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About the Factsheets

Purpose
Since 2001, the University of Michigan’s Center for Sustainable Systems (CSS) has developed a growing set of sustainability factsheets. They address important challenges facing society including such topics as energy security and declining fossil resources, global climate change, freshwater scarcity, ecosystem degradation, and biodiversity loss. In addition to highlighting these impacts, a series of factsheets are focused on the systems that provide basics services such as mobility, shelter, water, energy, and food. For each system, the patterns of use, life cycle impacts, and sustainable solutions and alternatives are presented.

Audience and Dissemination
The current suite includes 29 factsheets and covers a range of topics including waste, buildings, impacts, water, energy, food, materials, and transportation. The factsheets are an excellent resource for legislative aides in Congress and in federal agencies, business and industry, educational institutions ranging from middle schools to universities, and the public who are looking for concise information regarding sustainability challenges and solutions in the U.S.

Authors and Peer Review
The factsheets are developed by graduate student interns in collaboration with faculty advisors and research staff at CSS. These factsheets synthesize data from government agencies, national laboratories, academia, industry sources, and NGO publications. These statistics are reported as concise facts, tables and figures in a two page document. Sources for all data are cited; any derived values are documented in a data repository maintained by CSS. The factsheets are updated on annual basis, and new factsheets on emerging sustainability issues are also created. Factsheets are reviewed externally by subject matter experts and the CSS External Advisory Board.

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About the Center for Sustainable Systems

The Center for Sustainable Systems (CSS) was established in March 1999 in the School for Environment and Sustainability (SEAS) at the University of Michigan. CSS is an evolution of the National Pollution Prevention Center (NPPC) that was created by an EPA competitive grant involving 28 colleges and universities in October 1991. The NPPC collaborated with faculty from a wide range of disciplines across campus and with other leading programs throughout the U.S. Indeed, NPPC was the foundation for many of the relationships CSS has today.

In 1997, NPPC’s Advisory Board approved a transition plan to launch CSS to better focus its mission on systems analysis and sustainability. Universities establish centers to ensure that disciplines and faculty that historically have not worked together do, in fact, work collaboratively in interdisciplinary teams on critically important problems facing society.

Since its inception as the NPPC, the Center has completed more than 150 research projects on topics such as renewable energy, hydrogen infrastructure, transportation, green buildings, consumer products and packaging. A complete list of projects and publications is listed on the Center’s website (css.umich.edu). Methods and tools employed in these research endeavors include life cycle assessment, life cycle design, life cycle costing, life cycle optimization, agent based modeling and big data. In addition, the Center has promoted sustainability education at the University of Michigan by initiating the Sustainable Systems field of study in SEAS, the graduate certificate Program in Industrial Ecology (PIE), and the Engineering Sustainable Systems dual Master’s degree program between SEAS and the College of Engineering. Finally, CSS has sought to reach a broader audience by publishing a series of factsheets on an array of sustainability topics, as well as organizing the Wege Lecture, one of the University’s premier lecture series.

Celebrating 27 Years at the Center for Sustainable Systems

1991 An EPA grant establishes the National Pollution Prevention Center (NPPC) at the University of Michigan.
1992 NPPC releases its first of 16 compendia (topic-based collections of bibliographies, syllabi and case studies) on pollution prevention.
1992 The NPPC external advisory board holds its first meeting.
1994 The EPA awards $0.5 million to NPPC for the development and demonstration of the Life Cycle Design Methodology.
1997 The external advisory board approves transition from NPPC to CSS.
1999 The graduate certificate Program in Industrial Ecology (PIE) is established under CSS guidance.
1999 The Wege Foundation pledges $1.8 million in support of the CSS endowment.
2001 The first annual Wege lecture is inaugurated by CSS.
2002 A prototype University of Michigan sustainability report is released by the Center.
2003 CSS hosts the biennial meeting of the International Society for Industrial Ecology (ISIE).
2003 National Science Foundation (NSF) awards CSS $1.7 million for study of sustainable concrete infrastructure (MUSES project).
2004 Provost recognizes CSS as a permanent University Center.
2005 Alcoa Foundation Conservation and Sustainability Fellowship program supports six post-docs researching Enabling Technology for a Sustainable Energy Future.
2005 SEAS Sustainable Systems Master’s degree field of study opens for fall enrollment.
2007 Engineering Sustainable Systems (ESS) dual Master’s degree program with the College of Engineering and SEAS is launched.
2008 His Holiness the 14th Dalai Lama gives ‘Earth Day Reflections’ talk to 8,000 in Crisler Arena.
2010 Four new SEAS faculty join CSS.
2011 Jonathan Bulkley, co-director of CSS, retires after 43 years of teaching.
2011 Wege Lecture becomes an endowed lectureship.
2011 Jonathan W. Bulkley Collegiate Professor in Sustainable Systems is endowed.
2011 Peter M. Wege & Jonathan W. Bulkley Fellowship in Sustainable Systems is endowed.
2012 CSS sponsors Sustainability Without Borders student group.
2016 25th anniversary of the Center.
2017 School of Natural Resources & Environment (SNRE) becomes School for Environment & Sustainability (SEAS).
Sustainability Indicators

U.S. Environmental Footprint

The U.S. population is expected to grow from 328 million in 2018 to 404 million by 2060. One way to quantify environmental impacts is by estimating how many Earths would be needed to sustain the global population if everyone lived a particular lifestyle. One study estimates it would take 5 Earths to support the current human population if everyone’s consumption patterns were similar to the average American. Pressure on the environment will increase unless consumption patterns are significantly adjusted to account for the finite natural resource base. Factsheets expanding on the topics below are available from the Center for Sustainable Systems.

Food
- The average American’s daily Calorie consumption increased from 2,024 in 1970 to 2,476 in 2010.
- In 2003, the average American consumed 46 gallons of soft drinks, a 330% increase since 1947. Between 1970 and 2014, per capita milk consumption decreased 41%, down to 18 gallons per year.
- The average American consumes about 22.5 teaspoons of added sugars and sweeteners per day; the American Heart Association recommends between 6 and 9 teaspoons daily for an average adult.
- U.S. per capita consumption of added fats increased by 66% from 1970 to 2010.
- More than 70% of U.S. adults are overweight or obese (body mass index of 25 or more), and approximately 17% of children age 2-19 are obese.
- An estimated 21% of available edible food is wasted by U.S. consumers, 50% more than in 1970. This food waste accounts for roughly 15% of the municipal solid waste stream and represents a loss of $450 per person each year.

Water
- In 2015, total water withdrawals in the U.S. for all uses were estimated to be 322 billion gallons per day, 9% less than in 2010. The biggest uses are thermoelectric power (41%), irrigation (37%), and public supply (12%).
- Water use per person was roughly 48% higher in western states than eastern states in 2015, mostly due to crop irrigation in the west. Over 50% of water withdrawals occurs in 12 states, 9% in California.
- The average North American household uses roughly 240 gallons of water per day for indoor and outdoor uses.
- Households with more efficient fixtures and no leaks can drop their water usage to 40 gallons per person per day.

Material Use and Waste Management
- In 2000, per capita consumption of all materials in the United States was 23.7 metric tons, 52% more than the European average.
- In 1900, raw material consumption (non-fossil fuel or food) was less than 2 metric tons per person. By 2014, it had grown to over 12 metric tons per person.
- In 2015, the average American generated 4.5 lbs of municipal solid waste (MSW) each day, with only 1.6 lbs recovered for recycling or composting. For comparison, MSW generation rates (lbs/person/day) were 2.20 in Sweden, 2.98 in the U.K., and 3.71 in Germany.
- In 2015, 35% of U.S. MSW was recovered for recycling or composting, diverting 91 million tons of material from landfills and incinerators—more than double the value from 1990.
- Automated curbside recycling currently serve only 53% of people in the U.S.; 82% of cities with curbside recycling collect material single-stream, meaning materials such as glass and paper are separated at the recycling plant.

Greenhouse Gases (GHG)
- In 2016, U.S. GHG emissions were 20.15 metric tons CO2-equivalent per person.
- From 1990-2016, total annual U.S. GHG emissions increased by 2.4%. Emissions from electricity generation, one-third of the U.S. total, are allocated to sectors in the figure (at right) according to their electricity consumption.
- In 2013, the Intergovernmental Panel on Climate Change (IPCC) concluded that “It is extremely likely (>95% certainty) that human influence has been the dominant cause of the observed warming since the mid-20th century.”
- By choosing energy efficient products to reduce electricity consumption and by making smart transportation choices, individuals can immediately reduce the greenhouse gas emissions they are responsible for.

U.S. Daily Per Capita Caloric Intake by Food Type, 1970-2015

North American Household Water Use

Average American Lifetime Material Consumption

U.S. GHG Emissions, 2016

Every American Born Will Need...
Residential and Commercial Buildings

- Since 1950, average residential living trends in the U.S. have been towards bigger houses with fewer occupants:
  - Number of occupants per house decreased 23%, 24,25
  - Single occupant houses increased from 9% to 28%, 26,27
  - Living space per person increased 257%, 24,28,29
  - House size increased 169%, 28,29
- Significant energy savings could be realized by better insulating residential buildings to reduce the space heating and cooling loads, using energy efficient appliances, and using more efficient lighting in commercial buildings.
- Commercial building average site energy intensity per square foot decreased 14% from 115,000 Btu/sqft in 1979 to 99,200 Btu/sq ft in 2016.23,30
- The amount of developed U.S. land increased by 59% from 1982 to 2012, making up 6% of total U.S. surface area in 2012.31

Transportation

- In 2016, the U.S. had 268 million vehicles, 47.1 million more than licensed drivers.32
- Drivers traveled over 3 trillion vehicle-miles in the U.S. in 2016, a 108% increase since 1980.32 This is equivalent to more than 6 million round-trips to the moon.23
- Compared to 1988 models, the average 2017 vehicle’s weight increased by 17%, horsepower increased by 71%, and acceleration increased (i.e., 0-60 mph times dropped) by 38%.34,35
- Fuel economy surpassed 1988 levels in 2009 after years of decline.28,29
- The average vehicle occupancy for a passenger car is 1.6, compared to 26.1 for rail and 9.1 for a transit bus.36
- Congestion is a worsening urban problem, causing an additional 6.9 billion hours of travel time, 3.1 billion gallons of fuel use, and 60.7 billion pounds of CO₂ emissions by urban Americans in 2014.37

Energy

- In 2016, the U.S. spent $1.0 trillion on energy, or 5.6% of GDP. When spread over the population, annual costs were $3,211 per person.39
- More U.S. energy comes from petroleum than any other source, comprising over 36% of consumption.38
- Each day, U.S. per capita energy consumption includes 2.5 gallons of oil, 12 pounds of coal, and 227 cubic feet of natural gas. Residential daily electricity consumption is 11.6 kilowatt-hours (kWh) per person.38,40
- With less than 5% of the world’s population, the U.S. consumes 17% of the world’s energy and accounts for 15% of world GDP. In comparison, the European Union has 7% of the world’s population, uses 14% of the world’s energy, and accounts for 16% of world GDP; China has 19% of the world’s population, consumes 22% of the world’s energy, and accounts for 18% of its GDP.40,41

U.S. Modes of Transportation to Work in 201616

- Drive Alone: 76.4%
- Carpool: 9.3%
- Public Transit: 5.2%
- Walk: 2.8%
- Motorcycle/Bike/Other: 1.7%

U.S. Energy Consumption: Historic and Projected38,39

1. U.S. Census Bureau (2018) “U.S. and World Population Clock.”
Biodiversity

Biodiversity, or biological diversity, is the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part.1 Biodiversity shapes the ecosystem services that contribute to human well-being—material welfare, security, social relations, health, and freedom of choice.2 Biodiversity is considered on three levels: species diversity, genetic diversity, and ecosystem diversity.3

Species Diversity
- Species diversity can be measured in several ways, including diversity indices (species richness and evenness), rank abundance diagrams, and similarity indices.4
- There are an estimated 8.7 million eukaryotic species on earth, of which 86% of land species and 91% of ocean species have not yet been described.5
- 1.2 million species have been described globally.5
- 54,328 plant and animal species are listed in the U.S.; top-ranking states for species diversity are CA, TX, AZ, NM, and AL, respectively.6,7
- Freshwater habitats account for only 0.01% of the world’s water and make up less than 1% of the planet’s surface, but they support one-third of all described vertebrates and nearly 10% of all known animal species.8
- One study suggests Arctic and Antarctic waters, not tropical reefs, are hotspots of species formation—contrary to much of the previous thinking about evolution.9

Genetic Diversity
- Genetic diversity refers to the genetic variation within species (for both the same population and populations living in different geographical areas).3
- Individuals within a species have slightly different forms of genes through mutations, where alleles can code for different proteins and ultimately affect species physiology.3
- Genetic variations lead to differences in both genotype and phenotype, which are necessary for species to maintain reproductive vitality, resistance to disease, and the ability to adapt to changing conditions.10

Community/Ecosystem Diversity
- Ecosystem diversity describes different biological communities and their associations with the ecosystem in which they are part.3
- Within these ecosystems, species play different roles and have different requirements for survival (i.e., food, temperature, water, etc.). If any of these requirements become a limiting resource, a species population size becomes restricted.3

Goods & Services
- Ecosystem services are the conditions and processes that enable natural ecosystems to sustain human life.11
- Ecosystem services include: air and water purification; mitigation of floods and droughts; detoxification and decomposition of wastes; generation and renewal of soil and soil fertility; pollination of crops and natural vegetation; dispersal of seeds and translocation of nutrients; protection from the sun’s harmful ultraviolet rays; partial stabilization of climate; and moderation of temperature extremes and the force of winds and waves.11
- Biodiversity increases several ecosystem services, including crop yields, stability of fishery yields, wood production, fodder yield, resistance to plant invasion, carbon sequestration, soil nutrient mineralization, and soil organic matter.12
- These services provide goods, such as seafood, forage, timber, biomass fuels, natural fiber, pharmaceuticals, industrial products, and more.13

Biodiversity, Ecosystem Services, and Human Well-Being

ECOSYSTEM SERVICES

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<td>-Soil Formation</td>
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<tr>
<td>-Primary Production</td>
<td>-Wood and Fiber</td>
<td>-Access to Clean Air and Water</td>
<td>-Educational</td>
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CONSTITUENTS OF WELL-BEING

Freedom of Choice and Action

Arrow’s Color: Potential of Mediation by Socioeconomic Factors
- Low
- Medium
- High

Arrow’s Width: Intensity of Linkage
- Weak
- Medium
- Strong
Loss of Biodiversity

- In the last 50 years, alteration of biodiversity related to human activities was greater than any time in human history, driven by habitat loss from agriculture, infrastructure, over-exploitation, pollution, and invasive alien species.\(^\text{1,2}\)
- Climate change is potentially a pervasive threat to biodiversity, because it can affect areas uninhabited by humans.\(^\text{3}\)
- Higher temperatures could increase drying, resulting in dieback in the Amazon, which has the highest biodiversity of all forests.\(^\text{4}\)
- Habitat loss can increase greenhouse gas emissions – 8% of global emissions derive from tropical deforestation.\(^\text{5}\)
- Over-fishing and harvesting also contributes to a loss of genetic diversity and relative species abundance of individuals and groups.\(^\text{6}\)

Biodiversity Loss Due to Agriculture

- Of the 30 mammalian and bird species used extensively for agriculture, half account for over 90% of global livestock production.\(^\text{7}\)
- Genetic diversity within breeds is declining, and 17% of 8,774 livestock breeds identified are classified as at risk.\(^\text{8}\)
- Of the 30,000 wild edible and 7,000 cultivated plants, only 30 crops provide 95% of dietary energy or protein. Wheat, rice, and maize provide more than half of the global plant-derived calories.\(^\text{9}\)
- In the last 100 years, about 75% of the genetic diversity of agricultural crops was lost.\(^\text{10}\)

Extinction

- In earth’s history, there have been five mass extinctions defined as time periods where extinction rates accelerate relative to origination rates such that over 75% of species disappear over an interval of 2 million years or less.\(^\text{11}\)
- Globally, 1% or less of assessed taxa have gone extinct. However, 20-43% of species in these taxa are labeled as threatened.\(^\text{12}\)
- 228 plants and animals have gone extinct in the U.S. and 2,339 are threatened or endangered.\(^\text{13}\)
- Habitat loss can increase greenhouse gas emissions – 8% of global emissions derive from tropical deforestation.\(^\text{14}\)
- Current extinction rates are higher than those leading to the five mass extinctions, and could reach mass extinction magnitude in three centuries.\(^\text{15}\)

Sustainable Actions

Policy

- Examples of treaties to protect species include: The Convention on Wetlands of International Importance (1971); The Convention of International Trade in Endangered Species (1973); The Convention of the Conservation of Migratory Species of Wild Animals (1979); and the Convention on Biological Diversity (CBD) (1992).\(^\text{16}\)
- The Endangered Species Act (1973), administered by the Interior Department’s Fish and Wildlife Service and the Commerce Department’s National Marine Fisheries Service, aims to protect and recover imperiled species and the ecosystems they depend on.\(^\text{17}\)
- 190 parties have National Biodiversity Strategic Action Plans for the conservation and sustainable use of biological diversity.\(^\text{18}\)
- Over 209,000 protected areas (such as national parks and reserves) have been established, 23 times more than in 1962, covering around 13% of the Earth’s land surface and less than 1.5% of marine areas.\(^\text{19,20}\)

Global Initiatives

- The Strategic Plan for Biodiversity 2011-2020 is a framework of five strategic goals and twenty Aichi Targets adopted by the Convention on Biological Diversity in 2010.\(^\text{21}\)
- The International Union for the Conservation of Nature (IUCN) Species Program and the IUCN Species Survival Commission assess the conservation status of species, subspecies, varieties, and subpopulations to identify threatened and endangered species and promote conservation.\(^\text{22}\)
- The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012 to provide scientific information to guide policy decisions relating to biodiversity, human well-being and sustainable development.\(^\text{23}\)
- The United Nations developed a list of Sustainable Development Goals (SDG’s) in 2015 that commit to preserving biodiversity of aquatic and terrestrial organisms, among other things. Fulfilling the SDG’s has the potential to greatly increase biodiversity and its associated benefits.\(^\text{24}\)

Cite as: Center for Sustainable Systems, University of Michigan. 2018. "Biodiversity Factsheet." Pub. No. CSS09-08. August 2018
Sustainability Indicators

Social Development Indicators

Standards of living are difficult to measure, but indicators of social development are available. A basic measure, Gross Domestic Product (GDP) per capita, is the value of all goods and services produced within a region over a given time period, averaged per person. A more advanced metric, the Human Development Index (HDI), considers life expectancy, education, and GDP. The three highest HDI-ranked countries in the world are Norway, Australia, and Switzerland. Many of the indicators discussed below are used to measure progress towards the Millennium Development Goals (MDG), a set of targets agreed upon by United Nations member states as crucial for global human progress.

Population

- The 2018 U.S. population is 328 million and world population is over 7 billion.
- Global population is projected to reach 9.6 billion by 2050, with 6.4 billion people living in urban areas—a 61% increase from 2015.
- Significant issues affecting population, as reported by governments around the world in 2007, include HIV/AIDS, infant and child mortality, maternal mortality, adolescent fertility, and life expectancy at birth.
- Fertility rate, or number of births per woman (of child-bearing age), is projected to fall from a global average of 2.5 in 2010 to 2.0 by 2100. Currently, Niger has the highest fertility rate at 7.40; the U.S. fertility rate is 1.88.
- Life expectancy averages 64 years in Least Developed Countries (LDC); life expectancy at birth in the U.S. is 79 years.
- Globally, contraceptive use is increasing. Currently, contraceptive use is 3.8 times higher today when compared to 1970 and is 32 times higher in least developed countries. However, 20-40% of women of reproductive age still don’t have access to contraceptives in 50 countries.
- The U.S. is one of only three developed countries with an adolescent birth rate at 27.9 or greater (per 1000 births).

