & Meironyte, 2000). Studies of PBDEs in Indiana, Texas, and San Francisco Bay area (average concentrations of PBDEs = between 74 and 86 nanograms per gram of fat) in the late 1990s and early 2000s showed approximately 21 times higher PBDE level in women's breast milk when compared to the Swedish study (NRDC, 2005).

With regard to building materials, there is a huge gap of knowledge regarding the health data for the chemical substances that comprise the building material. For example, approximately 15,000 chemical substances are added daily to the Chemical Abstracts Service (CAS) Registry, a database containing over 87 million unique chemical substances (Binetti et al., 2008; CAS, 2014). In general, if the production volume exceeds 10,000 pounds per year, the chemical substance has to be listed in the Toxic Substances Control Act (TSCA) inventory. Although the TSCA inventory currently contains over 84,000 chemical substances, over 62,000 chemicals were "grandfathered" into the inventory without heath data evaluation (Wilson & Schwarzman, 2009) and roughly 85% of the added chemicals have no health data (EPA, 2007).

Figure 4. Trends in chemicals in breast milk, Sweden



(Sources: Oecotextiles, "What are PBDE's and why should I be concerned."Please note that original data sources for PBDEs, PCBs & DDT metabolite; 1. Meironyte, D. & et al., Analysis of polybrominated diphenyl ethers in Swedish human milk. A time-related trend study, 1972-1997 for data of PBDEs; 2. Noren & Meironyte, Certain organochlorine and organobromine contaminants in Swedish human milk in perspective of past 20-30 years, data for DDT metabolite and PCBs)

In comparison, chemical substances having enough health data (e.g., cellular, animal and human studies) to produce a recommended exposure limit are orders of magnitude lower. As examples, the total number of chemical substances for the Environmental Protection Agency's Integrated Risk Information System (IRIS) is currently at 555 (EPA, 2014d) and is similar in magnitude to other entities such as the Occupational Safety and Health Administration (517), the National Institute for Occupational Safety and Health (677), and the American Council for Governmental Industrial Hygienists (over 700)(ACGIH, 2014; CDC, 2013; OSHA, 2014).

Therefore, a huge disparity exists between what is known versus what is out there with respect to manufactured chemicals, especially when considering that building materials are typically composed of complex mixtures. The health effects of mixtures are important due to a number of toxicology studies demonstrating synergistic effects where the toxic effects of chemicals are multiplicative rather than additive. Also, the burgeoning use of nanotechnology can be demonstrated by the 20.7% growth rate of nanotechnology publications from 1991 to 2004 (Li et al., 2008), which introduces a new dimension to the potential for human exposure and toxicological properties. As an illustrative example, bulk titanium dioxide typically is thought of as an unreactive white metal oxide while nano-scale titanium dioxide become transparent, conductive, and photoactive (Warheit, 2008). These property changes of nano-scale TIO_2 have been broadly used on consumer products, such as pigment, solar cells, self-cleaning windows, and cement (Lee, Mahendra, & Alvarez, 2010). Material data sheet information is often prepared from parent material and does not contain additional information regarding the changed chemical and material properties or potential health effects of the nano-scaled material (Lee et al., 2010).

Economic pillar of B&I

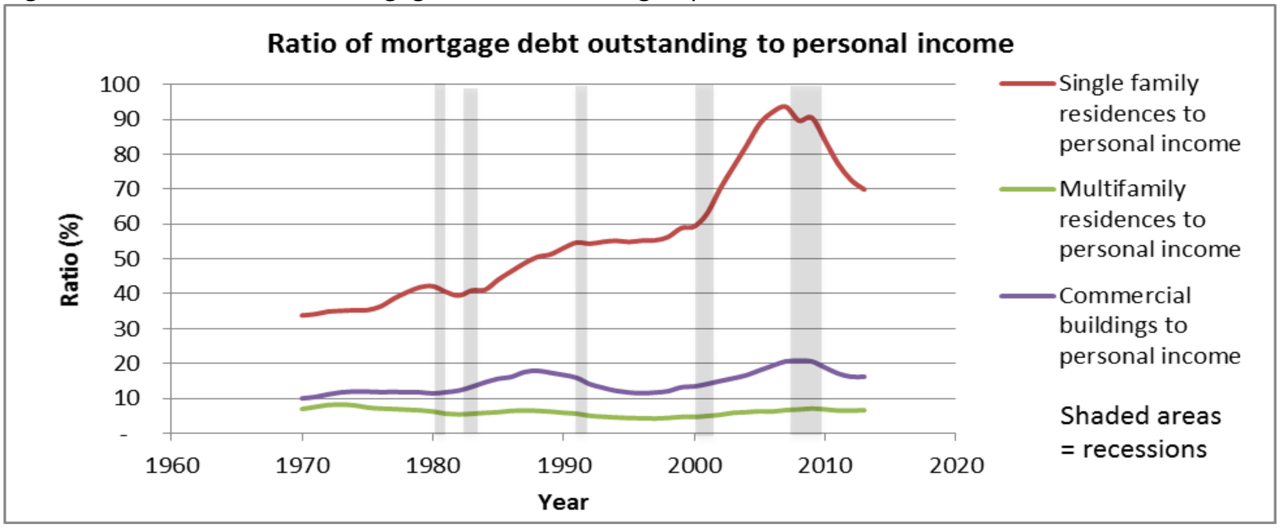
Impact on US gross domestic product (GDP)

The construction and utility industry sectors represent the economic value of buildings and infrastructure in our economy. In 2007, the construction industry contained approximately 730,000 companies with over 7.3 million employees. The utility industry (e.g., power, water/wastewater) contained approximately 16,600 establishments with over 635,000 employees (USCB, 2007). The economic value of the U.S. construction sector, including sales, shipments, receipts, revenue, or business transacted was approximately 1.73 trillion dollars, and utilities economic value was approximately 580 billion dollars (USCB, 2007). Given that the U.S. GDP was 14.48 trillion (BEA, 2013), both sectors accounted for 16% of the total expenditures for all goods and services produced in 2007.

Recent financial trends

As a result of the recent housing bubble, an excess real estate inventory created economic uncertainty and may have simultaneously dampened the economic recovery. In addition, a shadow inventory existed of homes in the process of foreclosure and those that would be put on the market as soon as the market improved enough to sell. By late 2009, the delinquency rate for subprime (i.e., buyers turned away by traditional lending institutions due to factors such as low credit scores) ARMs (adjustable rate mortgages) and fixed rate mortgages was 40% and 20%, respectively (FCIC, 2010). Comparatively, prime ARMs and fixed rate mortgages delinquencies were 17% and 5%, respectively. About 40% of the mortgages were loans with little or no documentation and 43% of first-time home buyers purchased their home with zero down payment loans (Knox, 2006). As a consequence of the weakened real estate market, home equity, a major source of wealth for most owners, dramatically decreased from $13 trillion in 2006 to $6.5 trillion in 2011 (JCHS, 2013). The ratio of mortgage debt to personal income trend is illustrated by Figure 5, which reveals the substantial increase of our household economic burden from mortgage in the 2000s.

Figure 5. Trends in ratio of mortgage debt outstanding to personal income



(Sources: 1. Board of Governors of the Federal Reserve System (FRS), mortgage debt outstanding, historical data (CSV), 2014; 2. BEA, Total personal income by year)

In addition, the housing market collapse and subsequent economic downturn resulted in a substantial decrease both in new construction and construction-related employment (Holtz-Eakin & Winkler, 2012). In 2010, new building construction was down 55% from its peak in 2006 while construction employment decreased 27% to 5.7 million (EERE, 2012e). The home construction dropped to 327,000 units in 2012, a 67% drop compared to approximately 1 million units in the early 2000s (USCB, 2012).

New market potential with green B&I

For individuals ranging from architects to community planners, the abundance of potentially green products and technologies make it difficult to make informed decisions (Herrera, 2012). This is especially true for building owners who carry high mortgage debts (Figure 5) and are primarily driven by economic decisions. Typically, initial costs are a primary concern while factors such operation and maintenance costs are considered secondary. As an example, green retrofits such as WaterSense products and ENERGY STAR products typically result in considerable reductions in water, energy, and materials consumption. However, these products are also associated with higher initial costs. Given that the lifespan of B&I range in decades, the inherent efficiency of green products result in significantly lower O&M costs with break-even points ranging from 2 to 12 years, depending on the applied retrofits (DBG, 2012).

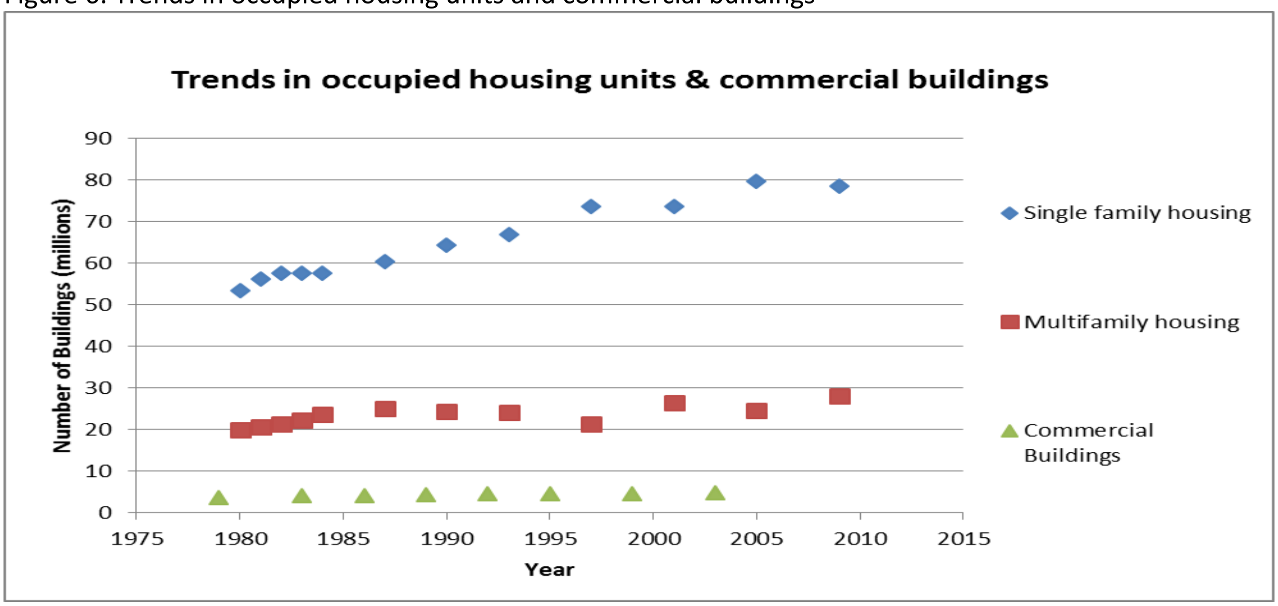
Given the current state of the housing market, green buildings are providing a strong, niche area of economic growth. With the current decrease in new construction, green building construction has maintained its market share of buildings, growing in several sectors (Marcacci, 2012; McGraw-Hill, 2012). However, a significant source of this construction revenue can be attributed to government economic stimulus aid. As an example, the American Recovery and Reinvestment Act of 2009 (ARRA) invested about $31 billion in green building-related construction stimulus (McGraw-Hill, 2014). About half of the economic effects by green construction market are attributed to government stimulus (Marcacci, 2012; McGraw-Hill, 2012).

An additional factor is that federal law has mandated green building construction for federal facilities. Executive Orders 13423 and 13514 *Federal Leadership in Environmental, Energy, and Economic Performance* requires that federal agencies implement the *Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings* in all new construction and major renovation projects and in at least 15% of their existing building inventory (by number of buildings) by the end of FY 2015 (EPA, 2013b). In addition, federal agencies are mandated to achieve an annual 3% reduction in energy intensity and cumulative 30% reduction by 2015 (compared to an FY 2003 baseline). All new federal buildings must be designed to achieve "zero net energy" by FY 2030 (EPA, 2013b).

Building demographics

Buildings also have increased steadily, both in numbers and size. Occupied housing units increased from 80 million units in 1980 to 114 million in 2010, a 43% increase (EERE, 2012b). In comparison, commercial buildings increased from 3.8 million units in 1979 to nearly 4.9 million units in 2003, a 26% increase (EIA, 2013b). Although housing units outnumber commercial units by 23 to 1, a comparison of floor space shows a 3 to 1 difference. This makes intuitive sense in that commercial facilities are significantly larger than residential facilities. The historical trends of several types of building are illustrated by Figure 6 with single family units representing both the largest and fastest growing segment. According to EIA's Annual Energy Outlook 2012, housing units are expected to increase in number by 28% by 2035, while commercial buildings are expected to increase floor space by 27% (EIA, 2012a).