Standard of Living

- In 2013, 0.8 billion people lived below the world poverty line of $1.90 USD per day, down from 1.8 billion in 1990.
- According to the Gini Index, Ukraine, Slovenia, and Norway have among the most equal income distributions in the world. With a rating of 41.1, the U.S. ranks in the bottom 50% in terms of income equality.
- In 2016, 12.7% of the U.S. population—40.6 million people—were living in poverty (income under $24,339 for a family of 4 with 2 children). For Hispanic and Black populations in the U.S., approximately 25% of each group was living below the poverty line.
- More than 550,000 people were homeless in the U.S. in 2017.

Food

- Average consumer expenditures on food ranges from 15% in developed countries to 25% in developing countries in 2016. On average, Americans spend less than 7%, while Nigerians spend 59%.
- Globally, 45% of deaths of children under 5 are caused by under-nutrition.
- The Green Revolution led to large increases in agricultural yields and helped feed the rapidly growing global population in the second half of the 20th century. Sub-Saharan Africa was the only developing region where increased food production was primarily due to increased crop area, not crop yield.
- The United Nations Food and Agriculture Organization publishes a comprehensive set of food security statistics annually.

Water and Sanitation

- Approximately 2.3 billion people lack access to proper sanitation. Access is lowest in sub-Saharan Africa, where only one in three people have proper facilities. Worldwide, urban areas have better sanitation coverage—83% have access to proper facilities, compared to 50% in rural areas.
- In 2015, 89% of the world population had access to an improved drinking-water source within a round trip of 30 minutes to collect water; 71% of the world population had access to clean drinking water. However, in Oceania and Sub-Saharan Africa only 40% and 43% of the rural populations, respectively, have access to improved water resources.
- Only 17% of the rural population in Sub-Saharan Africa has water piped directly into their house or property.
Healthcare and Disease

- Globally, 37 million people were infected with HIV and 1.0 million died from AIDS in 2016. Most cases—25.5 million—are in sub-Saharan Africa. Globally, the number of new HIV infections declined by 11% between 2010 and 2016; however, it increased in Eastern Europe and Central Asia by 60%.20
- Diarrheal diseases killed 80,000 people from 90 different countries in 2012 due to inadequate water, sanitation, and hygiene services. Over 40% of those deaths occurred in India.21 801,000 children die each year from diarrhea. 88% of the infections are attributable to unsafe drinking water, improper sanitation services, and hygiene.22
- In 2015, approximately 429,000 people died from malaria, of whom 92% lived in Africa, and 70% were children under 5.23 Preventive measures such as treated bed nets, indoor insecticide spraying, and anti-malarial drugs have reduced deaths. Since 2010, malaria mortality rates have decreased by 32% globally, and of the countries and territories with cases of malaria in 2016, approximately 16 saw a reduction of more than 20% in malaria cases compared with 2015.24
- Indoor air pollution, caused from smoke while cooking contributes to two million premature deaths of women and children each year.1
- Cardiovascular diseases are the leading cause of death in the world. A healthy diet, regular physical activity, and avoiding tobacco could reduce the major risk factors associated with premature deaths from cardiovascular diseases and strokes.25
- Approximately 23% of deaths in 2012 were caused by communicable diseases.26
- Globally, about 100 million people fall under the poverty line each year due to out-of-pocket health care costs.27

Education and Employment

- Global literacy is significantly improving. For example, global youth literacy has risen from 83% in 1990 to 91% in 2016. The gap in female and male literacy rates is also closing; in 1991, literacy rates were 86.6% and 77.3% for boys and girls, respectively. In 2016, the literacy rates were 93% and 91%.28
- Lithuania and Cuba spend the highest percentage of GDP on education, devoting between 12-18% each year from 2010-2015. The U.S. spends around 5.1% each year.29
- Sub-Saharan Africa primary school enrollment increased from 52% to 80% from 1990-2015; the 2015 world average is 95.5%.30
- In countries with Low Human Development, the average amount of schooling is 4.6 years. In Very High Human Development nations, the average is 12.2 years of school.1
- Top employers in developing countries are agriculture (64%), services (26%), and industry (10%); 60% of these jobs pay $1.25 USD/day or less.34

Environment

- It is “extremely likely” (>95% certainty) that the majority of global warming is caused by anthropogenic greenhouse gas emissions.30 In the 21st century, natural and social systems will likely face increasing risks of extinction for 20-30% of plant and animal species; more coastal flooding and erosion, heat waves, droughts, and tropical storm intensity; and health risks associated with malnutrition and water-related diseases. Declines in crop productivity in lower latitudes and freshwater availability are likely. Poor communities are especially vulnerable to climate change because of their low adaptive capacity and high dependence on climate conditions (e.g., rain for agriculture).30
- The Stern Review found that investing 1% of global GDP annually in GHG reductions could avert a permanent reduction of 5-20% GDP per capita due to climate change impacts.27

Conclusions

- In 2000, the UN established eight Millennium Development Goals (MDGs), including reducing child mortality and ensuring environmental sustainability. Great progress has been made towards achieving these goals within the last decade.35
- Through 2015, Denmark, Luxembourg, Norway, Sweden, and the United Kingdom continued to exceed giving 0.7% of their Gross National Income (GNI) as Official Development Assistance (ODA) towards achieving the MDGs.36 The U.S. donates a lower percentage of GNI, but the greatest dollar amount of any nation. In 2016, U.S. ODA totaled $36.2 billion.38

Cite as: Center for Sustainable Systems, University of Michigan. 2018. “Social Development Indicators Factsheet.” Pub. No. CSS08-15. August 2018
Carbon Footprint

“A carbon footprint is the total greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organization, event or product.” It is calculated by summing the emissions resulting from every stage of a product or service’s lifetime (material production, manufacturing, use phase, and end-of-life disposal). Throughout a product’s lifetime, or lifecycle, different greenhouse gases (GHGs) may be emitted, such as methane and nitrous oxide, each with a greater or lesser ability to trap heat in the atmosphere. These differences are accounted for by calculating the global warming potential (GWP) of each gas in units of carbon dioxide equivalents (CO$_2$e), giving carbon footprints a single unit for easy comparison. See the Center for Sustainable Systems’ “Greenhouse Gases Factsheet” for more information on GWP.

Sources of Emissions

Food
- On average, U.S. household food consumption emits 8.1 metric tons of CO$_2$e each year. The production of food accounts for 83% of emissions, while its transportation accounts for 11%.
- The emissions associated with food production consist mainly of carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (NO$_2$), which result primarily from agricultural practices.
- Meat products have larger carbon footprints per calorie than grain or vegetable products because of the inefficient transformation of plant energy to animal energy.
- Ruminant animals such as cattle, sheep, and goats produced 170 million metric tons (mmt) in CO$_2$e of methane in the U.S. in 2016 through digestion.
- Eating all locally grown food for one year could save the GHG equivalent of driving 1,000 miles, while eating a vegetarian meal one day a week could save the equivalent of driving 1,160 miles.
- A vegetarian diet greatly reduces an individual’s carbon footprint, but switching to less carbon intensive meats can have a major impact as well. For example, replacing all beef consumption with chicken for one year leads to an annual carbon footprint reduction of 882 pounds CO$_2$e.
- Organic food typically requires 30-50% less energy during production but requires one-third more hours of human labor compared to typical farming practices, making it more expensive.

Household Emissions
- For each kilowatt hour generated in the U.S., an average of 0.954 pounds of CO$_2$ is released at the power plant. Coal releases 2.2 pounds, petroleum releases 2.0 pounds, and natural gas releases 0.9 pounds. Nuclear, solar, wind, and hydroelectric release no CO$_2$ when they produce electricity, but emissions are released during upstream production activities (e.g., solar cells, nuclear fuels, cement production).
- Residential electricity use in 2016 emitted 667.5 mmt CO$_2$e, 10.3% of U.S. total.
- Heating and cooling account for about 53% of the energy use in a typical U.S. home. Space heating with wood emits the least CO$_2$e (31.4 tons per million BTU) followed by 64.2 for natural gas, with the highest being 210.5 for electric heaters.
- Refrigerators are one of the largest users of household appliance energy; in 2015, an average of 726.9 pounds of CO$_2$e per household was due to refrigeration.
- Washing clothes on ‘cold’ reduces CO$_2$ emissions by 1.2-14.9 pounds per laundry load, depending on washing machine type, hot water temperature, and electricity source.

Personal Transportation
- Cars and light trucks emitted 1.1 billion metric tons CO$_2$e or 17% of the 2016 total U.S. greenhouse gas emissions.
- Of the roughly 126,000 pounds of CO$_2$e emitted in a car’s lifetime (assuming 120,000 miles for a 1995 mid-sized sedan), 86% is from burning fuel.
- Gasoline releases 19.6 pounds of CO$_2$ per gallon when burned, compared to 22.4 pounds per gallon for diesel. However, diesel has 11% more BTU per gallon, which improves its fuel economy.
• The average passenger car emits 0.78 pounds of CO₂ per mile driven.\(^{13}\)
• Automobile fuel economy can improve 7-14% by simply observing the speed limit. Every 5 mph increase in vehicle speed over 50 mph is equivalent to paying an extra $0.20-$0.40 per gallon.\(^{16}\)
• Commercial aircraft GHG emissions vary according to aircraft type, the length of trip, occupancy rates, and passenger and cargo weight, but totaled 121.5 mmt CO₂ in 2016.\(^{4}\) In 2016, the average domestic commercial flight emitted 0.39 pounds of CO₂ per passenger mile. Emissions per domestic passenger-mile decreased 4.4% from 1990-2016, due to increased occupancy and fuel efficiency.\(^{4,10}\)
• On average, trains release 0.31 pounds of CO₂ per passenger mile, but this varies with occupancy and the length of the trip.\(^{20}\)

### Solutions and Sustainable Actions
#### Ways to Reduce Carbon Footprint

- **Eat local, vegetarian, or organic foods.** For non-vegetarians, replace some beef consumption with chicken.\(^{2,3,6}\)
- **Walk, bike, carpool, use mass transit, or drive a best-in-class vehicle.**\(^{21}\)
- **Smaller homes use less energy.** Average household energy use is highest in houses (82.3 million BTU), followed by mobile homes (59.8 million BTU), apartments with 2-4 units (33.5 million BTU), and apartments with 5+ units in the building (34.2 million BTU).\(^{11}\)
- **Using a low-flow shower head can save 350 pounds of CO₂ per year.** Setting the temperature to 120°F can help improve a hot water heater’s efficiency.\(^{22}\)
- **Turn off your TV, computer, and other electronics when not in use to reduce your carbon footprint by thousands of pounds of CO₂ each year.** Unplug unused electronics to further reduce your footprint.\(^{2}\)
- **Choose energy-efficient lighting.** If every home in the U.S. replaced their 5 most used light bulbs with Energy Star bulbs, the reduction in carbon emissions would be equivalent to removing 10 million cars from the road.\(^{23}\)
- **Recycling half a household’s waste can save 2,400 pounds of CO₂ per year.** Buying products with minimal packaging also helps reduce waste. For every 10% of waste reduction, 1,200 pounds of CO₂e are avoided.\(^{22}\)
- **Shop smart and purchase items with a comparatively low carbon footprint when possible.** Some manufacturers have begun assessing and publishing their products’ carbon footprints.
- **Replacing 80% of conditioned roof area on commercial buildings in the U.S. with solar reflective material would offset 125 mmt CO₂ per year.** Buying products with minimal packaging also helps reduce waste. For every 10% of waste reduction, 1,200 pounds of CO₂e are avoided.\(^{22}\)
- **Replace 80% of conditioned roof area on commercial buildings in the U.S. with solar reflective material would offset 125 mmt CO₂ per year.**
- **Replacing the global fleet of shipping containers’ roof and wall panels with aluminum would save $28 billion in fuel.**

#### Carbon Footprint Calculator

Use one of these tools to estimate your personal or household greenhouse gas emissions and explore the impact of different techniques to lower those emissions:

2. The Nature Conservancy: [www.nature.org/greenliving/carboncalculator/](http://www.nature.org/greenliving/carboncalculator/)

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Environmental Justice

Environmental Justice (EJ) is defined as the equal treatment and involvement of all people in environmental decision making. Inspired by the Civil Rights movement, EJ became widespread in the 1980’s at the intersection of environmentalism and social justice. Environmental injustice is experienced through heightened exposure to pollution and corresponding health risks, limited access to adequate environmental services, and loss of land and resource rights. EJ and sustainability are interdependent and both necessary to create an equitable environment for all.

Built Environment

- The changing demographics of urban areas, loose permitting requirements, and exclusionary zoning laws have funneled racial and ethnic minorities into areas with a greater degree of environmental degradation and reduced support.
- When urban areas were developing across the country, zones reserved exclusively for residential purposes were often expensive. Meanwhile, mixed-use zones were more affordable but allowed residential and industrial buildings to be built side by side. This led to a higher population density in areas closer to environmental hazards.
- Residents of environmentally degraded areas do not or can not move because of a lack of financial resources, ownership of current land, and sense of place.
- The Toxic Release Inventory (TRI) was created in 1986 under the Emergency Planning and Community Right-to-Know Act to support emergency planning and publicize information about toxic releases.
- On average, people of color comprise 56% of the population living in neighborhoods with TRI facilities, compared to 30% elsewhere.
- Availability of cheap land in urban centers has led to gentrification, an increase in property values that often makes the area unaffordable to existing (generally lower-income) residents. This leads to displacement as well as social, economic, and cultural stress.
- Green spaces improve the physical, social, and economic well being of a community by providing places to exercise, socialize, and organize, while supporting stable community development.
- Due to uneven distribution patterns, minority and low income communities have far less access to green spaces than white, affluent communities and have limited resources to maintain the green spaces they do have.

Food

- In 2016, 12.3% of U.S. households experienced food insecurity at some point during the year – reducing their access to adequate food for an active, healthy lifestyle.
- In 2016, rates of food insecurity were higher than the national average for Black and Hispanic households and higher in rural versus urban areas.
- Food prices are higher and food quality is poorer in areas with higher rates of poverty. The average U.S. household in 2016 spent about 12% of its income on food; low-income families spent more than 30%.
- Mexican-American and Black children have higher obesity rates than White children.
- In 2015, about 54.4 million people (17.7% of total U.S. population) had low access to a supermarket due to limited transportation and uneven distribution of supermarkets.
- A case study in Detroit showed that households in Black communities were on average 1.1 miles farther from the closest supermarket than the poorest White neighborhoods.

Energy

- The presence of power plants and mining operations for fuel resources places a significant environmental burden on neighboring communities. Minority and low-income communities are directly and disproportionately affected by polluting facilities and are rarely included in discussions and decision-making processes regarding such facilities.
- The average income of residents living within three miles of a coal power plant is $18,400 compared to the national average of $21,587. A case study found that energy-efficient bulbs are less available and more expensive in higher poverty urban areas.

Hydropower and Dams

- Dams threaten vulnerable populations through loss of land and water access, jobs and homes; food insecurity; increased morbidity.
- Dam construction often displaces low income communities because they are incentivized by wealthier ones and private investors to build.
- Environmental concerns associated with hydropower include fish mortality, water quality impairment, alteration of natural landscapes and destruction of sacred Indigenous sites.

Fuel Poverty

- Nearly 16.2 million American homes suffer from fuel poverty, the inability to pay for adequate energy services. This makes them vulnerable to detrimental health effects during periods of intense heat or cold.
- Fuel poverty results from income inequality and inequalities in energy prices, housing, and energy efficiency.
- Low-income households spend twice as much of their gross income on energy costs than the national average, despite consuming less energy.
Materials
Mining
- Roughly 3% of the country’s oil and natural gas reserves, 15% of coal reserves and between 37-55% of uranium reserves are located on Indigenous land. These resources and their associated land are sometimes taken away from Indigenous people once they are discovered.2
- The U.S. imports more than 90% of the elements critical to advanced energy generation, transmission and storage.23
- Since 2004, metal mining in Peru has boosted economic growth by 6% each year. Local, often low-income communities continue to protest against mining operations due to concerns about pollution. The government of Peru is ambivalent due to the economic benefits of keeping the mines open.24
- Artisanal and small scale mining (ASM) accounts for 15-20% of global production of minerals and metals. ASM often utilizes unsafe working conditions and irresponsible environmental practices, such as use of child labor and high mercury emissions.26

Electronic Waste
- In 2016, approximately 45 metric tons (MMT) of electronic waste (e-waste) were generated worldwide, with Asia being the largest contributor.25
- Improper recycling and recovery procedures can lead to exposure to carcinogenic and toxic materials, which often occur in developing nations where recycling regulations to limit worker exposure are lax or nonexistent.26
- An estimated 6-29% of the 40 million computers used in the U.S. were exported in 2010.27 The International Trade Commission found that the U.S. exported 7% of its used electronics by value in 2011.28

Climate
- The World Health Organization estimates that climate change will cause an additional 250,000 deaths per year between 2030 and 2050.20
- Though wealthy, developed nations like the U.S. emit larger concentrations of GHG per capita, developing nations experience the worst effects of climate change relative to wealthier countries due to their limited resources and ability to adapt.2,26
- Low-income communities are more likely to be exposed to climate change threats (e.g., flooding, storms, and droughts) due to inadequate housing and infrastructure.29
- People living closer to the coast and small, island nations are more vulnerable to severe storms, sea level rise, and storm surges as a result of climate change.29
- Indigenous populations that rely on subsistence farming practices for food have limited options for adapting to climate change threats.29
- Areas with weak healthcare infrastructure - mostly in developing countries - will be the least able to cope with catastrophic effects of climate change such as heat waves, droughts, severe storms, and outbreaks of waterborne diseases.20

Solutions
- In 1994, President Bill Clinton signed an executive order for all government organizations to create strategic plans to address EJ and outline the consequences for failing to consider possible environmental injustices.31
- The EPA launched EJSSCREEN in 2015, making data on environmental and demographic characteristics across the country accessible to the public.32
- Improper recycling and recovery procedures can lead to exposure to carcinogenic and toxic materials, which often occur in developing nations where recycling regulations to limit worker exposure are lax or nonexistent.26
- An estimated 6-29% of the 40 million computers used in the U.S. were exported in 2010.27 The International Trade Commission found that the U.S. exported 7% of its used electronics by value in 2011.28

32. U.S. EPA (2016) “How was EJSSCREEN Developed?”
Energy plays a vital role in modern society, enabling systems that meet human needs such as sustenance, shelter, employment, and transportation. In 2016, the U.S. spent $1.0 trillion on energy, or 5.6% of Gross Domestic Product (GDP). When spread over the population, annual costs were $3,211 per person. Environmental impacts associated with the production and consumption of energy include global climate change, acid rain, hazardous air pollution, smog, radioactive waste, and habitat destruction. The nation’s heavy reliance on fossil fuels (primarily imported petroleum) poses major concerns for energy security. Potential gains in energy efficiency in all sectors may be offset by increases in consumption, leading to overall increases in energy use. The unsustainable nature of the current U.S. energy system is described below.

Patterns of Use

Demand

• With less than 5% of the world’s population, the U.S. consumes 17% of the world’s energy and accounts for 15% of world GDP. To compare, the European Union has 7% of the world’s population, uses 14% of its energy, and accounts for 16% of its GDP, while China has 19% of the world’s population, consumes 22% of its energy, and accounts for 18% of its GDP.
• Each day, U.S. per capita energy consumption includes 2.5 gallons of oil, 12 pounds of coal, and 227 cubic feet of natural gas.
• Residential daily consumption of electricity is 11.6 kilowatt-hours (kWh) per person.
• In 2017, total U.S. energy consumption was 3.25% below 2007 peak levels, similar to total energy consumption in 2002.