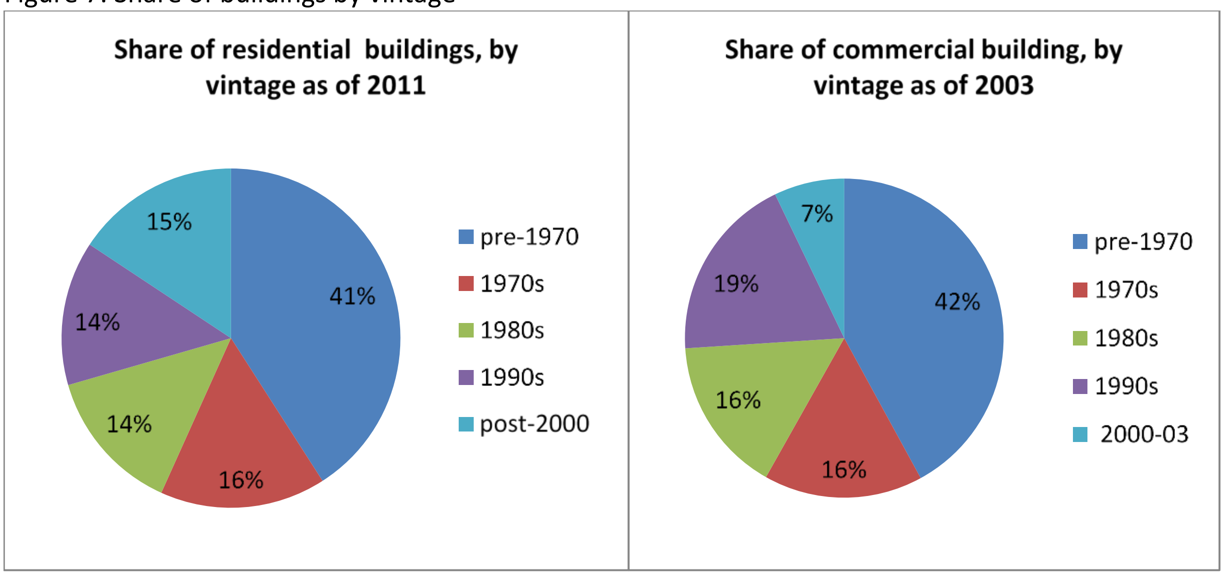
Figure 6. Trends in occupied housing units and commercial buildings



(Sources: 1. EIA, residential energy consumption survey (RECS) data 2. EIA, commercial buildings energy consumption survey (CBECS) data)

As the number of buildings have increased, so too have their age. The median age of housing units is 37 years (2011) (USCB, 2011a) while the average age of commercial buildings is 42 years (2009) (SMR, 2009). One of the problems associated with older buildings is that they were built long before the development of modern building and energy codes (REIC, 2012). Buildings constructed before Energy Policy Act of 1992 accounted for approximately 71% of residential and 74% of commercial facilities (Figure 7) (EIA, 2006a, 2013a). Given the significant number of older facilities, this represents a significant opportunity to implement thoughtful green retrofits including: (1) reducing energy expenditures (economic and environmental pillars), (2) improving indoor environmental air quality (societal pillar), (3) improving/reducing water use (economic and environment), and (4) construction/retrofit employment opportunities (economic pillar). As a TRIO example focusing upon the economic pillar, retrofitting the United States building stock provides an employment advantage generating about 50% more jobs when compared to new construction (Alter, 2011).

Figure 7. Share of buildings by vintage



(Sources: 1. USCB, American fact finder: Selected housing characteristics: 2011 American community survey 1-year estimates; 2. EIA, 2003 CBECS survey data: Table C1A. Total energy consumption by major fuel for all buildings, 2003)

Economic impact of green projects

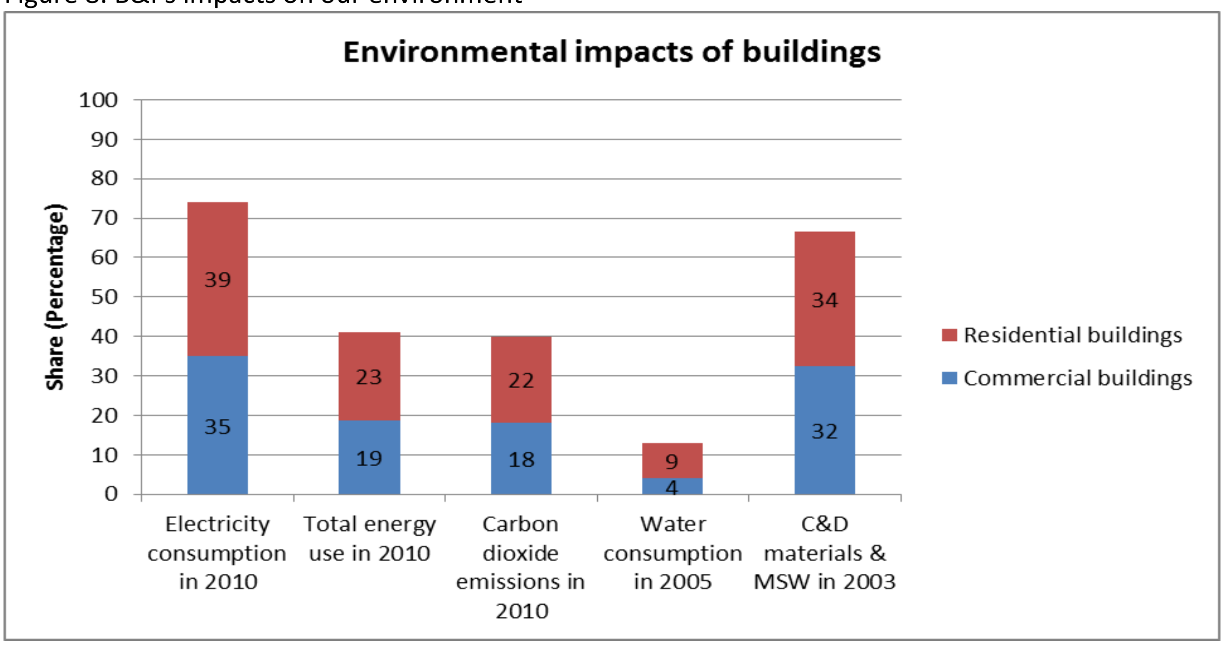
Recently, the number of green building projects has increased, however, in relation to the total building stock, their contribution is minor. Cumulative new and existing residential units certified as ENERGY STAR by 2012 were approximately 1.7 million (EPA, 2014b) and LEED had 47,000 units certified (USGBC, 2013). Out of roughly 133 million residential units, slightly higher than 1% of total residential units were certified. In terms of commercial buildings, each of LEED and ENERGY STAR certified roughly 20,000 commercial buildings (EPA, 2014b; USGBC, 2013). Therefore, approximately 1% of the total commercial buildings were certified by LEED and/or ENERGY STAR.