Supply

• By current estimates, 78% of U.S. energy will come from fossil fuels in 2050.
• Renewable energy consumption is projected to increase annually at an average rate of 1.6% between 2017 and 2050, compared to 0.4% growth in total energy use. Photovoltaics are projected to grow the fastest. At these rates, renewables would only provide 14% of U.S. energy consumption in 2050, which is more than today’s 11.27% renewable energy consumption.
• U.S. net imports met 19% of domestic oil demand in 2017. This figure is projected to drop to 4% in 2050. Canada, Saudi Arabia, and Mexico are the three largest foreign suppliers of U.S. oil.
• The Persian Gulf region accounted for 18% of U.S. petroleum imports in 2017 and contains 48% of the world’s oil reserves. OPEC controlled 31.4% of the oil imported by the U.S. in 2017.
• There is disagreement as to when oil production will peak. Assuming reserves of 3.3 trillion barrels and a production growth rate of 2%, the U.S. Department of Energy (DOE) projects global oil production to peak in 2044.

Life Cycle Impacts

• Air emissions from the combustion of fossil fuels are the primary environmental concern of the U.S. energy system. Such emissions include carbon dioxide (CO₂), nitrogen oxides, sulfur dioxide, volatile organic compounds, particulate matter, and mercury.
• U.S. total GHG emissions increased by 2.4% from 1990 to 2016. 76% of total U.S. GHG emissions were energy-related CO₂ emissions in 2016.
• Other energy sources also have environmental implications. For example, issues associated with nuclear power generation include radioactive waste and a high energy requirement to build the plants and mine the uranium; large hydroelectric power plants cause habitat degradation and fish kills; and wind turbines alter landscapes in ways some find unappealing and can increase bird and bat mortality.
Solutions and Sustainable Alternatives

Consume Less

- Reducing energy consumption not only brings environmental benefits, but also can result in cost savings for individuals, businesses and government agencies.
- Living in smaller dwellings, living closer to work, and utilizing public transportation are examples of ways to reduce energy usage. See the Center for Sustainable Systems’ factsheets on personal transportation and residential buildings for additional ways to trim energy consumption.

Increase Efficiency

- An aggressive commitment to total cost-effective energy efficiency could reduce U.S. carbon emissions by 500 million metric tons per year. 16
- Additional information on energy efficiency can be found at the following organizations’ websites:

Increase Renewables

- U.S. installed wind capacity grew 8.9% in 2017, expanding to 89 GW. 18 If 224 GW of wind capacity were installed by 2030, an amount determined feasible by one U.S. DOE study, wind would satisfy 20% of projected electricity demand. 16
- Solar photovoltaic modules covering 0.6% of the land in the U.S. could supply all of the nation’s electricity. 17

Encourage Supportive Public Policy

- The U.S. currently produces 15% of the world’s energy-related CO2 emissions, which are expected to increase by 2.5% between 2017 and 2050. 6,10 The Clean Energy and Security Act, passed by the House in June 2009, would have required emissions reductions of 3% below 2005 levels in 2012, 20% below 2005 levels in 2020, 42% below 2005 levels in 2030, and 83% below 2005 levels in 2050. 19 The Act was not brought to a vote in the Senate and did not become law. 20 In comparison, the United Kingdom established a goal of reducing CO2 emissions 80% below their 1990 level by 2050. 21
- A joint rule issued by the U.S. EPA and National Highway Traffic Safety Administration (NHTSA) in 2012 set new auto manufacturing standards for model years 2017-2025, raising corporate average fuel economy (CAFE) standards to 54.5 miles per gallon for new light-duty vehicles in 2025. This rule is projected to save 4 billion gallons of fuel, between $326 and $451 billion, and cut CO2 emissions by 2 billion metric tons. 22
- If the Arctic National Wildlife Refuge (ANWR) were opened to oil drilling, production would peak at 321.2 million barrels of oil per year in 2041. 23
- The growth of wind and biomass was spurred by the 2.3¢/kWh Federal Production Tax Credit (PTC), as well as state Renewable Energy Portfolio Standards (RPS) that require a certain percentage of electricity be derived from renewable sources. The PTC for wind will expire December 31, 2019. 24 Thirty-seven states, the District of Columbia, and four U.S. territories had renewable portfolio standards or goals in place as of August 2017. 25
- A $2,500-$7,500 federal tax credit is available for electric and plug-in hybrid electric vehicles purchased after January 1, 2010. 26
- Residential consumers can receive tax credits for up to 30% of purchase and installation costs for renewable energy additions to new and existing houses until 2019. Eligible renewable technologies include geothermal heat pumps, solar water heaters, solar panels, small wind turbines, and residential fuel cells. 27

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**kWh** = kilowatt hour. One kWh is the amount of energy required to light a 100 watt light bulb for 10 hours.

**Btu** = British Thermal Unit. One Btu is the amount of energy required to raise the temperature of a pound of water by 1° Fahrenheit.

**Quad** = quadrillion (10^{15}) Btu. One Quad is equivalent to the annual energy consumption of ten million U.S. households.

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U.S. Renewable Energy

Patterns of Use
While energy is essential to modern society, most primary sources are unsustainable. The current fuel mix is associated with a multitude of environmental impacts, including global climate change, acid rain, freshwater consumption, hazardous air pollution, and radioactive waste. Renewable energy has the potential to meet demand with a much smaller environmental footprint and can help to alleviate other pressing problems, such as energy security, by contributing to a distributed and diversified energy infrastructure. About 80% of the nation’s energy comes from fossil fuels, 8.6% from nuclear, and 11% from renewable sources. Wind is the fastest growing renewable source but contributes only 2.4% of total energy used in the United States. The examples below illustrate the progress and potential of U.S. renewable energy.

Major Renewable Sources

Wind
- U.S. onshore wind resources have the potential to generate almost 11,000 GW of electricity, 123 times more than the current installed capacity of 82.1 GW. In 2013, the U.S. installed 11.1 GW of wind capacity, a 92% decrease from 2012. This significant drop resulted from the expiration of the federal production tax credit (PTC) in 2013. Since 2013, the PTC has been retroactively reinstated with an expiration date of December 31, 2019. 7.017 GW of wind capacity were installed in the U.S. in 2017, a 9% increase in cumulative wind power capacity from 2016. Future estimates range from 80 GW to almost 400 GW by 2050. Based on the average U.S. electricity fuel mix, a 1 MW wind turbine can displace 1,800 tons of CO₂ emissions per year. With a wind power capacity of 400 GW, wind could account for 35% of U.S. electricity demand and 12.3 gigatonnes of CO₂ emissions could be avoided annually, resulting in a 14% reduction in CO₂ emissions when compared to 2013. Wind turbines generate no emissions and use no water when producing electricity, but concerns include bat and bird mortality, land use, noise, and aesthetics.

Solar
- Assuming intermediate efficiency, solar photovoltaic (PV) modules covering 0.6% of U.S. land area could meet national electricity demand. PV module prices have significantly declined, costing $0.65-$0.73/Watt in residential systems. U.S. market share of PV production dropped from 30% to 7% between 2000 and 2010. Solar PV installations reached an all-time high of 14,762 MWdc in 2016, increasing by 97% compared to 2015 installations. In 2017, 10.6 GWdc of solar photovoltaic capacity was added, which was 30% less than that in 2016 but still exceeded 2015 level by 40%, raising total installed capacity to 53 GW. Solar accounted for 30% of new generating capacity in 2017. The U.S. Department of Energy’s SunShot Initiative aims to reduce the price of solar energy 75% from 2010 to 2020, which is projected to lead to 27% of U.S. electricity demand met by solar technology and a 28% decrease in electricity sector greenhouse gas emissions by 2050. While solar PV modules produce no emissions during operation, toxic substances (e.g., cadmium and selenium) are used in them.

Biomass
- Wood—mostly as pulp, paper, and paperboard industry waste products—accounts for 44% of total biomass energy consumption. Waste—municipal solid waste, landfill gas, sludge, tires, and agricultural by-products—accounts for an additional 10%. Biomass has low net CO₂ emissions compared to fossil fuels. At combustion, it releases only CO₂ previously removed from the atmosphere. Additional emissions are associated with processing and 12.4 acres of land are required to generate one GWh of electricity per year. U.S. ethanol production is projected to reach 40 million gallons per day in 2050.
Geothermal

- Hydrothermal resources, i.e., steam and hot water, are available primarily in the western U.S., Alaska, and Hawaii, yet geothermal heat pumps can be used almost anywhere to extract heat from shallow ground, which stays at relatively constant temperatures year-round.21
- U.S. geothermal power offsets 22 million metric tons of CO₂ emissions, 200,000 metric tons of nitrogen oxides, and 110,000 metric tons of particulate matter from coal-powered plants each year.22 Some geothermal facilities produce solid waste such as salts and minerals that must be disposed of in approved sites, but some by-products can be recovered and recycled.23
- Electricity generated from geothermal power plants is projected to increase from 17 billion kWh in 2017 to 61.75 billion kWh in 2050 and has the potential to exceed 500 billion kWh, which is half of the current U.S. capacity.24,25

Hydroelectric

- In the U.S., net electricity generation from conventional hydropower peaked in 1997 at 356 TWh/yr. Currently, the U.S. gets about 300 TWh/yr of electricity from hydropower.12,26
- While electricity generated from hydropower is virtually emission free, significant levels of methane and CO₂ may be emitted through the decomposition of vegetation in the reservoir.27 Other environmental concerns include fish injury and mortality, habitat degradation, and water quality impairment. “Fish-friendly” turbines and smaller dams help mitigate some of these problems.28

Advancing Renewable Energy

Encourage Supportive Public Policy

- Renewable Portfolio Standards (RPS) that mandate certain levels of renewable generation are proving successful. For example, Texas installed 10,000 MW of renewable energy generating capacity in 2010, meeting its 2025 mandate 15 years early.28 Thirty-seven states, the District of Columbia, and four U.S. territories had renewable portfolio standards or goals in place as of February 2017.29 State standards are projected to support 103,000 MW of renewable electricity by 2050.30
- Renewable energy growth is driven by important federal incentives such as the Investment Tax Credit, which offset upfront costs by 30%.31 Tax credits, grants, and other incentives are also offered to the residential, commercial, and industrial sectors for renewable energy installations, some defraying up to 30% of the cost.32
- Eliminating subsidies for fossil and nuclear energy would encourage renewable energy. Congress allocated over $12.3 billion in tax relief to coal-powered plants in the case of an accident, amounts to a subsidy of $366 million to $3.5 billion annually.33
- Net metering enables customers to sell excess electricity to the grid, eliminates the need for on-site storage, and provides an incentive for installing renewable energy devices. Thirty-eight states, the District of Columbia, and three U.S. territories have some form of net metering program.34

Engage the Industrial, Residential, and Commercial Sectors

- Renewable Energy Certificates (RECs) are sold by renewable energy producers in addition to the electricity they produce; for a few cents per kilowatt hour, customers can purchase RECs to “offset” their electricity usage and help renewable energy become more cost competitive.35 Nearly 800 utilities in the U.S. offer consumers the option to purchase renewable energy, or “green power.”36
- Many companies purchase renewable energy as part of their environmental programs. Microsoft, Intel, Google, Apple and Equinix were the top five users of renewable energy as of April 2018.37

kWh = kilowatt hour. One kWh is the amount of energy required to light a 100 watt light bulb for 10 hours.

Btu = British Thermal Unit. One Btu is the amount of energy required to raise the temperature of a pound of water by 1°F Fahrenheit.

Quad = quadrillion (10¹⁵) Btu. One Quad is equivalent to the annual energy consumption of ten million U.S. households.

References

8. DSIRE (2016) “Renewable Electricity Production Tax Credit (PTC).”

Wind Energy

Wind Resource and Potential

Approximately 2% of the solar energy striking the Earth’s surface is converted to kinetic energy in wind. Wind turbines convert the wind’s kinetic energy to electricity without emissions. The distribution of wind energy is heterogeneous, both across the surface of the Earth and vertically through the atmosphere. Class 3 winds (average annual speed of 14.3 to 15.7 mph at 50m) are the minimum needed for a commercially viable project. Only 3% of U.S. electricity was derived from wind energy in 2017, but wind capacity is increasing rapidly.

- High wind speeds yield more power because wind power is proportional to the cube of wind speed.
- Wind speeds are lower close to the Earth’s surface and more wind power is available at higher altitudes. The average hub height of most modern wind turbines is 83.0 meters off the ground.
- Potentially, global onshore and offshore wind power at commercial turbine hub heights could provide 840,000 TWh of electricity each year, while total global electricity consumption from all sources in 2015 was about 21,153 TWh. Similarly, the U.S. annual wind potential of 68,000 TWh (lower 48 states) exceeds annual U.S. electricity consumption by about 64,318 TWh.
- A 2015 study by the U.S. Department of Energy found wind could provide 20% of U.S. electricity by 2030 and 35% by 2050.
- Wind’s variability increases the cost to operate the grid by less than 0.7¢/kWh of electricity (at 40% electricity from wind).

Wind Technology and Impacts

Horizontal Axis Wind Turbines

- Horizontal axis wind turbines (HAWT) are the predominant turbine design in use today. The HAWT rotor comprises blades (usually three) symmetrically mounted to a hub. The rotor is connected via a shaft to a gearbox, and the generator is housed within the nacelle. The nacelle is mounted atop a tower connected to a concrete foundation.
- HAWT come in a variety of sizes, ranging from 2.5 meters in diameter and 1 kW for residential applications up to 100+ meters in diameter and over 3.5 MW for offshore applications.
- The theoretical maximum efficiency of a HAWT is ~59%, also known as the Betz Limit. Most HAWT extract about 50% of the energy from the wind that passes through the rotor area.
- The capacity factor of a wind turbine is its average power output divided by its maximum power capability. On land, capacity factors range from 0.26 to 0.52. Offshore winds are generally stronger than on land, and capacity factors are higher on average, but offshore wind farms are more expensive to build and maintain. Offshore turbines are currently placed in depths up to 40-50m (about 131-164ft).

Installation, Manufacturing, and Cost

- More than 54,000 utility-scale wind turbines are installed in the U.S., with a cumulative capacity of 89.4 GW. U.S. wind capacity increased by 43% between 2007 and 2017, a 18% average annual increase. Global wind capacity increased by 19% annually, on average, from 2007 to 2017, reaching 540 GW in 2017.
- U.S. average turbine size was 2.15 MW in 2016, up from 1.94 MW between 2011 and 2015.
- Average capacity factor has increased from 0.25 for projects installed from 1998 to 2001 to around 0.42 for projects built in 2014 and 2015.
- On a capacity-weighted average basis, installed wind project costs declined by roughly $3,000/kW between the early 1980’s and 2016. In 2016, costs were $1,590/kW.
- The installed cost of a small (<100 kW) turbine is approximately $5,900 per kW, on average.
- In 2016, commercial wind energy cost approximately 2.5¢/kWh wholesale. The 2017 average U.S. residential electricity price was 12.9¢/kWh.
- Texas (22,799 MW), Oklahoma (7,495 MW) and Iowa (7,312 MW) are the leading states in total installed wind capacity. Iowa generated over 37% of its electricity from wind, the highest percent in the U.S.
• Wind turbines and components are manufactured at more than 500 U.S. facilities.18
• In 2017, 103,500 full-time workers were employed in the U.S. wind industry.18
• Large (>20 MW) wind projects require roughly 85 acres of land area per MW of installed capacity, but 1% or less of this total area is occupied by roads, turbine foundations, or other equipment; the remainder is available for other uses.8
• For farmers, annual lease payments provide a stable income of around $3,000/MW of turbine capacity, depending on the number of turbines on the property, the value of the energy generated, and lease terms.8 For a 250-acre farm, with income from wind at about $55 an acre, the annual income from a wind lease could be $14,000.19

Energy Performance and Environmental Impacts

Wind turbines can reduce the impacts associated with electricity generation. The 2017 U.S. wind capacity of 89 GW annually avoids an estimated 189 million metric tons of CO2 emissions and reduces water use by about 95 billion gallons compared with conventional power plants.13,20

• According to a 2015 study, if 35% of U.S. electricity was wind-generated by 2050, electric sector GHG emissions would be reduced by 23%, eliminating 110 billion kg of CO2 emissions annually, or 12.3 trillion kg cumulatively from 2013, and decreasing water use by 15%.8
• A 2005 study of two U.S. wind farms found life cycle net energy ratios (energy generated/energy invested) of 47 and 65.21
• Annual avian mortality from collisions with turbines is 0.2 million, compared with 150 million mortalities due to power lines and 300-1,000 million from buildings. The best way to minimize mortality is careful siting.8 Bat mortality due to wind turbines is less well studied, but research shows that a large percentage of bat collisions occur in summer and fall months when bats are most active.22 The wind industry has been testing methods that potentially reduce bat mortality by more than 50%.8
• Noise 350m from a typical wind farm is 35-45 dB(A). For comparison, a quiet bedroom is 35 dB(A) and a 40 mph car 100m away is 55 dB(A).23
• As of 2013, several studies have conclusively determined that sound generated by wind turbines has no impact on human health.8

Solutions and Sustainable Actions

Policies Promoting Renewables

Policies that support wind and other renewables can address externalities associated with conventional electricity, such as health effects from pollution, environmental damage from resource extraction, and long-term nuclear waste storage.
• A Renewable Portfolio Standard (RPS) requires electricity providers to obtain a minimum fraction of their energy from renewable resources.24
• Feed-in tariffs set a minimum price per kWh paid to renewable electricity generators by retail electricity distributors.24
• Net metering - one of 38 states, D.C., and three U.S. territories - allows customers to sell excess electricity back to the grid.25
• Capacity rebates are one-time, up-front payments for building renewable energy projects, based on the capacity (in watts) installed.26
• The federal production tax credit (PTC) provides a 2.36/kWh benefit for the first ten years of a wind energy facility’s operation, for projects started by the end of 2014. In 2015, the Consolidated Appropriations Act retroactively reinstated the tax credit for projects started by December 31, 2019.27 Small (<100 kW) wind installations can receive tax credits for up to 30% of the capital and installation cost.28
• Qualified Energy Conservation Bonds (QECBs) are interest-free financing options for state and local government renewable energy projects.29
• Section 9006 of the Farm Bill is the Rural Energy for America Program (REAP) that funds grants and loan guarantees for agricultural producers in addition to the electricity they produce; for a few cents per kilowatt hour, customers can purchase RECs to “offset” their electricity usage and help renewable energy become more competitive.30

What You Can Do

• Make your lifestyle more efficient to reduce the amount of energy you use.
• Invest in non-fossil electricity generation infrastructure by purchasing “green power” from your utility.
• Buy Renewable Energy Certificates (RECs), also known as green tags or green energy certificates. RECs are sold by renewable energy producers in addition to the electricity they produce; for a few cents per kilowatt hour, customers can purchase RECs to “offset” their electricity usage and help renewable energy become more competitive.31

Consider installing your own wind system, especially if you live in a state that provides financial incentives or has a net metering policy.

Data sources:
26. DSIRE (2016) “Renewable Electricity Production Tax Credit (PTC).”
29. DSIRE (2016) “USDA - Rural Energy for America Program (REAP) Grants.”