The number of green infrastructure projects that have been deployed on a community-scale is low but increasing, because many communities are recognizing potential economic benefits where green infrastructure can reduce the source (stormwater runoff) and decrease the amount of updates needed to the sewer systems (EPA, 2014g). According to American Society of Civil Engineers (ASCE), some of our water infrastructure is approaching the end of its service life (e.g., pipelines dating back to the Civil War era). These latent issues are often addressed when a problem actually occurs (e.g., 240,000 annual water main breaks) (ASCE, 2013). In response, approximately 4,000 to 5,000 miles of drinking water mains are replaced annually (ASCE, 2013) while 225,000 miles of new pipelines have been added over last 5 years (2001-2006) (EPA, 2009a). ASCE estimated $255 billion for the next five years would be needed to maintain the national water/wastewater infrastructure (ASCE, 2009).

Environmental pillar of B&I

Buildings and infrastructure have a significant impact on the environment. The production and manufacture of building components consumed 6 billion tons of basic materials annually, or 40% of extracted materials in the U.S. (Yuan, Chini, Lu, & Shen, 2012). Along with consuming natural resources during B&I's lifespan, buildings and their occupants continuously generate wastes that effect the environment. More than 130 million residential and commercial buildings are served by approximately 250,000 utilities (i.e. 6,997 power plants, 166,000 water suppliers and 16,000 wastewater treatment plants) (EIA, 2013c; EPA, 2014c). Consumption and emissions are substantial when considering the total life cycle of commercial and residential buildings: total energy use = 41%; total electrical use = 74%; total carbon dioxide (CO_2) emissions = 40%; total freshwater withdrawals = 13% and non-industrial solid waste = 67% (Figure 8).

Figure 8. B&I's impacts on our environment



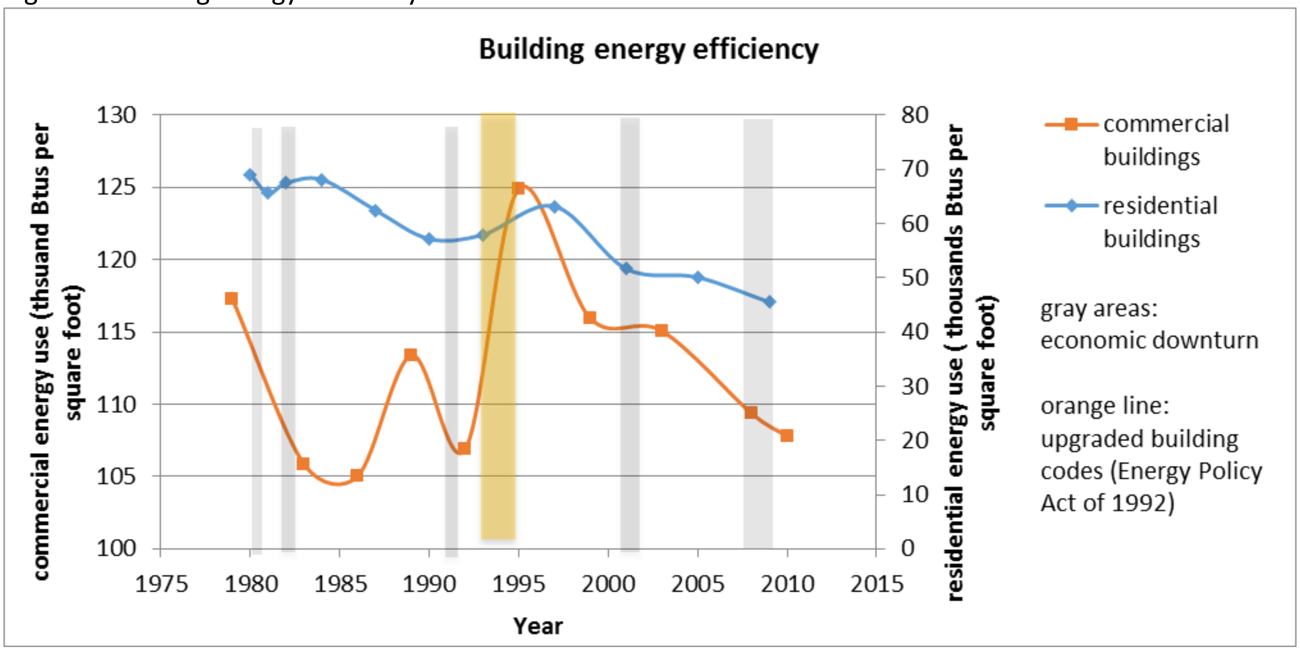
(Sources: 1. EERE, building energy data book, table 1.1.3 & 1.1.9 for electricity consumption, table 2.4.1 & 3.4.1. for CO2 emission, table 8.1.1 for water consumption, and table 1.4.14 for C&D materials; 2. EPA's buildings and their Impact on the environment: Statistical summary for MSW; 3. Kenny et al., USGS, estimated use of water in the United States in 2005)

Energy consumption & increasing efficiency

Commercial and residential buildings have steadily decreased their energy intensity (Figure 9), primarily due to energy saving technologies. For example, residential units built between 2000 and 2005 used

14% less energy per square foot than those in the 1980s and 40% less than those built before 1950 (EERE, 2012a). Additionally, the average energy use of commercial buildings was reduced about 14% from 1995 to 2010 (Figure 9) and is forecasted to steadily decrease (EIA, 2014b).