Photovoltaic Energy

Solar energy can be harnessed in two basic ways. First, solar thermal technologies utilize sunlight to heat water for domestic uses, warm building spaces, or heat fluids to drive electricity-generating turbines. Second, photovoltaics (PVs) are semiconductors that convert sunlight to electricity. Only 1.3% of U.S. electricity is generated with solar technologies, in part because direct costs are high.\(^1\)

Solar Resource and Potential

- On average, 1.05 x 10\(^5\) terawatts (TW) of solar radiation reach the Earth’s surface, while global electricity demand averages 2.4 TW.\(^2,3\)
- Solar resource availability is well correlated with daily patterns of electricity consumption. However, the sun is not always shining; energy storage is necessary in order for solar energy to meet total electricity demand.\(^4\)
- PVs can be installed where electricity is used to reduce stress on electricity distribution networks, especially during peak demand.\(^5\)
- PV conversion efficiency is the percentage of incident solar energy that a PV converts to electricity. For production modules, conversion efficiency is 6% to 21%.\(^6\)
- Assuming intermediate efficiency, PVs covering 0.6% of U.S. land area would generate enough electricity to meet national demand.\(^6\)
- Residential PV systems require a modest amount of roof space to install. The average residential system in the U.S. is just over 5.0 kW and takes up approximately 500 square feet.\(^7\)
- The U.S. Department of Energy’s SunShot Initiative aims to reduce the price of solar energy by 75% from 2010 to 2020, which is projected to lead to 27% of U.S. electricity demand being met by solar technologies in 2050.\(^6\)

PV Technology and Impacts

PV Cells

- PV cells are made from semiconductor materials that produce electrons when photons strike the surface.\(^8\)
- Most PV cells are square or rectangular, several inches on a side, and produce a few watts of direct current (DC) electricity.\(^9\)
- PV cells also include electrical conductors called contacts, which allow for the flow of electrons, and surface coatings to reduce light reflection.\(^10\)
- A variety of semiconductor materials can be used for PVs, including silicon, copper indium diselenide (CIS), and cadmium telluride (CdTe).\(^11\) See table for common material types and their production efficiencies.
- Although PV conversion efficiency is an important metric, cost efficiency—the cost per watt of power—is more important for most power applications. Some very cost efficient cells do not have high conversion efficiencies.

PV Modules and Balance of System (BOS)

- PV modules typically comprise a rectangular grid of 60 to 72 cells, connected in several parallel circuits and laminated between a transparent front surface and a protective back surface. They usually have metal frames for strength and weigh 34 to 62 pounds.\(^12\)
- A PV array is a group of modules, connected electrically and fastened to a rigid structure.\(^13\)
- BOS components include any elements necessary in PV systems in addition to the actual PV panels, such as wires that connect modules in series, junction boxes to merge the circuits, mounting hardware, and power electronics that manage the PV array’s output.\(^14\)
- An inverter is a power electronic device that converts electricity generated by PV systems from DC to alternating current (AC).\(^15\)
- A charge controller is another power electronic device, used to manage energy storage in batteries.\(^16\)
- In contrast to a rack-mounted PV array, Building Integrated PV (BIPV) replaces building materials to improve PV aesthetics and costs.\(^17\)
- Some PV arrays track the sun’s daily movement to generate up to 46% more energy than fixed systems.\(^18\)
PV Installation, Manufacturing, and Cost

- Global cumulative capacity of PV systems grew 45-fold between 2006 and 2016, reaching 306.5 GW.20
- Global installed PV capacity grew 49% annually between 2006 and 2016.19,20
- 76.6 GW of newly installed PV capacity was added in 2016. The top three countries for new installations were China (44.5 GW), the U.S. (14.8GW) and Japan (8.6 GW).20
- In 2017, the US increased total PV capacity by 25%, totaling 53 GW.21
- PV module prices, a large part of total system cost, fell 82.5% from 2008 to 2017.25
- Global investment in the solar sector is the highest of renewable energies. In 2017, $154 billion was invested in wind, $3 billion was invested in biomass and waste-to-energy.23
- PV systems or components are manufactured in over 100 factories across 30 states.14
- Between 2000 and 2010, U.S. market share of PV production dropped from 30% to 7%.24
- PV energy costs 11¢/kWh for commercial and 16¢/kWh for residential in 2017.20,29 Retail electricity averages 10.3¢/kWh for all users and 12.9¢/kWh for residential.1

Energy Performance and Environmental Impacts

- Net energy ratio compares the life cycle energy output of a PV system to its life cycle primary energy input. One study shows that amorphous silicon PVs generate 3 to 6 times more energy than are required to produce them.26
- Recycling multi-crystalline cells can reduce manufacturing energy over 50%.27
- Although pollutants and toxic substances are emitted during PV manufacturing, life cycle emissions are low. For example, the life cycle emissions of thin-film CdTe are roughly 14 g CO₂ per kWh delivered, far below electricity sources such as coal (1,001 g CO₂/kWh).28,29
- PVs can reduce environmental impacts associated with fossil fuel electricity generation; for example, thermoelectric plants use an average of 15 gallons of water to produce one kWh of electricity.20 U.S. air pollutant emissions were 692.3 kg CO₂/MWh, for the 2.5 x 10³ MWh of electricity generated from fossil fuels in 2017.¹

Solutions and Sustainable Actions

Policies Promoting Renewables

- PV energy costs are currently higher than conventional electricity; however, the price consumers pay for electricity does not cover externalities such as the cost of health effects from air pollution, environmental damage from resource extraction, or long-term nuclear waste storage. Policies that support PVs can address these externalities to make PV energy more cost-competitive.31
- Proposed carbon cap-and-trade policies would work in favor of PVs by increasing the cost of fossil fuel energy generation.32
- PV policy incentives include renewable portfolio standards (RPS), feed-in tariffs (FIT), capacity rebates, and net metering.33
  - An RPS requires electricity providers to obtain a minimum fraction of their energy from renewable resources by a certain date.33
  - An FIT sets a minimum per kWh price that retail electricity providers must pay renewable electricity generators.33
  - Capacity rebates are one-time, up-front payments for building renewable energy projects, based on installed capacity (in watts). With net metering, PV owners get credit from the utility (up to their annual energy use) if their system supplies power to the grid.

What You Can Do

- Reduce the total amount of energy used in the first place by increasing your energy efficiency. Consider installing a PV system for your home or business, especially if your state offers capacity rebates or a net metering policy.
- “Green pricing” allows customers to pay a premium for electricity that supports investment in renewable technologies. In 2012, more than 850 utilities nationwide offered green pricing options.²⁴ Renewable Energy Certificates (RECs) also known as green tags or green certificates, can be purchased in addition to commodity electricity to “offset” electricity usage and help renewable energy become more competitive.35

A watt is a unit of power, or a rate of energy flow. 1 TW = 1,000 GW = 1,000,000 MW = 1,000,000,000 kW. A kilowatt-hour is a unit of energy. 1 kWh is the electricity energy required to light a 100 watt light bulb for 10 hours.

Cite as: Center for Sustainable Systems, University of Michigan. 2018. “Photovoltaic Energy Factsheet.” Pub. No. CSS07-08. August 2018

Biofuels

Biofuels have the potential to reduce the energy and greenhouse gas emission intensities associated with transportation but can have other significant effects on society and the environment. Depending on demand, crop growing conditions, and technology, they may require significant increases in cropland and irrigation water use. Also, biofuels may have already affected world food prices.

Patterns of Use

Production
- In the U.S., ethanol is primarily derived by processing and fermenting the starch in corn kernels into a high-purity alcohol—96% of ethanol was derived from corn in 2011. Brazil uses sugar cane as the primary feedstock for ethanol production.\(^1\)
- The U.S. and Brazil produced about 85% of the world’s ethanol in 2016.\(^2\)
- In 2017, 5.4 billion bushels of corn, 38% of the U.S. supply, became ethanol feedstock.\(^3\)
- Cellulosic ethanol feedstocks are abundant and include corn stalks, plant residue, waste wood chips, and switchgrass. Making ethanol from these sources is more difficult because the cellulose doesn’t break down into usable sugars as easily.\(^7\)
- Biodiesel can be made from animal fats, recycled grease, vegetable oils, and algae. In the U.S., soybean oil and recycled cooking oils are the most common feedstocks.\(^1\)
- Biodiesel from algae is an area of ongoing research. Algae could potentially produce 10 to 300 times more fuel per acre than other crops.\(^4\)

Consumption and Demand
- In 2017, U.S. petroleum consumption averaged 20 million barrels per day, of which 19% was imported.\(^8\)
- In January 2018, there were 201 ethanol refineries in operation, 7 more under construction, and 78 biodiesel production plants in the U.S.\(^9,10\)
- U.S. Biodiesel production facilities operated at 68% capacity in 2016.\(^8,10\)
- Many biodiesel producers are reliant on federal production tax credits and remain sensitive to volatile feedstock (soybean oil) and energy (petroleum) prices. The $1/gallon tax credit expired three times in five years and was retroactively reinstated in January of 2014 and lapsed in December 2016.\(^11,12\)
- In 2017, 10% of U.S. vehicle fuel consumption (by volume) was ethanol and over 98% of U.S. gasoline contains ethanol.\(^5,13\)
- E85 may sell for less than regular gasoline, but contains less energy per gallon. Flex-fuel vehicles running on E85 typically see a 15-30% reduction in fuel economy.\(^14\)

Life Cycle Impacts

Energy
- The Fossil Energy Ratio (FER) is the ratio of energy output to nonrenewable energy inputs.\(^15\) Gasoline has a value of 0.8 (1.2 BTU of fossil fuel needed to supply 1 BTU of gas at the pump).\(^16\) Some controversy exists about whether corn ethanol has a better ratio than gasoline. However, most recent studies find FERs of 1 to 1.6, with GREET weighing in at 1.3.\(^16,17\)
- Cellulosic ethanol studies estimate potential FER’s of 4.4 to 6.6; using these fuels could greatly reduce fossil fuel use (FER range due to new technology and feedstock variation).\(^17\)
- From 1990-2006, the FER for soybean biodiesel improved from around 3.2 to 5.5.\(^18\) In comparison, petroleum-based diesel has an FER of 0.83.\(^19\)

![Graph showing Biofuel Yields by Feedstock](image1)

![Graph showing U.S. Biofuel Production, 2001-2017](image2)

![Graph showing World Fuel Ethanol Production, 2017](image3)
Under the Energy Independence and Security Act of 2007, the Renewable Fuel Standard (RFS2) requires that 36 billion gallons per year of biofuels be produced by 2022: 16 bg/y from cellulosic sources, 5 bg/y from other advanced sources, and no more than 15 bg/y of corn ethanol. Life cycle GHG standards are also in place, to ensure the biofuels produce fewer emissions than their petroleum counterparts. Fuel content standards are one policy option to encourage biofuel use. Regular gasoline sold in Brazil is required to contain 27% ethanol. The use of B20 (20% biodiesel, 80% petroleum diesel), a common biodiesel blend in the United States, is expected to increase to 35 billion gallons per year by 2022. Biofuels provide several environmental benefits, including lower emissions of harmful pollutants and lower embodied energy compared to petroleum. However, there are concerns about land use change, deforestation, and greenhouse gas (GHG) emissions from biofuel production.

**Solutions and Sustainable Actions**

- Under the Energy Independence and Security Act of 2007, the Renewable Fuel Standard (RFS2) requires that 36 billion gallons per year (bg/y) of biofuels be produced by 2022: 16 bg/y from cellulosic sources, 5 bg/y from other advanced sources, and no more than 15 bg/y of corn ethanol. Life cycle GHG standards are also in place, to ensure the biofuels produce fewer emissions than their petroleum counterparts.
- U.S. ethanol blenders and resellers were supported by a federal tax credit of $0.45/gallon of ethanol, which expired in December 2011. Fuel content standards are one policy option to encourage biofuel use. Regular gasoline sold in Brazil is required to contain 27% ethanol.
- Ethanol thus makes up 56% of transportation fuel in Brazil, compared to 8% in the U.S.
- The U.S. EPA and the National Highway Traffic Safety Administration jointly issued rules in 2010 and 2012 establishing new GHG emissions and corporate average fuel economy (CAFE) standards. Vehicle manufacturers’ new passenger car and light-duty truck fleets must average 250 g/mi of CO₂ and 34.1 mpg by model year 2016 and 163 g/mi of CO₂ and -49 mpg by 2025.
- Public transportation, carpooling, biking, and telecommuting are excellent ways to reduce transportation energy use and related impacts. See the Center for Sustainable Systems’ “Personal Transportation Factsheet” for more information.

Nuclear Energy

Nuclear power plants generate electricity by using controlled nuclear fission chain reactions (i.e., splitting atoms) to heat water and produce steam to power turbines. Nuclear is often labeled a “clean” energy source because no greenhouse gases (GHGs) or other air emissions are released from the power plant. As the U.S. and other nations search for low-emission energy sources, the benefits of nuclear power must be weighed against the operational risks and the challenges of storing radioactive waste.

Nuclear Energy Use and Potential

- Nuclear energy provides about 20% of U.S. electricity. Nuclear is a resource that runs at full capacity 92% of the time.1
- The first U.S. nuclear power plant was completed in 1957.2 During the 1970s, more than 50 nuclear reactors went online.1 Presently, 30 states have at least one nuclear plant and each plant may have multiple reactors.3 Since 1995, U.S. nuclear electricity generation has grown despite no new reactors and 10 shutdowns, due to higher capacity factors from existing plants.1,2
- The U.S. has 99 of the world’s 450 commercial nuclear reactors. As of June 2018, 58 reactors are under construction, including 2 in the U.S. and 19 in China.4
- In 2015, the U.S. generated nearly a third of the world’s nuclear electricity. The next largest generators of nuclear electricity were France, Russia, and China.5
- Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) are the most common technologies in use.6 Two-thirds of U.S. reactors are PWRs.7
- Levelized cost of energy (LCOE) includes the expected costs of building, operating & maintaining, and fueling a power plant. Estimated LCOE for plants built in the near future are: combined cycle natural gas: 5.01 ¢/kWh; coal with 30% carbon capture and sequestration: 13.01 ¢/kWh; nuclear: 9.26 ¢/kWh; and biomass: 9.53 ¢/kWh.8

Nuclear Fuel

- Most nuclear reactors use “enriched” uranium, meaning the fuel has a higher concentration of uranium-235 (U-235) isotopes, which are easier to split to produce energy. When it is mined, uranium ore averages less than 1% U-235.9
- Milling and enrichment processes crush the ore to extract uranium oxide (UO2, i.e., yellowcake), chemically convert this to uranium hexafluoride gas (UF6), then concentrate the U-235 into ceramic uranium dioxide (UO2) pellets with 3%-5% U-235 concentrations.10
- Uranium can be enriched by gaseous diffusion or gas centrifuge. Both concentrate the slightly lighter U-235 molecules from a gas containing mostly U-238, the former with membrane filters and the latter by spinning. Other technologies are currently in development, with laser enrichment processes closest to commercial viability.11
- In 2017, 1.2 million pounds of U3O8 were extracted from 7 uranium mines in the U.S.12 Although even the highest grade ore deposits in the U.S. average less than 1% uranium, some Canadian ore is more than 15% uranium.15,14
- Less than 2% of uranium available at reasonable cost is found in the U.S. The largest deposits are in Australia, Kazakhstan, Canada, and Russia.14 U.S. nuclear plants purchased 43 million pounds of uranium in 2017.15 7% of the fuel originated in the U.S.; the remainder was imported mostly from Canada (33%), Australia (19%), Russia (16%) and Kazakhstan (11%).15
- Globally, nuclear power reactors required 65,014 metric tons of uranium in 2017.4

Energy and Environmental Impacts

The nuclear fuel cycle is the entire process of producing, using, and disposing of uranium fuel. Powering a one-gigawatt nuclear plant for a year can require mining 20,000-400,000 metric tons (mt) of ore, processing it into 27.6 mt of uranium fuel, and disposing of 27.6 mt of highly radioactive spent fuel and 200-350 m3 of low- and intermediate-level radioactive waste.16,17 U.S. plants currently use “once-through” fuel cycles with no reprocessing.18
- A uranium fuel pellet (1/2 in. height and diameter) contains the energy equivalent of one ton of coal or 17,000 ft3 of natural gas.13 Typical reactors hold 18 million pellets.8
- Each kWh of nuclear electricity requires 0.1–0.3 kWh of life cycle energy inputs.20
- Although nuclear electricity generation itself produces no GHG emissions, other fuel cycle activities do release emissions.21
Nuclear Waste

The U.S. accumulates about 2,000-2,400 mt of spent fuel each year.27 During reactor operation, fission products and transuranics that absorb neutrons accumulate, requiring a third of the fuel to be replaced every 12-18 months. Spent fuel is 95% non-fissile U-238, 3% fission products, 1% fissile U-235, and 1% plutonium.16

Spent fuel is placed in a storage pool of pumped, cooled water to absorb heat and block the high radioactivity of fission products, where it typically remains for at least 5 years.27 Some countries (excluding U.S.) reprocess spent fuel for reuse as mixed oxide fuel, which reduces the volume of radioactive waste but raises proliferation concerns.28 Many U.S. spent fuel pools are reaching capacity, necessitating the use of dry cask storage. Dry casks, large concrete and stainless steel containers, are designed to passively cool radioactive waste and withstand natural disasters or large impacts. In 2011, 27% of spent fuel was held in dry casks, after sufficient cooling in storage pools.29

Currently, 34 states have complexes designed for interim storage of spent nuclear fuel, or Independent Spent Fuel Storage Installations (ISFSD).30 Ten years after use, the surface of a spent fuel assembly releases 10,000 rem/hr of radiation (in comparison, a dose of 500 rem is lethal to humans if received all at once).31 Managing nuclear waste requires very long-term planning. U.S. EPA was required to set radiation exposure limits in permanent waste storage facilities over an unprecedented timeframe—one million years.32 The U.S. has no permanent storage site. Nevada’s Yucca Mountain was to hold 70,000 mt waste but is no longer under consideration.32 The Nuclear Waste Policy Act required the U.S. federal government to begin taking control of spent nuclear fuel in 1998. When this did not occur, the government became liable for the costs associated with continued on-site, at-reactor storage.33

Safety and Public Policy

After an earthquake and tsunami in March 2011, Japan’s Fukushima Daiichi nuclear plant lost the ability to cool reactors and spent fuel, resulting in large releases of radiation.34 Nuclear radiation at the plant was around 13 rem/hr with some localized dose rates greater than 1,000 rem/hr. By April 2011, 17 million curies of radiation had been released—4.5% the amount emitted during the 1986 Chernobyl accident.35 A recent report by the World Health Organization estimates that residents of the most affected areas were exposed to radiation doses of 1.2 to 2.5 rem in the first year after the incident.36 The U.S. Price-Anderson Act limits the financial liability of nuclear plant owners if a severe radioactive release occurs to $375 million for individual plants and $12.6 billion across all plants.37 Incentives for new nuclear plants include a production tax credit of 1.8¢/kWh of electricity generated, $18.5 billion for federal loan guarantees, and insurance against regulatory delays.38


24. WNA (2014) “In Situ Leach (ISL) Mining of Uranium.”


31. WNA (2016) “U.S. Spent Fuel Storage Data.”


**Geothermal Energy**

**Geothermal Resource and Potential**
- Geothermal energy is derived from the natural heat of the earth.\(^1\) It exists in both high enthalpy (volcanoes, geysers) and low enthalpy forms (heat stored in rocks in the Earth’s crust). Nearly all heating and cooling applications utilize low enthalpy heat, called ground source heat.\(^2\)
- Geothermal energy has two primary applications: heating/cooling and electricity generation.\(^1\)
- Ground source heat pumps for heating and cooling use 30-60% less energy than traditional heating and cooling systems and could potentially reduce U.S. residential energy use by 3 Quadrillion Btu (~3% of total U.S. energy use).\(^3\)
- The U.S. has tapped less than 0.6% of geothermal electricity resources; the majority can become available with Enhanced Geothermal System technology.\(^5\)
- In 2016, there were 3,567 MW of geothermal power plants in operation in the United States—the most of any country—and 1,270 MW of projects in development.\(^6\)
- Electricity generated from geothermal power plants is projected to increase from 15.98 billion kWh in 2017 to 65.75 billion kWh in 2050.\(^7,8\) In 2016, California, Nevada, Utah, Alaska, and Hawaii were the states with the most installed geothermal energy capacity.\(^8\)
- The U.S., the Philippines, Indonesia, Mexico, New Zealand, Italy, Iceland, and Turkey have 84% of the world’s total geothermal electricity generating capacity.\(^8\)