Figure 9. Building energy efficiency

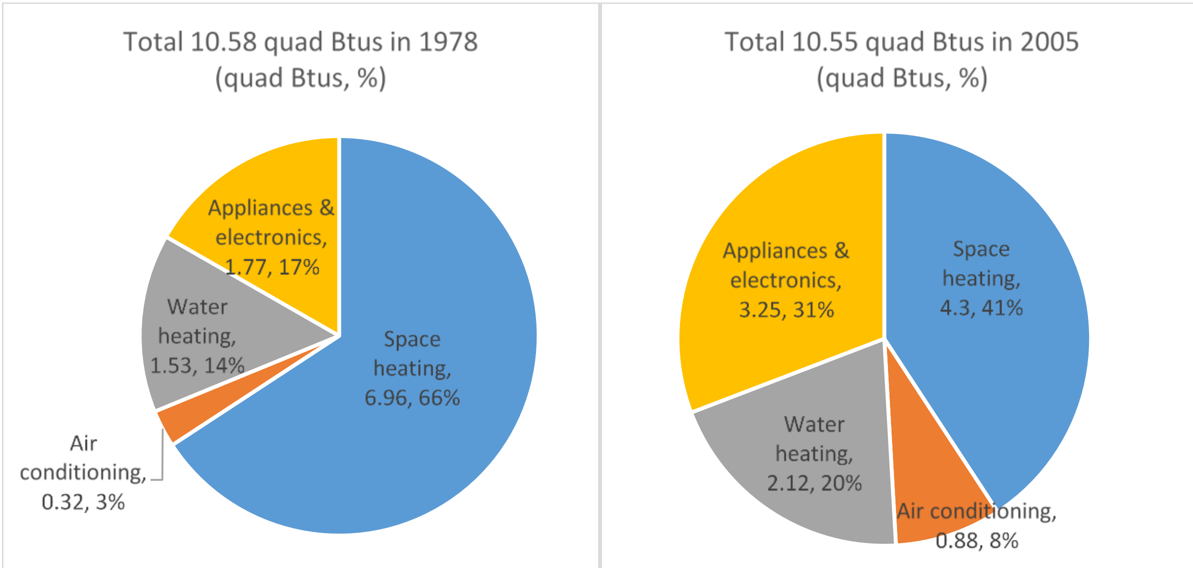


(Sources: 1. EIA, residential energy consumption survey data and commercial buildings energy consumption survey data; 2 EERE, building energy data book, table 3.1.1 & 3.2.1)

This decrease in energy intensity has been attributed to many factors including more efficient equipment and insulation systems. The use of ENERGY STAR products has increased seven fold when comparing 2012 to 2000 purchases (EPA, 2014b). This translated to an 11% savings in electrical consumption (EPA, 2014b). As examples, the average refrigerators' energy use per year decreased 61% from 1980 to 2010 (EERE, 2012c) while the average clothes washers' energy use decreased 68% from 1981 to 2008 (ACEEE, 2012). In regards to insulation in homes, double or triple-pane glass accounted for about 80% of homes built during the 2000s compared to 50% of homes built during the 1970s (ACEEE, 2012).

In contrast, there are also two major trends countering the efficiency gains over the past decades: the increased average size of buildings and the increased number of electric intensive devises and appliances (ACEEE, 2012). With an increase in sizes of buildings comes an accompanying increase in the area that needs to be heated and cooled. Homes built during the 2000s are 46% larger than those built during the 1970s (EIA, 2012b). An average size of commercial buildings built in the last two decades is 22% larger than those built before 1990, and commercial buildings built since 2000 is on average 54% larger than those built during the mid-1900s (EIA, 2014a). Additionally, the share of energy use for appliances and electronics such microwave, clothes water, clothes dryer, dishwasher, and computers and rechargeable electronic devices increased significantly from 17% in 1978 to 31% in 2005 (Figure 10) (ACEEE, 2012; EIA, 2011).

Figure 10. Total energy use in homes



(Source: EIA, RECS, Share of energy used by appliances and consumer electronics increases in U.S. homes. Please note that "quad Btus" is 10^{15} British Thermal Units)

Greenhouse gases from power plants

The building sector has contributed significantly to greenhouse gas (GHG) emissions. GHG emissions are produced by combustion of fossil fuels for energy. Major sources of GHG emissions include the combustion of coal or natural gas to generate electricity and heat as well as combustion of gasoline for automobiles (EPA, 2014a). In 2008, buildings were responsible for about 37% of the U.S. total GHGs emissions (Figure 11). As an example, residential CO_2 emissions from electricity and heating increased 35% from 1980 through 2008 while commercial buildings increased 60% (EIA, 2009).

Figure 11. Greenhouse gas emissions in the U.S., 2008 (in MMTCO2e)

Sector / GHGs	Residential	Commercial	Residential & Commercial	U.S. Totals
CO2	1230	1084	2314	5839
Methane	5	203	208	737
Others	9	66	75	476
Total Emissions	1244	1353	2597	7053
Share of total GHGs (%)	18	19	37	100