**Geothermal Technology and Impacts**

**Direct Use and Heating/Cooling**
- Geothermal (or ground source) heat pumps (GHPs) are the primary method for direct use of geothermal energy. GHPs use the shallow ground as an energy reservoir because it maintains a nearly constant temperature between 50°-60°F (10°–16°C).\(^10\)
- GHPs transfer heat from a building to the ground during the cooling season, and from the ground into a building during the heating season.\(^10\)
- Direct-use applications include space and district heating, greenhouses, aquaculture, and commercial and industrial processes.\(^11\)

**Electricity Generation**
- Geothermal energy currently accounts for 0.4% of net electricity generation in the United States.\(^7\)
- Hydrothermal energy, typically supplied by underground water reservoirs, is the main source of geothermal electricity. The water is often pumped as steam to the earth’s surface to spin turbines that generate electricity.\(^12\)
- Dry steam power plants use steam from a geothermal reservoir and route it directly through turbines, which drive generators to produce electricity.\(^12\)
- Flash steam power plants pump hot water under high pressure into a surface tank at much lower pressure. This pressure change causes the water to rapidly “flash” into steam, which is then used to spin a turbine/generator to produce electricity. Flash steam plants are the most common type of geothermal power plants.\(^12\)
- Binary cycle power plants feature geothermal water and a working fluid that are confined to separate circulating systems, or “closed loops.” A heat exchanger transfers heat from the water to the working fluid, causing it to “flash” to steam, which then powers the turbine/generator to produce electricity.\(^12\)
- An Enhanced Geothermal System (EGS) is a technology under development that could expand the use of geothermal resources to new geographic areas. The EGS concept is to create a subsurface fracture system to increase the permeability of rock and allow for the injection of a heat transfer fluid (typically water). Injected fluid is heated by the rock and returned to the surface to generate electricity.\(^13\)
- According to the U.S. Department of Energy, there may be over 100 GW of geothermal electric capacity in the continental U.S., which would account for nearly 10% of current U.S. electricity capacity and be 40 times the current installed geothermal capacity.\(^13\)
Installation, Manufacturing, and Cost
- The main stages of geothermal power development are resource exploration, drilling, reservoir/plant development, and power generation.15
- Capital costs for conventional geothermal power plants in the U.S. are approximately $2,500 per installed kilowatt of capacity.16
- Although the development of geothermal power requires a large capital investment, geothermal has low operating costs and a high capacity factor (ratio of actual power production to production potential).15
- With tax incentives, geothermal electricity costs an estimated 4.2-6.9¢ per kilowatt-hour (kWh), depending on the type of technology. Without tax incentives, costs are 7.8-11.6¢ per kWh.15

Energy Performance and Environmental Impacts
- Depending on the method of electricity generation, a geothermal power plant emits roughly 11 times less carbon dioxide (CO2) per unit of electricity than the average U.S. coal power plant.17
- Binary cycle power plants and flash power plants consume around 0.24-4.21 gallons and 1.59-2.84 gallons of water per kWh, respectively (compared to 15 gallons of water per kWh used by thermoelectric plants in 2015).18,19
- Each year, U.S. geothermal power offsets the emission of 4.1 million tons of CO2, 80 thousand tons of nitrogen oxides and 110 thousand tons of particulate matter from coal-powered plants.20
- Current research suggests storing CO2 in geothermal reservoirs may be possible, although the seismic risks of long-term and high-volume geologic carbon sequestration are uncertain.21,22
- Some geothermal facilities produce solid waste that must be disposed of in approved sites, though some by-products can be recovered and recycled.23

Solutions and Sustainable Actions

Funding Opportunities
- The American Recovery and Reinvestment Act of 2009 provided up to $364 million in new funding for geothermal research, development, demonstration, and deployment activities.24
- With a capacity factor of over 90%, geothermal electricity generation could offset coal, natural gas, or nuclear power as baseload supply in the electricity market.25
- The growth of geothermal deployment has been aided by state Renewable Energy Portfolio Standards (RPS) that require a certain percentage of electricity be derived from renewable sources.21,26
- Renewable Energy Certificates (RECs) are sold by renewable energy producers in addition to the electricity they produce; for a few cents per kilowatt hour, consumers can purchase RECs to “offset” their usage and help renewable energy become more competitive.26
- Across the U.S., nearly 80 utilities offer “green pricing” programs that provide consumers with the option to purchase renewably generated electricity at a small premium.27
- Many companies purchase renewable energy as part of their environmental programs. Microsoft, Intel, Google, Apple and Equinix were the top five users of renewable energy as of April 2018.28

30. Photo courtesy of National Renewable Energy Laboratory.

Cite as: Center for Sustainable Systems, University of Michigan. 2018. “Geothermal Energy Factsheet.” Pub. No. CSS10-10. August 2018
Unconventional Fossil Fuels

Patterns of Use
Globally, fossil fuels supply 81% of primary energy.\textsuperscript{1} In 2017, 80% of U.S. primary energy consumption came from fossil fuels.\textsuperscript{2} Conventional and unconventional fossil fuels differ in their geologic locations and accessibility; conventional fuels are often found in discrete, easily accessible reservoirs, while unconventional fuels may be found within pore spaces throughout a wide geologic formation, requiring advanced extraction technologies.\textsuperscript{3} If unconventional oil resources (oil shale, oil sands, extra heavy oil, and natural bitumen) are taken into account, the global oil reserves quadruple current conventional reserves.\textsuperscript{4} The price of crude oil increased 223% from 2000 to 2013, making unconventional fossil fuels more cost-competitive. However, in 2017, the price of crude oil fell to $50.8 per barrel from its 2013 peak of $97.98.\textsuperscript{5} The Energy Policy Act of 2005 includes provisions to promote U.S. oil sands, oil shale, and unconventional natural gas development.\textsuperscript{6}

Major Unconventional Sources
Oil Sands
- Oil sands, i.e., “tar sands” or “natural bitumen,” are a combination of sand (83%), bitumen (10%), water (4%), and clay (3%).\textsuperscript{8} Bitumen is a semisolid, tar-like mixture of hydrocarbons.\textsuperscript{9}
- Known oil sands deposits exist in 23 countries. Canada has 73% of global estimated oil sands, approximately 2.4 trillion barrels (bbls) of oil in place.\textsuperscript{10} The U.S. has less than 2% of global oil sands resources; however, 43% of U.S. crude oil imports came from Canada in 2017, and over 63% of Canadian production comes from oil sands.\textsuperscript{10,11,12}
- Deposits less than 250 feet below the surface are mined and processed to separate the bitumen.\textsuperscript{13} Bitumen must be upgraded to synthetic crude oil (SCO) before it’s refined into petroleum products; non-upgraded bitumen must be diluted (“dilbit”) or mixed with SCO (“synbit”) before transport.\textsuperscript{14} Deeper deposits employ \textit{in situ} (underground) methods, including steam or solvent injection, or “firefloods”—oxygen injection with a portion of oil sands burned for heat.\textsuperscript{9} Cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) are the most common \textit{in situ} methods used in Canada.\textsuperscript{15}
- Two tons of oil sands produce one barrel of SCO.\textsuperscript{9}

Oil Shale
- Oil shale is a sedimentary rock with deposits of organic compounds called kerogen, that has not undergone enough geologic pressure, heat, and time to become conventional oil. Oil shale contains enough oil to burn without additional processing, but it can be heated (“retorted”) to generate petroleum-like liquids.\textsuperscript{14}
- Oil shale deposits exist in 33 countries.\textsuperscript{16} The U.S. has the largest oil shale resource in the world, approximately 6 trillion bbls of oil in place, with the Green River formation in the Western U.S. accounting for 83% of the U.S. total.\textsuperscript{14,15} Roughly 353 billion bbls is considered to be “high grade” (>25 gallons of oil per ton of shale), representing a 50-year supply of oil for the U.S.\textsuperscript{17} However, oil shale is far from commercial development.\textsuperscript{7}
- Oil shale can be processed in two ways. In the first method, oil shale is mined and brought to the surface to be retorted to temperatures above 900\textdegree F.\textsuperscript{18} The second method, \textit{in situ} conversion process (ICP), involves placing electric heaters throughout the shale for up to three years until it reaches 650-700\textdegree F, at which point oil is released.\textsuperscript{14}
- Oil retorted above-ground must be further processed before refining and disposing of the spent shale. Oil extracted through ICP can be sent directly to the refinery.\textsuperscript{14}

Unconventional Natural Gas
- Unconventional natural gas (UG) comes primarily from three sources: shale gas found in low-permeability shale formations; tight gas found in low-permeability sandstone and carbonate reservoirs; and coalbed methane (CBM) found in coal seams.\textsuperscript{17}
- Although several countries have begun producing UG, many global resources have yet to be assessed. According to current estimates, China has the largest technically recoverable shale gas resource with 1,115 trillion cube feet (Tcf), followed by Argentina (802 Tcf) and Algeria (707 Tcf).\textsuperscript{18} Global tight gas resources are estimated at 2,684 Tcf, with the largest in Asia/Pacific and Latin America.\textsuperscript{19} Resources of CBM are estimated at 1,660 Tcf, with more than 75% in Eastern Europe/Eurasia and Asia/Pacific.\textsuperscript{17}
- U.S. resources that are recoverable with current technologies are estimated at 122.8 Tcf from shale and tight gas and 109 Tcf from CBM.\textsuperscript{19}
- UG, particularly shale and tight gas, is most commonly extracted through hydraulic fracturing, or “fracking.” A mixture of fluid (usually water) and sand is pumped underground at extreme pressures to create cracks in the geologic formation, allowing gas to flow out. When the pressure is released, a portion of the fluid returns as “flowback,” and the sand remains as a “proppant,” keeping the fractures open.\textsuperscript{17}
- UG accounted for 77% of total U.S. natural gas production in 2016 and is expected to account for 90% of production by 2050.\textsuperscript{20}
Life Cycle Impacts

Greenhouse Gases

- Fossil fuel combustion accounted for 76% of U.S. greenhouse gas (GHG) emissions in 2016.21
- Equivalent amounts of GHGs are released by conventional and unconventional fuels at the point of use. 
- Some studies suggest the life cycle emissions for unconventional oil sources are similar to or slightly lower than conventional oil.22 On average, however, life cycle emissions for unconventional oil are higher. Studies have found life cycle emissions for Canadian oil sands are 17% higher than average crude refined in the U.S., and oil shale emissions are 21% to 47% higher than conventional oil.23,24
- Studies of life cycle emissions for UG have resulted in estimates from 6% lower to 43% higher than conventional natural gas sources.25,26
- Overall, natural gas combustion generates fewer GHG emissions than other fossil fuels.27

Water

- Producing one barrel of oil from oil shale uses 2.6 to 4 barrels of water; one barrel of oil from oil sands uses 2.3 to 5.8 barrels of water.28 In comparison, producing one barrel of crude oil from Saudi Arabia’s Ghawar field requires 1.4 barrels of water.29
- A horizontal gas well can require 2 to 4 million gallons of water to drill and fracture.30 One study found shale gas production consumes up to four times more water than producing conventional natural gas.31
- CBM production requires groundwater extraction; U.S. CBM basins produce 32 million to 15 billion gallons of water per year.32
- Wastewater, produced water, and flowback water from oil and gas extraction can contain excess salts, high levels of trace elements (e.g., barium and iron), and naturally-occurring radioactive materials (NORM).33 Groundwater can be polluted through above- and below-ground activities, including construction, drilling, chemical spills, leaks, and discharge of wastewater.34

Land Impacts and Waste

- More than 70% of U.S. oil shale is on federal land, of which 678,700 acres has been designated for development.35 A 20,000 bbl/day oil sands facility requires 2,950 acres of land and creates 52,000 tons/day of sand waste; a 25,000-30,000 bbl/day oil shale facility requires 300-1,200 acres and creates 17 to 23 million tons/year of waste per retort.36
- One gas well requires one to two hectares of land, in addition to road networks.37 Drilling fluid, or “mud,” is used to cool the drill bit, regulate pressure, and remove rock fragments.38 One well may require hundreds of tons of mud and produce 110 to 550 tons of rock cuttings.39
- Small to moderate magnitude (≤6) seismic activity has been linked to underground injection of wastewater produced in oil and gas operations, including a 5.3 and a 5.6 magnitude earthquake in 2011.38,39 Hydraulic fracturing has been associated with microearthquakes (magnitude <2), but no association has been found with larger magnitude events.40 However, there has been an increase in seismic activity in the past several years. There were an average of 99 M3+ earthquakes in central and eastern U.S. between 2009-2013 and 68 M3+ earthquakes were recorded across the country in 2014. There were, on average, 21 M3+ earthquakes per year between 1973 and 2008.41
- The human toxicity impact (HTI) of electricity produced from shale gas is estimated to be 1-2 orders of magnitude less than that from coal. Particulate matter is the dominant factor for both systems.42

Solutions and Sustainable Alternatives

- Chemicals used in hydraulic fracturing fluid are often considered proprietary.43 Requiring companies to disclose these chemicals will lead to better understanding of the risk to public health from their use.44 18 U.S. states require disclosure and 9 others have proposed legislation.45
- Careful siting and monitoring of injection wells can reduce the potential for seismic events.46
- Water consumption in oil and gas extraction can be significantly reduced through efficiency improvements and the recycling of wastewater.47
- Support policies that increase energy efficiency and renewable energy use. Although natural gas has been considered preferable to other fossil fuels because it is less expensive and burns more cleanly, it ultimately remains a nonrenewable, fossil-based resource.

38. USGS (2014) “Induced Earthquakes.”
U.S. Grid Energy Storage

Electrical Energy Storage (EES) refers to the process of converting electrical energy into a stored form that can later be converted back into electrical energy when needed. Batteries are the principal devices used for EES. The first battery—called Volta’s cell—was developed in 1800 and the first U.S. large-scale energy storage facility was the Rocky River Pumped Storage plant in 1929, on the Housatonic River in Connecticut. Research in energy storage has increased dramatically, especially after the first U.S. oil crisis in the 1970s, and with advancements in the cost and performance of rechargeable batteries. The impact energy storage can have on the current and future energy grid are substantial.

- EES systems are often expressed by rated power in megawatts (MW) and energy storage capacity in megawatt-hours (MWh): the maximum charge/discharge power and the amount of energy capable of being stored, respectively.
- As of June 2018, the U.S. had over 25.2 GW of rated power in energy storage compared to 1,082 GW of total in service installed generation capacity. Globally, installed energy storage totaled 175.8 GW.
- 2.5% of delivered electric power in the U.S. is cycled through a storage facility. For comparison, 10% of delivered power in Europe and 15% of delivered power in Japan are cycled through energy storage facilities.
- Globally, 1,361 energy storage projects were operational in 2018, with 18 projects under construction. 41% of operational projects and 31% of projects under construction are located in the U.S.
- California leads the U.S. in energy storage with 220 operational projects (4.2 GW), followed by Virginia and South Carolina.
- U.S. energy storage projects increased by 174% from 2013 to 2018.

Deployed Technologies

Several EES technologies are in research phases, but four storage technology types are considered deployed: Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES), Advanced Battery Energy Storage (ABES), and Flywheel Energy Storage (FES). Thermal Energy Storage (TES) is also considered deployed. PHS and CAES are large-scale technologies capable of discharge times of tens of hours but are geographically limited. ABES and FES have lower power and shorter discharge times (from seconds to 6 hours) but are often not limited by geography. FES also suffers from short durations of storing energy (without significant self-discharge).

Pumped Hydroelectric Storage (PHS)
- PHS systems generate electricity by pumping water from a low to a high reservoir, releasing the water from the higher reservoir through a hydroelectric turbine when electricity is needed.
- 94% of U.S. energy storage is from PHS, equating to 23.6 GW as of June 2018.
- PHS plants have long lifetimes (50-60 years) and operate at 76-85% efficiency.

Compressed Air Energy Storage (CAES)
- CAES captures and stores compressed air in an underground cavern. To create electricity, the pressurized air is heated and expanded in an expansion turbine, driving a generator.
- As of June 2018, there are 4 operating CAES systems in the U.S. with a combined rated power of 0.114 GW.
- Existing CAES plants are based on the diabatic method, where the compression of the combustion air is separate from the gas turbine. The diabatic method can generate 3 times the output for every natural gas input, reduce CO₂ emissions by 40-60%, and enable plant efficiencies of 42-55%.

Advanced Battery Energy Storage (ABES)
- ABES stores electrical energy in the form of chemical energy, which is then converted back into electricity when needed.
- Batteries contain two electrodes (anode and cathode), two terminals composed of different chemicals, and the electrolyte that separates the terminals. The electrolyte enables the flow of ions between the two electrodes and external wires to allow for electrical charge to flow.
- The U.S. has several operational battery-related energy storage projects based on lead-acid, lithium-ion, nickel-based, sodium-based, and flow batteries. These batteries account for 0.75 GW of rated power in 2018 and have efficiencies between 60-95%.
Flywheel Energy Storage (FES)

- FES is mainly used for power management rather than longer-term energy storage. FES systems store electric energy via kinetic energy by spinning a rotor in a frictionless enclosure. The rotor is sped up or down to shift energy to or from the grid, which steadies the power supply.
- There are two categories of FES: low-speed and high-speed. These systems rotate at rates up to 10,000 and 100,000 RPM (rotations per minute), respectively, and are best used for high power/low energy applications.
- In 2018, flywheels accounted for 0.018 GW of rated power in the U.S. and have efficiencies between 85-87%.

Applications

- EES has many applications, including energy arbitrage, generation capacity deferral, ancillary services, ramping, transmission and distribution capacity deferral, and end-user applications (e.g., managing energy costs, power quality and service reliability, and renewable curtailment).
- EES can operate at partial output levels with fewer losses and can respond quickly to adjustments in electricity demand. Much of the current energy infrastructure is approaching—or beyond—its intended lifetime. Storing energy during low demand and using that energy during high demand saves money and prolongs the lifetime of energy infrastructure.
- Round-trip efficiency, annual degradation, and generator heat rate have moderate to strong influence on the environmental performance of grid tied energy storage.
- Many renewable energy options, such as wind and solar, have intermittent power. Energy storage systems can enable these technologies to store excess energy for times when the sun is not shining and the wind is not blowing, making them more competitive with fossil-fueled energy sources.

Solutions Research & Development

- The U.S. Department of Energy (DOE) administered $185 million of the American Recovery and Reinvestment Act (ARRA) stimulus funding to support 16 large-scale energy storage projects with a combined capacity of over 0.53 GW.
- Storage technologies are becoming more efficient and economically viable. One study found that the economic value of energy storage at maximum market potential in the U.S. is $228.4 billion over a 10 year period.
- Lithium-ion batteries are one of the fastest-growing energy storage markets due to their high energy densities, high power, near 100% efficiency, and low self-discharge. The U.S. has 35,000 tonnes of lithium in reserves alone, capable of powering 12-25 million electric vehicles (EVs) or 4-9% of U.S. vehicles (automobiles, buses, trucks, and motorcycle). Globally, there are 16 million tonnes of Li reserves.