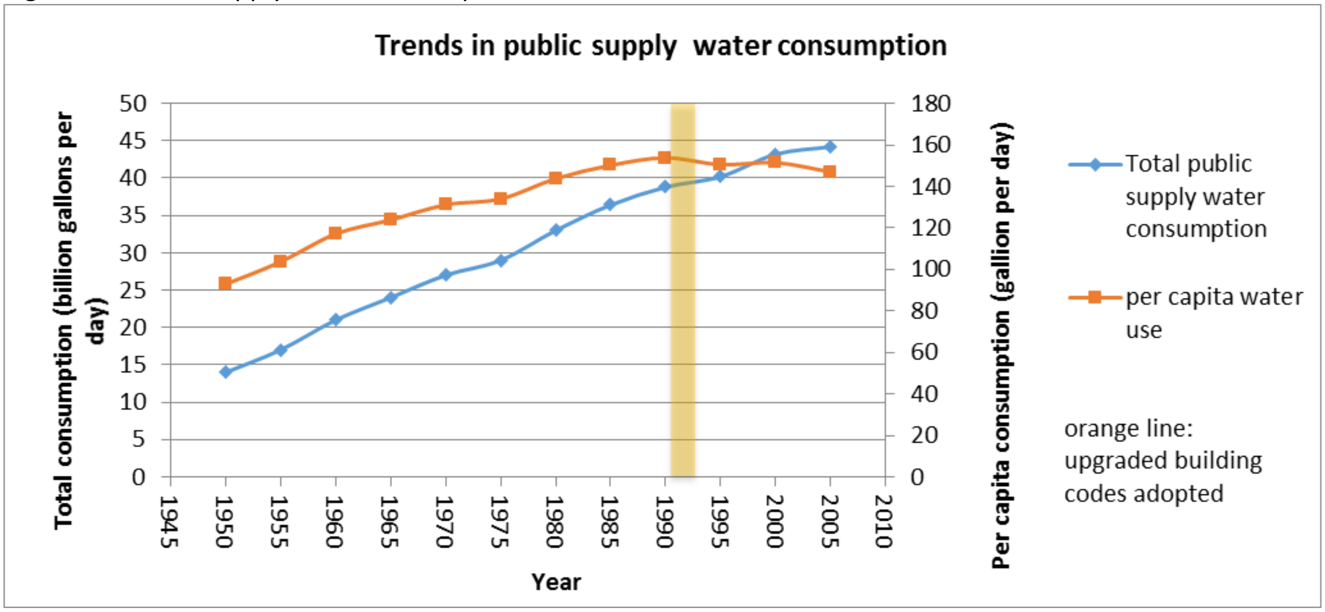
(Source: EIA, Emissions of Greenhouse Gases in the United States 2008, pp.6)

Improvements of buildings on space heating and cooling, lighting, and other electric appliances have clear potential to significantly reduce CO_2 emissions. Looking only at the residential sector, energy efficiency retrofits could reduce energy consumption by up to 40% per home and in turn lower associated GHGs emissions by up to 160 million metric tons annually by the year 2020 (MCTF, 2009).

Water consumption & increasing efficiency

As our population has increased, so too has water consumption. 93.4 million and 258.6 million people were served in 1950 and in 2005, respectively, by public supply. This represented a 177% increase in consumption (ASCE, 2009; Kenny & al., 2009). The total daily amount of drinking water produced for buildings was estimated at about 44.2 billion gallons per day (gpd) representing 13% of the total U.S. water use (Kenny & al., 2009). Also, water infrastructure loses approximately 7 billion gallons of drinking water every day through leaking pipes or about 15% of our daily drinking water usage (EPA, 2013d).

Figure 12. Public supply water consumption trends



(Source: Kenny et al., USGS, estimated use of water in the United States in 2005, Table 14. trends in estimated water use in the United States, 1950-2005)

However, per capita water use began to stabilize in the early 1990s after a steady previous increase in consumption (Figure 12). A potential explanation could be that water saving technologies had entered the market from efficiency standards set by Energy Policy Act (Vickers, 1993). Another potential explanation could be increased water costs driving water conserving behavior (Olmstead & Stavins, 2007). Examples include:

- Efficiency technologies: Residential toilets with maximum water use of 3.5 gallons per flush (gpf) were replaced with 1.6 gpf toilets, and maximum flow rates of both showerheads and faucets could not be more than 2.5 gallons per minute. In comparison, pre-1994 counterparts were 3 to 5 gpf (Vickers, 1990). WaterSense single family homes are expected to use approximately 21% less water indoors than a standard home, and 25% less water for landscaping over non-efficient irrigation systems (EPA, 2009b).
- Water price: Water charges increased on average 5% each year since 1996 while average annual inflationary increase was 2.5% (AWWA & RFC, 2012). In particular, the U.S. water charges in 100 large urban municipalities surveyed have increased, at least doubling in more than 25 locations between 2000 and 2012 (McCoy, 2012).

Such demand-side water savings at end users in buildings by the efficiency technologies and the increased water prices may have contributed to the level-off pattern of the recent average water use (Figure 12).

Energy used in treating water

The US water systems use energy efficiently from a per capita basis. 166,000 drinking water systems incorporate over 1 million miles of pipes, and 16,000 wastewater systems that comprise approximately 740,000 miles of public sewers and 500,000 miles of private lateral sewers (EPA, 2014c). Given the vast water systems, the energy use of public water supply and wastewater treatment, including conveyance and distribution pipelines of both public and private owned systems, was about 138 billion kWh or 4% of 2005 national electricity consumption (EIA, 2006b; Griffiths-Sattenspiel & Wilson, 2009).

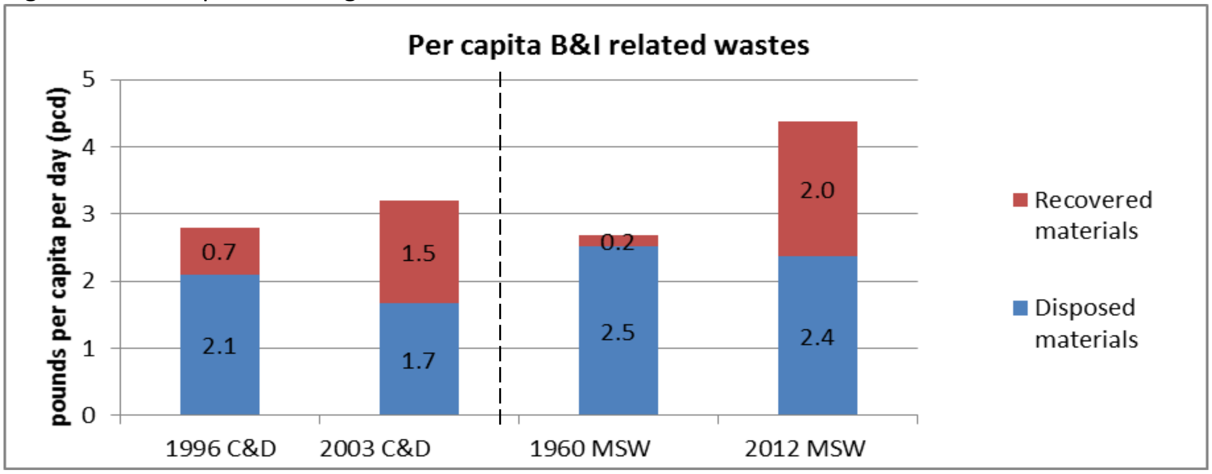
Green infrastructure and drinking water

On average, US citizens use approximately 140 gallons per day of water delivered to buildings (i.e., treated drinking water) for both potable and non-potable uses (Kenny & al., 2009; USCB, 2011b). We use less than 11% of total drinking water for drinking or cooking at home, while 50% of our potable water delivered to buildings is used in toilets and outdoor uses such as watering lawns and gardens and washing cars (EERE, 2012d; Kenny & al., 2009). The remainder of our drinking water is used for washing clothes, bathing, and dishwashing. Grey water reuse represents an open area of R&D with significant potential benefits from a sustainability perspective, especially in areas of the country experiencing water shortages. While 7% of the U.S. households reuse grey water, some states in arid climate appear to be ahead of the curve, such as Arizona with 13% of households (Roesner, Qian, Criswell, Stromberger, & Klein, 2006).