Policy & Standardization

- The Energy Independence and Security Act of 2007 enabled an Energy Storage Technologies Subcommittee to form through the Electricity Advisory Committee (EAC), where members assess and advise the U.S. DOE every two years on progress of domestic energy storage goals.
- In 2010, California approved Assembly Bill 2514, requiring the California Public Utilities Commission (CPUC) to set and meet energy storage procurement targets for investor-owned utilities, totaling 1.33 GW of storage capacity completed by 2020 and implemented by 2024.
- In July of 2013, the U.S. Federal Energy Regulatory Commission (FERC) issued Order No. 784, which revises the accounting and reporting requirements for public utilities to better account for the use of energy storage devices.
- In 2014, large Power Transformers and the U.S. Electric Grid April 2014 Update.
- In 2017, storage technologies are becoming more efficient and economically viable. One study found that the economic value of energy storage at maximum market potential in the U.S. is $228.4 billion over a 10 year period.
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U.S. Material Use

Patterns of Use

Raw materials are extracted, converted to engineered and commodity materials, and manufactured into products. After use, they are disposed of or returned to the economy through reuse, remanufacturing, or recycling. Sustainability in materials use has three components: 1) the relationship between the rate of resource consumption and the overall stock of resources; 2) the efficiency of resource use in providing essential services; and 3) the proportion of resources leaking from the economy and impacting the environment. The first two topics reflect the sustainability of resource supply, while the third affects the sustainability of ecosystems. The United States is a primary user of natural resources, including fossil fuels and materials. The increased use of renewable materials (e.g., agriculture, wood products, primary paper) and nonrenewable materials (e.g., nonrenewable organic, primary metals, industrial minerals, and construction materials) during the 20th century is illustrated in the figure to the right.

- U.S. raw material (non-fossil fuel or food) use rose 3.15 times more than the population from 1910 to 2014.1,2
- Including fuels and other materials, total material consumption in the U.S. rose 57% from 1970 to 2000, reaching 6.5 billion metric tons.3
- In 2000, U.S. per capita total material consumption (including fuels) was 23.6 metric tons, 51% higher than the European average.3
- After increasing by 30% from 1996 to 2006, U.S. raw material use decreased 33% from 2006 to 2010 following the global financial crisis.1
- Construction materials, including stone, gravel, and sand comprise around three-quarters of raw materials use.1
- The use of renewable materials decreased dramatically over the last century—from 41% to 5% of total materials by weight—as the U.S. economy shifted from agriculture to industrial production.4
- The ratio of global reserve to production rate is an indicator of the adequacy of mineral supplies; it can range from a few centuries (aluminum, chromium, lithium, platinum, phosphate rock), to several decades (copper, gold, iron).5
- Rare earth elements (REEs) are a group of 17 elements used in various products such as alloys, batteries, and catalysts.6 Substitute for REEs are available but are less effective. China controlled more than 80% of REE production in 2017.5

Intensity of Raw Material Use

- Material intensity of use refers to the amount of materials consumed per unit of economic output, generally measured by the total gross domestic product (GDP) of a country.7
- 44% of materials consumed in the U.S. economy are added to the long-term (>30 years) domestic stock, 2% remain in the stock between 2-30 years, 39% remain in the stock less than 2 years, and the remaining 15% are recycled back into the economy.3
- Of the materials remaining in the domestic stock less than 30 years, 73% are released into the atmosphere (mostly through fossil fuel combustion), 18% are disposed of in controlled areas (e.g., landfills, tailings ponds), and the remaining 9% are dispersed directly into the environment on land, in water, or through multiple paths.3
- There is an appreciable decline in the intensity of use of primary metals, except aluminum, while the use of plastics continues to grow.5
- Trends in the composition of materials used in the U.S. economy have changed from dense to less dense, i.e., from iron and steel to lighter metals, plastics, and composites.9
- The domestic processed output, or total weight of materials and emissions disposed of in the domestic economy, declined per unit of GDP by about 44% in the U.S. over the last few decades, similar to other industrialized nations.3
Environmental Impacts

Raw material extraction and use can create significant environmental impacts. 

- Mines and quarries, including coal but excluding oil and natural gas, occupy 0.3% of the land area in the U.S., of which 60% is used for excavation and the rest for disposal of overburden and other mining wastes.13
- As higher grade reserves are depleted, the quality of metal is degrading, leading to greater energy needed to extract and process ore, and thus greater releases of gases that contribute to climate change and acid precipitation.14
- The primary metals and metal mining sectors accounted for 54% of the total 3.4 billion pounds of toxic releases in 2016.15
- In 2015, more than 34 million metric tons of Resource Conservation and Recovery Act (RCRA) regulated hazardous waste were generated in the U.S. The largest sources were chemical manufacturing (59%) and petroleum and coal products manufacturing (14%).16
- In 2014, primary metal industries used 1.6 Quadrillion Btu (quads) of energy; nonmetallic mineral (stone, clay, glass, cement) manufacturing used 0.8 quads; chemical manufacturing used 6.3 quads; and petroleum and coal products used 4.2quads (total U.S. consumption was 98.5 quads).17,18
- Energy-related carbon dioxide emissions from the industrial sector have fallen 17% since 1990, mainly due to a structural shift away from energy-intensive manufacturing in the U.S. economy.19
- Human health risks arise from emissions and residues over a material’s life cycle. In many cases, pollutant releases have been substantially reduced from historical levels, e.g., mercury released by gold mining, fugitive volatile organic compound emissions from paints, and lead from the combustion of gasoline.20 However, in 2016, more than 330,000 tons of lead and lead compounds were released; 90% came from metal mining, while primary metal production and electric utilities accounted for 5.3% and <0.1%, respectively.21 New chemicals have been introduced that have been found to persist in the environment, bioaccumulate (move up the food chain), and/or are toxic, e.g., phthalates that are widely used in consumer products to make plastics soft and flexible.22

Solutions and Sustainable Actions

- **Conserve materials:** Follow the motto of “Reduce, Reuse, Remanufacture, and Recycle.” U.S. recycling and remanufacturing industries accounted for over 757 thousand jobs and more than $36 billion in revenue in 2007.23 In 2015, 34.7% of municipal solid waste in the U.S. was recovered for recycling and composting, diverting more than 91 million tons of material from landfills and incinertors.24
- **Change the material composition of products:** Create products using materials that are less toxic, easily recyclable, and less energy intensive during production and manufacturing. There are over 142 million commercially available chemical compounds.25
- **Reduce material intensity:** Technological advances can help reduce the raw material intensity of products while making them lighter and more durable. Aluminum beverage cans are 38% lighter today than they were three decades ago, allowing more cans to be produced from the same amount of aluminum. Additionally, beverage cans are made with an average of 70% recycled aluminum, representing a huge decrease in energy requirements and greenhouse gas emissions compared to using virgin materials.26
- **Promote product stewardship:** Appropriate policy and regulatory frameworks can help ensure product manufacturers’ responsibility for the environmentally conscious management of retired consumer goods. The European Union’s regulations on waste electrical and electronic equipment (WEEE) include a target of an 85% increase in proper WEEE collection and disposal by 2019.27
- **Encourage renewable material use:** Increase the use of renewable materials within products and in packaging. Biobased materials such as polyactic acid (PLA), a biodegradable polymer derived from corn, can provide performance characteristics similar to petroleum-based plastics. Although manufacturing these renewable materials requires less energy and emits fewer greenhouse gases, the use of land and chemicals required to grow the feedstock may have adverse environmental consequences.28

Municipal Solid Waste

Municipal Solid Waste (MSW), commonly called “trash” or “garbage,” includes wastes such as durable goods (e.g., tires, furniture), nondurable goods (e.g., newspapers, plastic plates/cups), containers and packaging (e.g., milk cartons, plastic wrap), and other wastes (e.g., yard waste, food). This category of waste generally refers to common household waste, as well as office and retail wastes, but excludes industrial, hazardous, and construction wastes. The handling and disposal of MSW is a growing concern as the volume of waste generated in the U.S. continues to increase.¹

Generation Statistics

• Total annual MSW generation in the U.S. has increased by 73% since 1980, to the current level of about 262 million tons per year.¹
• Per capita MSW generation increased by 22% over the same time period, from 3.7 pounds to 4.5 pounds per person each day, although per capita generation has decreased slightly since 1990.¹
• At the current per capita rate, an average American weighing 180 pounds generates their own weight in MSW every 41 days.³
• The generation of MSW from private consumption in the U.S. is approximately $21.32 per pound or 47 lbs per thousand dollars. Comparable generation rates (in lbs/thousand dollars) are 40 in the UK, 50 in Sweden, and 61 in Germany.²

Management Methods

Landfill

• In 2015, 52.5% of MSW generated in the U.S. was disposed of in 1,738 landfills.¹ ¹
• The 2017 combined capacity of the two largest landfill corporations in the U.S. was more than 10 billion cubic yards.⁹
• Landfill disposal fees, or “tipping” fees, in the U.S. currently average $50.59 per ton. Some local governments use the fees as a general income source, but there is still a lack of funding for research and technologies that prevent waste from ending up in a landfill.⁹
• Environmental impacts of landfill disposal include loss of land area, emissions of methane (CH⁴, a greenhouse gas) to the atmosphere, and potential leaching of hazardous materials to groundwater, though proper design reduces this possibility.⁷,⁸
• Landfills were the third largest source of U.S. anthropogenic CH⁴ emissions in 2016, accounting for 108 million metric tons CO₂-equivalent emissions, about 1.7% of total GHG emissions.⁷

Combustion

• In 2015, 12.8% of MSW generated in the U.S. was disposed of through waste incineration with energy recovery.¹
• Combustion reduces waste by about 75% by weight and 87% by volume, leaving behind a residue called ash. A majority of this ash is landfilled, although recent attempts have been made to reuse the residue.¹⁰,¹¹
• Biogenic MSW (paper, food, and yard trimmings) was converted into energy to provide 168 trillion Btu in 2009, less than 0.2% of total U.S. energy consumption.¹²
• In 2015, 75 power plants burned about 29 million tons of MSW and generated nearly 14 billion kilowatthours of electricity.¹¹
• Incineration of MSW generates a variety of pollutants (CO₂, heavy metals, dioxins, particulates) that contribute to impacts such as climate change, smog, acidification, asthma, and heart and nervous system damage.¹³
Recycling and Composting

- In 2015, 34.7% of MSW generated in the U.S. was recovered for recycling or composting, diverting 91.2 million tons of material from landfills and incinerators—almost 2.7 times the amount diverted in 1990.¹
- Composted materials represent nearly 26% of all recovered MSW.²
- Automated curbside recycling currently serve only 3% of people in the U.S.; 92% of cities with curbside recycling collect material single-stream, meaning materials such as glass and paper are separated at the recycling plant.³ The number of curbside programs in the U.S. has increased more than threefold since 1990.⁴,⁵
- 90% of corrugated boxes were recovered for recycling in 2015; other commonly recycled products include lead-acid batteries (99%), newspapers (71%), major appliances (62%), and aluminum beverage cans (55%).⁶
- Common products with poor recycling rates include: carpet (6%), small appliances (6%), and furniture (0.1%).⁷

Solutions and Sustainable Alternatives

Source Reduction

- Source reduction activities help prevent materials from entering the MSW stream and are the most effective way to reduce waste generation.⁸
- Packaging and containers made up 30% of the MSW generated in 2015. Minimize the volume of packaging material required by selecting products packaged efficiently or buying in bulk.¹
- Identify opportunities to reuse materials in the home or community. Purchase items like furniture and appliances from reuse centers and consignment shops.
- Purchase products with post-consumer recycled content and encourage companies to implement source reduction programs.
- More than two million tons of paper and plastic plates and cups were disposed of in 2015. Choose reusable plates, cups, and silverware over disposable goods.⁹
- Food waste makes up 15.1% of MSW in the U.S., and only 5.3% is recovered or composted. Reduce food waste through efficient meal planning and composting of scraps.¹⁰

Encourage Supportive Public Policy

- Many communities have implemented Pay-As-You-Throw programs, designed to limit the volume of MSW per household by charging residents for waste collection based on the amount they throw away.¹¹
- In 2013, the U.S. Department of Agriculture and Environmental Protection Agency launched the U.S. Food Recovery Challenge, with a goal to divert food from landfills by donating to food charities, composting, and generating electricity through anaerobic digestion of food scraps.¹²
- Implementation of curbside recycling and composting programs where currently unavailable can help reduce the burden of waste disposal.
- Although most states restrict landfill disposal of certain materials, some states do not restrict the disposal of potentially hazardous items (e.g., oil, batteries, scrap tires, and electronics). Many of these are difficult to recycle and have limited management options.¹³
- Ten states (CA, CT, HI, IA, ME, MA, MI, NY, OR, and VT) have deposit laws that encourage the return of empty beverage containers for refunds.⁴

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Critical Materials

Minerals are integral to the functioning of modern society. They are found in countless products such as aircrafts, communication systems, electric vehicles, lasers, naval vessels, and various types of consumer electronics and lighting. However, some of these minerals are in limited supply and techniques for their extraction incur high environmental and financial costs. Given their necessity in a plethora of technological applications, concern exists over whether supply can meet the needs of the economy in the future. Material criticality is assessed in terms of supply risk, vulnerability to supply restriction, and environmental implications. Rare earth elements (REEs) are a group of 17 elements used in various products such as alloys, batteries, and catalysts. No readily available substitutes exist for most REEs. Unless action is taken, the U.S. could face an annual shortfall of up to $3.2 billion worth of critical materials.

Critical Materials Categories

Energy Critical Elements

- Energy critical elements (ECEs) are elements integral to advanced energy production, transmission, and storage. This category includes lithium, cobalt, selenium, silicon, tellurium, indium, and Rare Earth Elements (REEs).
- An element might be classified as energy critical because of rarity in Earth’s crust, economically extractable ore deposits are rare, or lack of availability in the U.S. The U.S. is reliant on other countries for more than 90% of most ECEs used in the economy.
- Some ECEs form deposits on their own, others are obtained solely as byproducts or coproducts from the mining of other ores.
- Silicon, tellurium, and indium are necessary parts of solar photovoltaic (PV) panels.
- Platinum group elements (PGEs) are necessary components of fuel cells and have the potential for other advanced vehicle uses. Platinum and palladium production are concentrated in South Africa (70% and 37%, respectively) and Russia (11% and 39%, respectively).
- Lithium is an element of growing importance due to its use in batteries used in cell phones, laptops, and electric vehicles. Chile, Bolivia, and Argentina account for over 50% of easily extractable world lithium reserves. Australia, Argentina, and Chile account for a significant share of world lithium production.
- Efforts are underway to extract elements from lower quality resources. Lithium, along with materials such as vanadium and uranium, is present in seawater in small concentrations. Researchers have recently developed a method for extracting these materials from seawater.
- The U.S. Department of Energy (DOE) defines materials criticality based on the material’s supply risk and importance to clean energy. As of 2011, DOE found five elements to be critical in the short-term (2011 to 2015) and medium-term (2015-2025): dysprosium, terbium, europium, neodymium, and yttrium. These elements are used in magnets for wind turbines and electric vehicles or as phosphors in energy efficient lighting.
- Other key elements assessed by DOE include nickel, manganese, cobalt, lithium, gallium, indium, and tellurium. While these are important for renewable energy technology, they are not currently subject to nor predicted to be subject to supply disruptions.
- Current DOE strategies for addressing material criticality include diversifying supply, developing substitutes, and improving recycling of critical materials.
- Although not an ECE, copper is a key element in electrical wiring and appliances and may be a limiting factor in future renewable energy deployment. 26% of all available copper resources are either currently in use or have been discarded and are not feasibly recoverable. Top copper producing countries include Chile (27.1%), Peru (12.1%), China (9.4%), and the U.S. (6.5%). Copper is highly recyclable. Experts estimate that more than 99% of discarded copper is potentially recoverable and reusable.
Rare Earth Elements

- Rare earth elements (REEs) are a particularly important group of critical minerals. Although these minerals are moderately abundant in Earth’s crust, they are distributed diffusely and thus difficult to extract in large quantities.2
- There are 17 REEs, including the lanthanide elements (atomic numbers 57 through 71 on the periodic table), scandium, and yttrium. Light REES (LREEs) consist of elements 57 through 64, and heavy REEs (HREEs) consist of elements 65 - 71.1
- REEs have a variety of uses, including components in cell phones, energy efficient lighting, magnets, hybrid vehicle batteries, and catalysts for automobiles and petroleum refining.12 The REEs terbium, neodymium, and dysprosium are key components of the magnets used in wind turbine gearboxes.9 Substitute for REEs are available but are less effective.8
- In 2017, China controlled more than 80% of REE production, while the U.S. was almost fully reliant on REE imports. Suspension of illegal production caused prices to increase in first two quarters of 2017. However, producers stopped producing due to low demand by the end of 2017,6
- The U.S. has decreased REE production in recent years, from 3,900 tonnes in 2015 to 0 tonnes in 2017. U.S. REE reserves are estimated at 1.4 million tonnes. In comparison, China produced 105,000 tonnes of REEs in both 2016 and 2017 and possesses reserves estimated at 44 million tonnes. Australia is making significant strides in REE extraction but remain far below China’s production capacity.8
- Demand for ECEs, coupled with rising mining standards in many countries, has caused production to shift to countries with low costs and lax environmental regulations, thus increasing the impacts of ECE extraction. Nevertheless, it is worth noting that developing nations naturally contain greater quantities of ECE ore deposits.6

Life Cycle Impacts

- Mining is a destructive process that disrupts the environment and disperses waste widely. Chemical compounds used in extraction processes can enter the air, surface water, and groundwater near mines.13
- The grinding and crushing of ore containing critical elements often release dust, which can have carcinogenic and negative respiratory effects on exposed workers and nearby residents.13
- Some REE deposits contain thorium and uranium, which pose significant radiation hazards. While thorium and uranium can be used to generate nuclear energy, in this case, they are rarely commercially recoverable and thus are left in the tailings, where they can pose risks to environmental and human health.6
- Recycling critical materials results in much lower human health and environmental impacts compared to mining virgin material. Nevertheless, improper recycling and recovery procedures can lead to exposure to carcinogenic and toxic materials, which often occur in developing nations where recycling regulations to limit worker exposure are lax or nonexistent.15

Solutions and Sustainable Alternatives

- Recycle your electronics. Currently, less than 1% of REEs are recycled. Every year, thousands of electronic products such as cell phones, televisions, and computers are thrown away. Metals recovered from these products can be effectively reused or recycled.3
- Buy refurbished rather than new products. Rent products from companies with extensive take-back laws that require material recycling.6
- Support government programs like the Innovative Manufacturing Initiative, which funds projects related to reducing environmental impacts, lowering costs, and improving the process of renewable technology manufacturing. Approved projects include funding for gallium-nitride-based LED lights.10

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U.S. Food System

Americans enjoy a diverse abundance of low-cost food, spending a mere 10% of disposable income on food. However, store prices do not reflect the external costs — economic, social, and environmental—that impact the sustainability of the food system. Considering the full life cycle of the U.S. food system illuminates the connection between consumption behaviors and production practices.

Patterns of Use

Agricultural Production

- Farmers account for 1% of the population, and the average age of farmers is leveling off in the mid-50s after a rapid increase. Just 14.8¢ of every dollar spent on food in 2016 went back to the farm; in 1975, it was 40¢. In 2012, farmers were reliant on income sources outside the farm to make up 80% of their household income, on average. In 2013-2014, 47% of the hired agricultural labor force lacked authorization to work in the United States. From 1992 to 2012, total cropland decreased from 460 million acres to 392 million acres. Many parts of the U.S., including agricultural regions, are experiencing increasing groundwater depletion (withdrawal exceeds recharge rate). In 2013, 88.5 million acre-feet of water were used for irrigation—more than 520,000 gallons per acre; groundwater sources supplied more than half this amount.

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- Nutrient runoff from the upper agricultural regions of the Mississippi River creates a hypoxic “dead zone” in the Gulf of Mexico. 2017 hypoxic dead zone was the largest measured since 1985, at 8,776 sq mi.