B&I related wastes

Recycling has significantly reduced the amount of B&I wastes entering our landfills (Figure 13). Although per capita generation of construction and demolition (C&D) waste increased 14%, the material recovery markedly increased 114% when comparing 1996 to 2003 figures (EPA, 1998, 2009c). This effect is even more pronounced when comparing municipal solid waste (MSW) over a longer timespan (i.e., 1960 to 2012). In this case per capita MSW waste generation increased 63% and material recovery increased by 1000% (EPA, 2014e). Given the increase of material consumption with economic and population growth, recovery technologies and recycling practices reduced potential environmental impacts by diverting wastes from landfills.

Figure 13. Per capita wastes generation

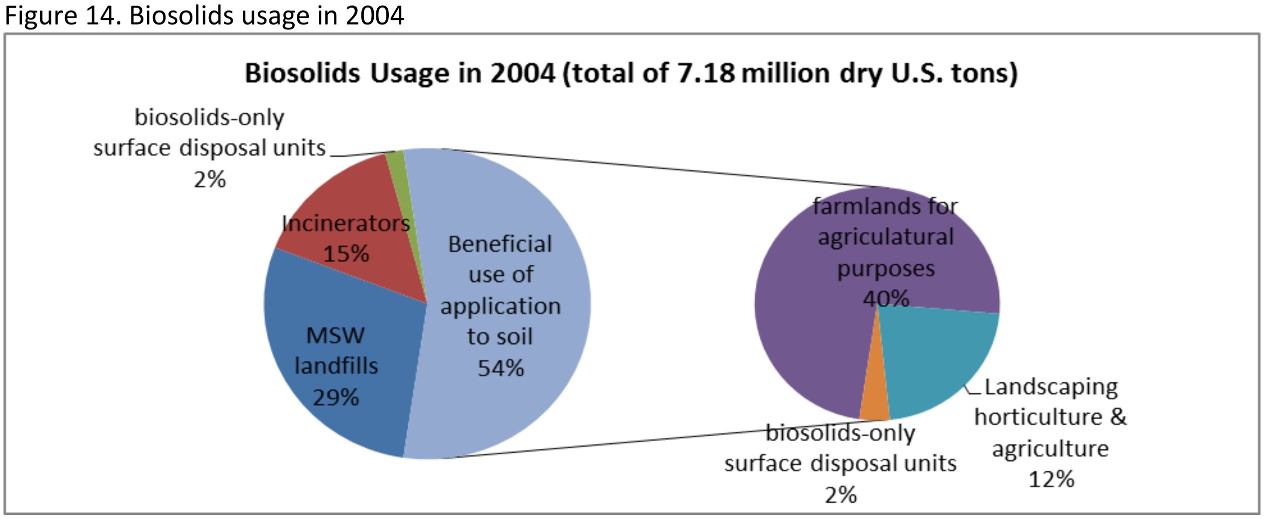


(Source: EPA, 1996 and 2003 C&D estimating publications; EPA, 1960 & 2012 MSW estimation)

Sanitary and stormwater

Wastewater conveyance and advanced treatment processing have followed both the rapid growth of US population. In the early 1900s, wastewater treatment served approximately 1% of the total population using basic treatment methods such as trickling filters for removal of settling and floating solids (CEAE, 2009). In 2004, about 75% of the population was served using both fundamental and advanced treatment methods (EPA, 2008a). Also, to treat more complicated effluents, advanced treatment practices started in the late 1960s and grew from 0.3 million people in 1968 to 109 million in 2004 (EPA, 2013a).

Figure 14. Biosolids usage in 2004



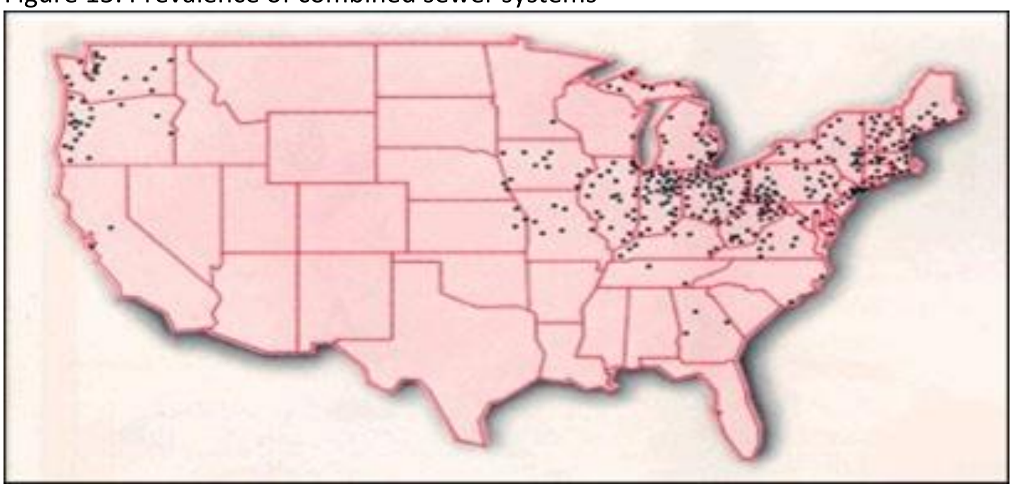
(Source: NEBRA, A national biosolids regulation, quality, end use & disposal survey)

Given the increase in treated wastewater and advanced treatment processes, treatment plants also have increased biosolids by about 22% from 1988 to 2004 as a byproduct of treatment (EPA, 1999, 2013a). However, as shown in Figure 14, 54% of the biosolids were used for beneficial purposes either for agricultural farmlands, landscaping, or horticulture (NEBRA, 2007).