- Although pesticide use declined 1.4% annually from 1996 to 2007, herbicide use increased significantly during the same period. In 2008, the U.S. agriculture sector used 516 million pounds of pesticides.

- Decreased pesticide use is due in part to widespread deployment of genetically engineered crops. Less than 20% of corn and soy plants were genetically engineered in 1996; by 2018, 92% of corn and 94% of soybeans were genetically modified.

- In 2012, 1.67 billion tons of topsoil were lost to erosion, equal to about 190,000 tons each hour.

- Agriculture was responsible for 8.6% of total U.S. greenhouse gas emissions in 2016.

Consumption Patterns

- In 2010, the U.S. food supply provided 4,000 calories per person per day. Accounting for waste, the average American consumed 2,476 calories per day in 2010, an increase of 22% from 1970.

- In 2015, 194 lbs of meat per person were available for consumption, up 23 lbs from 1965. Although red meat consumption declined almost 30% since 1970s, chicken consumption increased steadily.

- 32% of grains grown are used to feed animals, down from 50%+ in past years.

- The average American consumes about 22.5 teaspoons of added sugars and sweeteners per day; the American Heart Association recommends between 6 and 9 teaspoons daily for an average adult.

- More than 70% of U.S. adults are overweight or obese (body mass index ≥25), and 17% of children age 2-19 are obese.

- Diet contributes to heart disease, certain cancers, and stroke—leading causes of U.S. deaths.

- An estimated 21% of the edible food available is wasted at the consumer level, 50% more than in 1970. This waste accounts for roughly 15% of the municipal solid waste stream and represents a loss of $450 per person each year. One estimate suggests that 2% of total annual energy use in the U.S. is used to produce food that is later wasted.
Life Cycle Impacts

The energy used by a system is often a useful indicator of its sustainability. Food-related energy use accounts for nearly 16% of the national energy budget. Modern agriculture and the food system as a whole have developed a strong dependence on fossil energy; 13 units of (primarily) fossil energy are input for every unit of food energy available. 18,19,20,31,32

- Food production impacts of US self-selected diets amount to 4.7 kg CO2 eq. and 25.2 MJ non-renewable energy demand per person per day. 33
- Reliance on fossil fuel inputs makes the food system increasingly vulnerable to oil price fluctuations; 18
- Consolidation of farms, food processing operations, and distribution warehouses often increases distance between food sources and consumers; 18
- Consolidation in the food system is also concentrating management decisions into fewer hands. For example:
- Four firms control 85% of the beef packing market; 82% of soybean processing is controlled by 4 firms. 34,35
- The top four food retailers sold almost 45% of America’s food in 2016, compared to only 17% in 1993. 36

Solutions and Sustainable Alternatives

Eat Local

Fresh produce eaten in the Midwest travels an average of more than 1,500 miles. A study by the Leopold Center showed that increasing Iowa’s consumption of regionally grown fresh produce by only 10% would save more than 300,000 gallons of transportation fuel per year. 27 Community Supported Agriculture (CSAs) and Farmers Markets are both great ways to support a local food system.

Eat Less Meat

A meat-based diet (28% calories from animal products) uses twice as much energy to produce as a vegetarian diet. 18 Meat production as it is widely practiced today also has significant environmental impacts on land use, water use and water pollution, and air emissions. 38 20% of Americans cause half of the food-related GHG emissions; a diet shift away from meat could reduce this. 33

Eat Organic

Organic farms don’t use chemicals that require large amounts of energy to produce, pollute the soil and water, and present human health impacts. Sales of organic food in 2017 were 6.4% higher than in 2016; organic food now accounts for 5.5% of all food sold in the U.S. 28

Use Less Refrigeration

Home refrigeration accounts for 13% of all energy consumed by our food system. Today’s convenience foods rely heavily on refrigeration for preservation. Consider a smaller, more efficient refrigerator and buying smaller quantities of fresh produce more frequently. Refrigerator efficiency more than doubled from 1977 to 1997, but increases in size have largely offset this improvement. 40

Reduce Waste

Much of household food waste is due to spoilage. Prevent food from going bad by buying smaller amounts; planning meals and sticking to shopping lists; and freezing, canning, or preserving extra produce. 40 Many foods that are still safe are thrown out due to confusion about “sell-by” and “use-by” dates. 40 For further information on food product dating, see the USDA’s Food Safety and Inspection Service.

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34. USDA, ERS (2013) “Processing & Marketing: Manufacturing.”
41. USDA, ERS (2016) “Food Product Dating”
U.S. Water Supply and Distribution

Patterns of Use
All life on Earth depends on water. Human uses include drinking, bathing, crop irrigation, electricity generation, and industrial activity. For some of these uses, the available water requires treatment prior to use. Over the last century, the primary goals of water treatment have remained the same—to produce water that is biologically and chemically safe, appealing to consumers, and non-corrosive and non-scaling.

Water Uses
• In 2015, total U.S. water use was approximately 322 billion gallons per day (Bgal/d). Thermoelectric power (133 Bgal/d) and irrigation (118 Bgal/d) accounted for the largest withdrawals. 1
• Per capita use was roughly 48% higher in western states than in eastern states in 2015, primarily due to the volume of water used for crop irrigation in the west. 1
• In 2015, California and Texas accounted for 16% of U.S. total water withdrawals, even after reducing public-supply withdrawal by 18% and 28%, respectively, from 2010 levels. 1,2 Florida, New York and Maryland accounted for half of saline water withdrawals. 1

Sources of Water
• Approximately 87% of the U.S. population relied on public water supply in 2015; the remainder relies on water from domestic wells. 1
• Surface sources account for 74% of all water withdrawals. 1
• About 153,000 publicly owned water systems provide piped water for human consumption, of which roughly 51,000 (34%) are community water systems (CWSs). 3 8% of all CWSs provide water to 82% of the population served. 4
• In 2006, CWSs delivered an average of 96,000 gallons per year to each residential connection and 797,000 gallons per year to non-residential connections. 5

Energy Consumption
• 2% of total U.S. electricity use goes towards moving and treating water and wastewater, a 52% increase in electricity use since 1996. 4 Electricity use accounts for around 80% of municipal water processing and distribution costs. 4
• Groundwater supply from public sources requires 2,100 kilowatt-hours per million gallons—about 31% more electricity than surface water supply, mainly due to higher raw water pumping requirements for groundwater systems. 4
• The California State Water Project is the largest single user of energy in California, consuming 5 billion kWh per year, on average—more than 23% of the total electricity consumption for the entire state of New Mexico. In the process of delivering water from the San Francisco Bay-Delta to Southern California, the project uses 2%-3% of all electricity consumed in the state. 7

Water Treatment
• The Safe Drinking Water Act (SDWA), enacted in 1974 and amended in 1986 and 1996, regulates contaminants in public water supplies, provides funding for infrastructure projects, protects sources of drinking water, and promotes the capacity of water systems to comply with SDWA regulations. 8
• Typical parameters that the U.S. Environmental Protection Agency monitors for violations of drinking water standards include: microorganisms, disinfectants, radionuclides, organics (e.g., volatile organic compounds and synthetic organic chemicals), and inorganics (e.g., nitrates, arsenic, radionuclides, lead, and copper). 8
• Of all CWSs, 91% are designed to disinfect water, 23% are designed to remove or sequester iron, 13% are designed to remove or sequester manganese, and 21% are designed for corrosion control. 5

<table>
<thead>
<tr>
<th>System Size (population served)</th>
<th>Number of CWSs</th>
<th>Population Served (millions)</th>
<th>% of CWSs</th>
<th>% of U.S. Population Served by CWSs</th>
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</thead>
<tbody>
<tr>
<td>Very Small (25-500)</td>
<td>28,462</td>
<td>4.8</td>
<td>55%</td>
<td>2%</td>
</tr>
<tr>
<td>Small (501-3,300)</td>
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<td>19.7</td>
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<td>7%</td>
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<tr>
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<td>10%</td>
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<tr>
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<tr>
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<tr>
<td>Total</td>
<td>51,356</td>
<td>299.2</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Life Cycle Impacts

Infrastructure Requirements

- The 2015 Drinking Water Infrastructure Needs Survey and Assessment found that U.S. water systems need to invest $472.6 billion over the next 20 years to continue providing clean safe drinking water.
- 66% ($312.6 billion) of the total national investment need is for transmission and distribution. The remaining 34% of need is for treatment ($83.0 billion), storage ($47.6 billion), source development ($21.8 billion), and other systems ($7.5 billion).
- Water systems maintain more than 2 million miles of distribution mains. In 2000, nearly 80% of systems were less than 40 years old, while 4% were more than 80 years old. From 2001 to 2006, over 6,000 miles of distribution mains were replaced and 225,000 miles were newly added.

Electricity Requirements

- Supplying fresh water to public agencies required about 31 billion kWh of electricity in 2000.
- One study projects electricity consumption to exceed 36 billion kWh by 2020 and 46 billion kWh by 2050. This increased production of electricity may result in environmental burdens, whose magnitude will depend directly on the fuel mix at generating facilities—fossil, nuclear, hydropower, solar, wind, and biomass.
- Household appliances contribute greatly to the energy burden. Dishwashers, showers, and faucets require 0.312 kWh/gallon, 0.143 kWh/gallon, and 0.139 kWh/gallon, respectively.

Consumptive Use

- Consumptive use is an activity that draws water from a source within a basin and returns only a portion or none of the withdrawn water to the basin. The water might have been lost to evaporation, incorporated into a product such as a beverage and shipped out of the basin, or transpired into the atmosphere through the natural action of plants and leaves.
- Agriculture accounts for the largest loss of water (80-90% of total U.S. consumptive water use). Of the 118 Bgal/d freshwater withdrawn for irrigation, over half is lost as a consequence of consumptive use. Of the 133 Bgal/d of water withdrawn for thermoelectric power in the U.S., 3% is consumed (4.31 Bgal/d).

Solutions and Sustainable Alternatives

Supply Side

- Major components that offer significant energy efficiency improvement opportunities include pumping systems, pumps, and motors.
- Periodic rehabilitation, repair, and replacement of water distribution infrastructure would help improve water quality and avoid leaks.
- Achieve on-site energy and chemical usage efficiency to minimize the life cycle environmental impacts related to the production and distribution of energy and chemicals used in the treatment and distribution process.
- Reduce chemical usage for treatment and sludge disposal by efficient process design, recycling of sludge, and recovery and reuse of chemicals.
- On-site energy generation from renewable sources such as solar and wind.
- Effective watershed management plans to protect source water are often more cost-effective and environmentally sound than treating contaminated water. For example, NYC chose to invest between $1-1.5 billion in a watershed protection project to improve the water quality in the Catskill/Delaware watershed rather than construct a new filtration plant at a capital cost of $6-8 billion.
- Less than 4% of U.S. freshwater comes from brackish or saltwater, though this segment is growing. Desalination technology, such as reverse osmosis membrane filtering, unlocks large resources, but more research is needed to lower costs, energy use, and environmental impacts.

Demand Side

- Better engineering practices:
  - Plumbing fixtures to reduce water consumption, e.g., high-efficiency toilets, low-flow showerheads, and faucet aerators.
  - Water reuse and recycling, e.g., graywater systems and rain barrels.
  - Efficient landscape irrigation practices.
- Better planning and management practices:
  - Pricing and retrofit programs.
  - Proper leak detection and metering.
  - Residential water audit programs and public education programs.

References:

Patterns of Use

For many years, humans have treated wastewater to protect human and ecological health from waterborne diseases. Since the early 1970s, effluent water quality has been improved at Publicly Owned Treatment Works (POTWs) and other point source discharges through major public and private investments prescribed by the Clean Water Act (CWA). Despite the improvement in effluent quality, point source discharges continue to be a significant contributor to the degradation of surface water quality. In addition, much of the existing wastewater infrastructure, including collection systems, treatment plants, and equipment, has deteriorated and is in need of repair or replacement.

Contamination and Impacts

- Pollutants contaminate receiving water via many pathways: point sources, non-point sources (e.g., air deposition, agriculture), sanitary sewer overflows, stormwater runoff, combined sewer overflows, and hydrologic modifications (e.g., channelization and dredging).
- 53% of river and stream miles, 71% of lake acres, 79% of estuarine square miles, and 98% of Great Lakes shoreline miles that have been assessed are classified as impaired (unsatisfactory for at least one designated use) by the EPA.2
- 19% of households are not served by public sewers and usually depend on septic tanks to treat and dispose of wastewater.2 Failing septic systems may contaminate surface and groundwater.4

Treatment of Municipal Wastewater

- An estimated 14,748 POTWs provide wastewater collection, treatment, and disposal service to 238.2 million people.6 Use of reclaimed water for consumption is becoming more common, particularly in the fast-growing southwest region of the U.S.7
- In 2010, California recycled roughly 650,000 acre-feet of water per year (ac-ft/yr). They have set ambitious goals to increase water recycling, with at least 1 million ac-ft/yr recycled by 2020, and 2 million ac-ft/yr by 2030.8
- POTWs generate over 8 million tons (dry weight) of sludge annually.9 Sludge requires significant energy to treat—about one-third of total electricity use by a wastewater treatment system.10
- In the U.S., chlorination is the most common means of disinfection. Chlorination may be followed by dechlorination with sulfur dioxide to avoid deteriorating ecological health of the receiving stream and the production of carcinogenic by-products.11
- Ultraviolet (UV) disinfection is the most common alternative to chlorination and has comparable energy consumption.12
- Chemical additions of ferric salts and lime enhance coagulation and sedimentation processes for improved solids removal as well as removal of toxic pollutants. However, their production and transport have life cycle impacts.13
- Classes of unregulated compounds known as “contaminants of emerging concern” (CECs) are a concern for water treatment engineers, particularly pharmaceuticals, personal care products, and perfluorinated compounds.14 In the past decade, polybrominated diphenyl ethers (PBDEs) and perfluorinated compounds (PFCs) have become CECs due to their wide distribution and persistence in the environment.14 Some of these chemicals are endocrine disruptors, a class of compounds that alter the normal functioning of endocrine systems, including those that affect growth, reproduction, and behavior.15 Many of these chemicals are not removed by POTWs.16

Biosolids (Sludge) End-of-Life

- Qualified biosolids can be beneficially used after “stabilization,” which kills pathogens and decomposing vector attractive substances.17
- 54% of biosolids are beneficially used. Most of this is applied to agricultural sites, with minor amounts applied to forestry and reclamation sites (e.g., Superfund and Brownfield lands) and urban area (e.g., maintaining park land).18
Life Cycle Impacts
Wastewater treatment systems reduce environmental impacts in the receiving water but create other life cycle impacts mainly through energy consumption. Greenhouse gas (GHG) emissions are associated with both the energy and chemicals used in wastewater treatment and the degradation of organic materials in the POTW.

Electricity Consumption and Emissions
- 2% of total U.S. electricity use goes towards moving and treating water and wastewater.
- In 2000, energy-related emissions resulting from POTW operations, excluding organic sludge degradation, led to total emissions of 11.5 teragrams (Tg) of CO\(_2\) equivalents (CO\(_2\) eq.), an acidification potential of 145 gigagrams (Gg) of SO\(_2\) equivalents, and eutrophication potential of 4 Gg of P O\(_4\) \(_3\) equivalents.
- CH\(_4\) and N\(_2\)O are mainly emitted during organic sludge degradation by aerobic and anaerobic bacteria, wastewater treatment plant and receiving water body.
- One study found the electricity use of wastewater treatment facilities is responsible for 1.2% of total U.S. electricity use.

Social and Economic Impacts
- Population growth and urban sprawl increase the collection (sewer) system needed.
- Although the 50-year life expectancy of a sewer system is longer than treatment equipment (15 to 20 years), renovation needs of a sewer system can be more costly. If there is no renewal or replacement of existing 600,000 miles of sewer systems, the amount of deteriorated pipe will increase from 10% to 44% of the total network from 1980 to 2020.
- In 2012, U.S. clean water needs for building new and updating existing wastewater treatment plants, pipe repair and new pipes, and combined sewer overflow corrections were $102.0, $95.7, and $48.0 billion, respectively.

Solutions and Sustainable Alternatives
Administrative Strategy
- Investment in wastewater treatment systems is shifting from new construction projects to maintenance of original capacity and function of facilities (asset management). Life cycle costing should be embedded in capital budgeting, and combined sewer overflow, sanitary sewer overflow, and stormwater management programs need to be conducted continuously.
- In order to meet ambient water standards, total maximum daily loads (TMDLs) considering both point and non-point source pollutant loadings can be developed to achieve fishable and swimmable water quality. Watershed-based management of clean water is expected to facilitate establishment of these TMDLs.

Reduce Loading
- Examples of projects to reduce or divert wastewater flow include disconnecting household rainwater drainage from sanitary sewers, installing green roofs, and replacing impervious surfaces with porous pavement, swales, or French drains.
- Toilets, showers, and faucets represent 62% of all indoor water use. Install high-efficiency toilets, composting toilets, low-flow shower heads, faucet aerators, and rain barrels.
- One study found water-efficient appliances contributed to a 10% decline in household water use since 1990.

Technological Improvements and System Design
- The aeration process, which facilitates microbial degradation of organic matter, can account for 25% to 60% of the energy use in wastewater treatment plants. Flexible designs allow the system to meet oxygen demands as they fluctuate with time of day and season.
- Pumping systems, typically consuming 10-15% of energy at wastewater treatment plants, can lead to inefficient energy consumption when pumps, flow control, and motors are mismatched to treatment plant needs.
- A number of treatment plants are considering using methane generated from anaerobic digestion of biosolids as an energy resource.
- Water reuse can significantly decrease system energy use.

U.S. Cities

Large, densely populated, and bustling with activity, cities are cultural and economic centers, providing employment, leisure, and educational opportunities. Energy and resources flow in and out of cities to support their population and infrastructure. However, there is increasing attention on the environmental impacts of cities, and the significant opportunity for reducing the impact of the built environment and improving the livelihoods of urban residents.