The combined heat and power (CHP) at public wastewater treatment facilities have been utilizing biogas emitted by wastewater sludge treatment to augment their power consumption. Currently, there are 104 public wastewater treatment facilities that utilize CHP systems and 1,351 facilities having the technical potential to implement CHP systems (i.e., treat over 1 million gpd) (ERG & RDC, 2011). The existing and potential biogas based CHP systems have the potential to offset approximately 18% of their total electricity consumption (ERG & RDC, 2011; Griffiths-Sattenspiel & Wilson, 2009).

Combined sewer systems that combined and direct both sanitary and storm water to a treatment plant exist in approximately 772 communities primarily in older Northeastern US cities (Figure 15). An unintended consequence of this system is water quality degradation from overflows of untreated wastewater to surface waters primarily during high precipitation events. Combined sewer overflows (CSO) and sanitary sewer overflows (SSO) are estimated to be 850 and 10 billion gallons per year, respectively (EPA, 2004). This represents 8% of the total flow processed at municipal wastewater treatment facilities (EPA, 2004). These overflows are a large water pollution concern to rivers, lakes and estuaries, resulting in water degradation (EPA, 2008b).

Figure 15. Prevalence of combined sewer systems



(Source: EPA, combined sewer overflows demographics)

Green infrastructure is proposed as a sustainable practice that mimics natural processes to keep stormwater out of sewer and in turn reduce the issue of CSOs in urban areas. Rain gardens, rain barrels, stormwater wetlands, adopting porous materials for paving reduce the volume and rate of stormwater runoff from a developed landscape (EPA, 2013c). As an example, Portland Oregon's Downspout Disconnect Program directs more than 47,000 homeowners roof runoff to gardens and lawns, thus removing about 1.1 billion gallons of stormwater per year (Montalto et al., 2007) and reducing the need for using drinking water for non-potable purposes. Such green infrastructure can help urban areas with highly paved areas to reduce the CSOs and water body impairments. Green infrastructure is increasingly being recognized as a beneficial stormwater management approach but requires community-scale implementation to effectively reduce stormwater runoff that gets into the sewer systems. As discussed earlier, it can provide economic cost savings if it leads to reduced overall burden on the sewer system and upgrade requirements.

Discussion and conclusion from a R&D perspective

This paper attempts to view the building where we spent 90% of our time and its associated infrastructure from a sustainability framework. Typically, these pillars are only presented from a single facet, such as the health impact of a particular environmental contaminant or the environmental impact of a combined sewer system. In this paper, all of the pillars are discussed, presenting information within the pillar and showing how decisions in one of the pillars extends to the other pillars, creating intended as well as unintended consequences that effect sustainability.

This triple bottom line perspective presented the significant impact that our buildings and infrastructure has from a societal, economic, and environmental standpoint. Within the United States, buildings and infrastructure comprises 16% of the GDP (BEA, 2013), 41% of the primary energy consumption (EERE, 2012e), 13% freshwater withdrawals (Kenny & al., 2009), and 37% of greenhouse gas emissions (EIA, 2009). Yet, although we spend 90% of our time within buildings (EPA, 2012), building research accounts for 0.2% of all federally funded research (USGBC, 2006). The information presented on each sustainability pillar suggests a number of potential research areas for further investigation:

- **Building retrofits:** In addition to the significant number of older facilities in the US (Figure 7), approximately one fifth of the population will be over 65 in fifteen years (AOA, 2014). Given our extensive reliance upon our current building stock, how will our buildings be modified to provide comfort, emphasize green retrofits, and provide ease of use? Good R&D would be essential in providing communities with validated solutions regarding techniques, materials, and technologies. In addition, retrofitting an existing structure provides approximately 50% more jobs when compared to new construction (Alter, 2011).
- **Building materials:** Another fundamental aspect of B&I is the lack of knowledge regards the potential health consequences of the materials encountered within buildings on a daily basis. In addition to the previous discussion, history has provided several costly examples of extensively used legacy building materials, such as lead and asbestos that caused adverse impact to all of the sustainability pillars.
- **Uncertainty involving green B&I:** Given the abundance of potentially green products and technologies, making informed decisions is difficult (Herrera, 2012). Green buildings currently represent 1% of residential and commercial buildings with roughly half of the economic effects attributable to government stimulus (Marcacci, 2012; McGraw-Hill, 2012). Conducting unbiased and research to *validate* products and technologies is essential in obtaining full-scale societal adoption.
- **Community tools:** Although there are many tools available to assist communities in making decisions, such as the EPA stormwater calculator (EPA, 2014f), a collective centrally coordinated suite of tools does not yet exist that covers the set of options and decisions to be considered for sustainability of buildings and infrastructure. Developing and adapting existing tools for this purpose would require gathering and synthesizing data and information that is not necessarily available. Rather, a more feasible approach could be to apply and adapt existing tools in a testbed where sustainability goals are a fundamental component of the building and construction effort.

Specifically, green certified buildings comprise a majority EPA and other federal agency's recently constructed facilities. As of 2011, the federal government had 519 LEED certified projects, 40 Green Globes certified buildings (Wang et al., 2012), and over 130 ENERGY STAR certified buildings (GSA, 2010). Although limited research has been conducted to evaluate the overall building performance (GSA, 2011), these federal buildings represent a large, untapped existing resource to conduct research in a number of areas that include:

- Validating sustainability measurements (e.g., LEED points) that resulted in the green certification, both to qualify and quantify successes, failures and unintended consequences.
- Evaluating traditional metrics, such as water or energy use, but also novel metrics, such as human performance (TBG, 2012), to determine triple bottom line benefit provided by green buildings and infrastructure.
- Enlisting other Agency research program areas to evaluate novel buildings materials using rapid assays and/or computational toxicology (EPA, 2009d) in an attempt prevent future legacy material issues.

Focusing research on these topics would provide cost effective, yet critical information for communities to make informed decisions. This research would provide foundational support to address a primary issue surroundings full-scale societal adoption of green buildings and infrastructure - the uncertainty associated both with products, techniques, and technologies. This information could also serve as baseline information to supplement and create community tools to assist individuals ranging from building owners to directors of metropolitan sewer districts to make daily and long-term strategic decisions.

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