Urban Land Use Patterns

- Approximately 82% of the U.S. population lives in urban areas, up from 64% in 1950. By 2050, 90% of the U.S. population and 68% of the world population is projected to live in urban areas.1,2
- More than 270 urban areas in the U.S. have populations above 100,000; New York City, with 8.6 million inhabitants, is the largest.3,4
- The rate of urbanization, i.e., the changing of land from forest or agricultural uses to suburban and urban uses, is increasing.5 Between 2000 and 2010, urban land area in the U.S. increased by 15%. Urban land area is 106,386 square miles, or 3% of total land area in the U.S., and is projected to triple from 2000 to 2050.6,7
- The average population density of the U.S. is 87 people per square mile. The average population density of metropolitan areas (MSA) is 281 people per square mile; in New York City, the population density is 27,012 people per square mile. Guttenberg, New Jersey has the greatest density of housing units (24,195) per square mile of land area.8

- One study found that low-density development has 2.5 times the greenhouse gas (GHG) emissions and twice the energy use of high-density development on an annual per capita basis; on a per unit living area basis, low-density development has 1.5 times the annual GHG emissions and the same energy use as the high-density development.8
- Sprawl, the spreading of a city and suburbs into surrounding rural land, reduces green space and increases traffic, air pollution, school crowding, and taxes.9
- According to Smart Growth America's Sprawl Index (based on development density, land use mix, activity centering and street accessibility), the most sprawling metropolitan regions of the 221 surveyed are Hickory-Lenoir-Morganton, NC, Atlanta-Sandy Springs-Marietta, GA, Clarksville, TN-KY, and Prescott, AZ. The least sprawling metropolitan areas include New York/White Plains/Wayne, NY-NJ, San Francisco/San Mateo/Redwood City, CA, Atlantic City/Hammonton, NJ, and Santa Barbara/Santa Maria/Goleta, CA.10

Built and Natural Environment

- Residential (20.0 Quadrillion Btu; “quads”) and commercial (18.0 quads) sectors accounted for 39% of total energy consumption and 36% (1,869 million metric tons of CO₂) of energy-related emissions in 2017.12
- The “urban heat island effect,” in which average annual temperatures are 1.8-5.4°F higher in cities than surrounding suburban and rural areas, results in increased energy demand, air pollution, GHG emissions, and heat-related illness, as well as decreased water quality.13
- Urban tree canopies decrease the urban heat island effect. The recommended average canopy cover is 40% for metropolitan areas east of the Mississippi and in the Pacific Northwest and 25% for metropolitan areas in the Southwest and West.14 According to one study’s photo-interpretation, canopy cover in urban areas in the continental U.S. is 35.1%.15
- In 2010, the number of days with Air Quality Index values greater than 100 ranged from 0 days in five cities to 116 days in the Riverside, CA area (on a 0-500 scale where 0 is best and 100 generally corresponds to U.S. air quality standards).16
- Out of 315 contaminants detected in a national tap water quality study, 86 were sprawl- and urban-related pollutants resulting from road runoff, lawn pesticides, and human waste, of which 16 are unregulated.17
- Vegetation and topsoil loss and the constructed drainage networks associated with urbanization alter natural hydrology.18
- Stormwater runoff from the built environment is a principal contributor to water quality impairment of water bodies nationwide.19
Transportation and Mobility

- In 2015, 58.65 billion passenger-miles (PM) were traveled on public transit, and 3 trillion vehicle-miles are traveled (VMT) on public roads each year.19,20
- There are 22 light rail systems in the U.S.19 From 2013 to 2014, light rail ridership increased 5% (483 million trips) after declining for several years; the value is still below the 2009 high.21 Without public transportation, the annual impacts in the U.S. would include an additional 102.2 billion VMT, 5.3 billion gallons of gas, and 17 million metric tons of CO₂ emissions.22
- Congestion is a serious problem in urban areas, causing an additional 6.9 billion hours of travel time and an extra 3.1 billion gallons of fuel use by urban Americans in 2014.23
- In 2015, transit buses used 81.5 trillion Btu and traveled 20.2 billion PM, and rail used 46.3 trillion Btu and traveled 39.1 billion PM. In comparison, passenger cars and trucks used 13,666 trillion Btu and traveled 4,307 billion PM.24
- New York City has the most utilized heavy rail, commuter rail, and bus systems in the U.S., Los Angeles has the most utilized light rail system, and San Francisco has the most utilized trolley bus system.25

Socioeconomic Patterns

- U.S. metro economies account for 90.8% of GDP, 91.3% of wage income, and 87.7% of jobs. Only 9 countries (including the U.S.) have a higher GDP than the New York City area.26
- The median household income inside MSAs is $61,521; outside MSAs it is $45,830.27 The average unemployment rate of metropolitan areas in May 2018 was 3.6%, ranging from a low of 1.5% in Ames, IA MSA to a high of 16.0% in Yuma, AZ MSA.28
- Poverty rates in urban areas are higher than in suburbs - 15.9% compared to 10.0% in suburbs in 2016.29

Solutions and Sustainable Alternatives

A sustainable urban area is characterized by the preservation of a quality environment, use of renewable and efficient energy resources, the maintenance of a healthy population with access to health services, and the presence of economic vitality, social equity, and engaged citizenry.29 An integrated approach to environmental management, measures to counter sprawl, the establishment of linkages among community, ecology, and economy, and coordinated stakeholder interaction are necessary for achieving sustainability in cities.30,31
- The San Jose-Sunnyvale-Santa Clara metro region in California placed first on SDG Index city ranking based on 49 indicators across 16 of the 17 SDGs.32
- As of July 2018, 1,060 mayors have signed on to the 2005 U.S. Mayors Climate Protection Agreement, committing to reduce carbon emissions below 1990 levels, in line with the Kyoto Protocol.32
- A Living Cities Report found that over 75% of the 40 largest U.S. cities surveyed have plans for reducing greenhouse gases and most call for emissions reductions of 10-20% in the next 5-10 years.33 Many cities, including New York, Los Angeles, and Chicago, have created Climate Action Plans, demonstrating environmental leadership and commitment to reducing climate change.34
- The EPA offers many clean energy programs, information, training opportunities, grants, resources, and tools to assist local governments.
- In 2009, the U.S. Department of Housing and Urban Development, Department of Transportation, and Environmental Protection Agency created the Partnership for Sustainable Communities to promote sustainable communities through better access to affordable housing, more transportation options, and lower transportation costs.30
- ICLEI (International Council for Local Environmental Initiatives), an international association of local governments and national and regional local government organizations, develops locally designed initiatives to achieve sustainability objectives.35
- Smart Growth America is a coalition working to improve the planning and building of towns, cities, and metro areas.36
- The Solar Outreach Partnership is a component of the U.S. Department of Energy’s SunShot Initiative to make solar energy cost-competitive with other energy technologies. The Solar Outreach Partnership provides local governments with guidance on community-wide deployment of solar power.37

35. ICLEI Global (2014) “Who is ICLEI.”

Residential Buildings

Patterns of Use

Although climate-specific, resource-efficient house design strategies exist, per capita material use and energy consumption in the residential sector continue to increase. From 2000 to 2010, the U.S. population increased by 9.7%, while the number of housing units increased by 13.6% and urban land area increased by 15%. The following trends demonstrate usage patterns in the residential building sector.

Size and Occupancy

- Increased average area of a new U.S. single-family house:2,3,4
  1950 983 ft²; 1970 1,500 ft²; 2000 2,265 ft²
  2017 2,599 ft², a 164% increase from 1950.
- Decreased average number of occupants per U.S. household:2,5
  1950 3.37; 1970 3.14; 2015 2.62
  2017 2.54, a 21% decrease from 1950.
- Increased average area per person in a new U.S. single-family house:2,3,5
  1950 292 ft²; 1970 478 ft²; 2000 840 ft²
  2017 1,023 ft², a 250% increase from 1950.
- A majority of Americans live in single-family houses. In 2013, 64% of the 116 million U.S. households were single family.6
- In 1950, 9% of housing units were occupied by only one person.7 By 2017, this value had increased to 28%.3

Energy Use

- A 1998 study by the Center for Sustainable Systems of a single-family house in Michigan showed an annual energy consumption of 1.3 GJ/m².9
- A study of 3 houses in Sweden built in the 1990s estimated annual energy consumption from 0.49–0.56 GJ/m², less than half the energy consumed by the Michigan house.10
- Electricity consumption increased 13-fold from 1950 to 2017. In 2017, the residential sector used 1.38 trillion kWh of electricity, 37% of U.S. total electricity sales.11
- In 2017, the U.S. residential sector consumed 20 quadrillion Btu of primary energy, 20% of U.S. primary energy consumption.12
- Miscellaneous load per household doubled from 1976 to 2006.13 In 2017, miscellaneous loads consumed more electricity than any other residential end use (lighting, HVAC, water heating, and refrigeration), accounting for 39.7% of primary energy and 42.3% of a household’s electricity consumption.14
- Wasteful energy uses include heating and cooling of unoccupied homes and rooms, inefficient appliances, thermostat oversetting, and standby power loss. Together, these uses represent about 39% of residential primary energy use.15
- Home energy management systems display energy use via in-home monitor or mobile application and enable remote control of devices. Home energy management systems can reduce a house’s energy use by an estimated 4-7%.16

Material Use

- The average U.S. single-family house built in 2000 required 19 tons of concrete, 13,837 board-feet of lumber, and 3,061 ft² of insulation.16
- From 1975 to 2000, the consumption of clay for housing and construction more than tripled, due to its use in tiles and bathroom fixtures.17
- In 2012, around 24% of all wood products consumed in the U.S. were used for residential construction.18
- Approximately 10 million tons of waste was generated in the construction of new residential buildings in 2003—4.4 lbs per ft².19
- U.S. average recycling rate of waste from construction and demolition (C&D) is 20–30%.20 Seattle recycled 57% of its C&D waste in 2015.21

Codes and Standards

- DOE Pacific Northwest National Laboratory estimated cumulative savings from the International Energy Conservation Code (IECC) for 42 states. From 2010–2016, the IECC saved 0.27 quadrillion Btu of primary energy, 1.4% of residential primary energy consumption in 2016.12,22
- Cumulative energy savings generated $3.2 billion (2016 dollars) in cost savings and avoided 17.6 million metric tons of CO2.22
- For most building types, conventional energy efficiency technologies can achieve a 20% reduction in energy use relative to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1-2004 standard.23
- Florida’s 2007 energy code saved 13% relative to pre-2007 energy consumption through the reduction in heating, cooling and hot water demand. Efficiency gains were offset by increasing house sizes and plug loads.24
- The U.S. Green Buildings Council provides Leadership in Energy and Environmental Design (LEED) home rating system and certification.27
- Houses built to Energy Star program requirements are 15% more energy efficient than houses built to 2009 IECC or better.28
Life Cycle Impacts

- Between 1990 and 2005, total residential GHG emissions increased by 30%. In 2016, GHG emissions were reduced to 999.6 million metric tons, only 5% up from 1990 level.\textsuperscript{20}
- In 1998, the Center for Sustainable Systems conducted an inventory of the life cycle energy consumption of a 2,450 square foot, single-family house built in Ann Arbor, Michigan.\textsuperscript{9}
- Only 10% of the house’s life cycle energy consumption was attributed to construction and maintenance; 90% occurred during operation.\textsuperscript{9}
- Energy efficiency measures reduced life-cycle energy consumption by 61%. Careful selection of materials reduced embodied energy by 4%.\textsuperscript{9}
- Life cycle greenhouse gas emissions were reduced from 1,013 to 374 metric tons CO$_2$-equivalent over the 50-year life of the house.\textsuperscript{9}
- Top contributors to primary energy consumption were polyamide for carpet, concrete in foundation, asphalt roofing shingles, and PVC for siding, window frames, and pipes.\textsuperscript{21} Improved HVAC system and cellulose insulation were the most effective strategies to reduce energy costs.\textsuperscript{9}
- Substituting recycled plastic/wood fiber shingles for asphalt shingle roofing reduced embodied energy by 98% over 50 years.\textsuperscript{9}
- A 900-ft$^2$ house in Davis, CA, modeled innovative design and technologies to reduce energy consumption. Measures such as LED lighting, efficient appliances, graywater heat recovery and a radiant heating and cooling system brought annual energy consumption to 5,854 kWh, 44% less than a standard house of the same size and location. Electricity generation from rooftop PV made the house energy net-positive.\textsuperscript{20}
- Operating energy accounts for 80–90% of a building’s life cycle energy consumption and embodied energy accounts for 10–20%. As houses improve energy efficiency and reduce operating phase energy, embodied energy accounts for a larger fraction of life cycle energy. Design and materials selection are key ways to reduce embodied energy.\textsuperscript{31}

Solutions and Sustainable Alternatives

Reduce Operational Demand

Energy and water consumption during the life of a building contribute more to its environmental impact than do building materials. The following suggestions can significantly reduce operational energy demand:

- **Downsizing:** build smaller to reduce embodied and operating energy.\textsuperscript{22} Tiny houses are designed for the efficient use of space.\textsuperscript{22}
- **Space heating and cooling make up 35% of residential energy consumption.**\textsuperscript{3} Passive heating and cooling can reduce operating energy.\textsuperscript{3}
- **By adding ceiling fans, air conditioning can be comfortably set about 4°F higher.**\textsuperscript{23}
- **Adequate insulation can reduce heating and cooling costs.** R-value needs differ based on location, building design, and heating methods.\textsuperscript{24}
- **Water heating accounts for 14% of residential energy consumption.**\textsuperscript{3} Save energy with a graywater heat recovery system.\textsuperscript{35}
- **Install low-flow water fixtures (less than 2.5 gallons-per-minute of flow) to save both water and energy.**\textsuperscript{26}
- **Maximize natural lighting with south-facing windows.** Properly shade windows to minimize summer heat gain.\textsuperscript{27}
- **Purchase energy efficient appliances and lighting.** Appliances and lighting typically account for 25% of household energy costs.\textsuperscript{28}
- **Replace incandescent lamps and halogen lamps with compact fluorescent lamps or LEDs in order to reduce energy costs and GHG emissions.**\textsuperscript{30}

Select Durable and Renewable Materials

Durable building materials last longer and require fewer replacements than flimsier alternatives. Depending on the materials, building with more durables could lower longterm replacement costs and associated environmental burdens.

- **Durables:** cork or hardwood floors, standing-seam roofing.
- **Renewables:** cork, linoleum, wool carpet, certified wood and plywood, strawboard, cellulose insulation, straw-bale.

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Cite as: Center for Sustainable Systems, University of Michigan. 2018. "Residential Buildings Factsheet." Pub. No. CSS01-08. August 2018
Commercial Buildings

Commercial buildings include, but are not limited to, stores, offices, schools, churches, gymnasiums, libraries, museums, hospitals, clinics, warehouses, and jails. The design, construction, operation, and demolition of commercial buildings impact natural resources, environmental quality, worker productivity, and community well-being.

Patterns of Use

- In the U.S., 5.6 million commercial buildings covered 87 billion square feet of floor space in 2012—an increase of 46% in number of buildings and 70% in floor space since 1979.\(^1\)\(^2\)
- By 2050, commercial building floor space is expected to reach 126.1 billion square feet, a 39% increase over 2017 levels.\(^3\)
- Education, mercantile, office, and warehouse/storage buildings comprise 60% of total commercial floor space and 50% of buildings.\(^1\)

Resource Consumption

Energy Use

- Commercial buildings consumed 18% of all energy in the U.S. in 2017.\(^4\)
- In 2010, the commercial sector consumed 18.3 quadrillion Btu of primary energy, a 73% increase from 1980.\(^5\)
- Lighting and indoor climate control consumed 51% of commercial sector primary energy in 2010.\(^5\)
- Operating phase energy represents 80-90% of a building’s life cycle energy consumption.\(^6\) In under 2.5 years of operation, a UM campus building with an estimated lifespan of 75 years consumed more energy than material production and construction combined.\(^7\)

Material Use

- Typical buildings contain concrete, metals, drywall, and asphalt. One demolished non-residential building was 82% concrete by weight.\(^8\)
- In 2011, the construction of new low-rise non-residential buildings in the U.S. consumed about 627 million board feet of lumber, accounting for approximately 1% of all lumber consumed in the U.S.\(^9\)

Water Consumption

- In 2005, the commercial sector used an estimated 10.2 billion gallons of water per day, an increase of 23% from 1990 levels.\(^5\)
- Domestic/restroom water is the largest end use in commercial buildings except in restaurants where 52% of the water is used for dishwashing or kitchen use.\(^10\)

Life Cycle Impacts

Construction and Demolition Waste

- In 2003, the EPA estimated that construction, renovation, and demolition of non-residential U.S. buildings generated 103 million tons of waste.\(^12\) This amounts to 1.94 lbs per capita per day, compared to the U.S. average of 4.48 lbs per capita per day of municipal solid waste.\(^12,13\)
- Approximately 40% of building waste was recovered for processing and recycling in 2007.\(^14\) Most frequently recovered and recycled were concrete, asphalt, metals, and wood.\(^15\)

Indoor Air Quality

- Volatile Organic Compounds (VOCs) are found in concentrations 2 to 5 times greater indoors than naturally occurs in the environment. Exposure to high concentrations of VOCs can result in eye, nose, and throat irritation; headaches, loss of coordination, and nausea; and extreme effects, such as cancer or nervous system damage. VOCs are emitted in commercial buildings through carpet adhesive, paints, solvents, aerosol sprays, cleansers, disinfectants, and dry-cleaned clothing.\(^16\)

Greenhouse Gas Emissions

- The combustion of fossil fuels to provide energy to commercial buildings emitted 886 million metric tons of carbon dioxide (CO\(_2\)) in 2017, approximately 17% of all U.S. CO\(_2\) emissions that year.\(^5\)
Solutions and Sustainable Alternatives

Opportunities

- An estimated 72% of current buildings are more than 20 years old and were built with little concern for energy savings. For typical commercial buildings, current energy efficiency measures can reduce energy consumption by 20-30% with no significant design alterations.
- NREL found that 62% of office buildings, or 47% of commercial floor space, can reach net-zero energy use by implementing current energy efficiency technologies and self-generation (solar PV). By redesigning all buildings to comply with current standards, implementing current energy efficiency measures, and outfitting buildings with solar panels, average energy use intensity can be reduced from 1020 to 139 MJ/m²-y, an 86% reduction in energy use intensity.
- Energy Star’s Portfolio Manager tracks energy and water consumption. The tool includes over 300,000 commercial buildings, and could serve as a national database to benchmark building performance and provide more transparency to building managers and tenants.
- Erosion and pollution from stormwater runoff can be mitigated by using porous materials for paved surfaces and native vegetation instead of high maintenance grass lawns. A typical city block generates more than 5 times more runoff than a woodland area of equal size.

Design Guidelines and Rating Systems

- The U.S. Green Buildings Council developed the Leadership in Energy and Environmental Design (LEED) rating system. LEED is an evaluation metric for overall building performance, assigning points for design attributes that reduce environmental burdens and energy use.
- The Better Buildings Alliance is an industry network focused on advancing commercial energy efficiency. Members that accept the Better Buildings Challenge commit to 20% energy savings over ten years.
- The U.S. EPA Energy Star buildings program recognizes and assists organizations that have committed to energy efficiency improvement.
- The Living Building Challenge, a building initiative by the International Living Future Institute, comprises seven performance areas, or ‘petals’: place, water, health and happiness, energy, materials, equity, and beauty.

Case Studies

- The Samuel Trask Dana Building, a 100-year-old structure located on University of Michigan’s Ann Arbor campus, was renovated in 2004 to improve energy and environmental performance. Design features include photovoltaic electricity generation, natural lighting, radiant cooling, composting restrooms, and selective materials use and reuse. The renovation attained a LEED Gold rating.
- The Center for Sustainable Landscapes (CSL), recognized by the American Institute of Architects (AIA) in their 2016 Commitment to the Environment Top Ten Projects, was the first building to meet these four green certifications: Living Building Challenge v1.3, LEED Platinum, SITES certification for landscapes, and WELL Building Platinum.
- Comparing the materials used in CSL to those of a conventional building reveals a 10% higher global warming potential and near equal embodied energy, due mainly to solar panels and inverters, concrete, steel, and gravel. Embodied energy savings come from 40% flyash replacement in cement and the use of recycled steel.
- The AIA awarded the Edith Green - Wendell Wyatt Federal Building in Portland, Oregon the 2016 Top Ten Plus winner. This 121,474 square foot building achieved a 55% reduction in energy consumption, a 65% reduction in water consumption, and improved occupant satisfaction.
- The Energy Star buildings program sponsors a “Battle of the Buildings” each year. The 2015 team winner, Energy Service Company (ESCO) Project at Texas A&M University, reduced average energy usage by 35% in six buildings, which saved $548,900 and avoided 1,726 metric tons of greenhouse gas emissions. The top building winner was Woodville Chapel, which reduced energy usage by 89%.

Green IT

Green Information Technologies (Green IT) reduce the environmental impacts associated with conventional Information Technologies (IT). Examples of Green IT include energy efficient hardware and data centers, server virtualization, and monitoring systems. Green IT focuses on mitigating the material and energy burdens associated with conventional IT while meeting our information and communication demands.1

Patterns of Use
- The number of personal computers in use worldwide surpassed 1 billion units in 2008.4
- Globally, more people have mobile phones than access to working toilets.5
- 174 million smartphones were sold globally in 2009. 1.4 billion were sold in 2015.6,7
- In 2012, 79% of U.S. households had a computer or a tablet, compared to 51% in 2000.8
- In 2005, laptops comprised 31% of primary household computers. In 2009, that rose to 44%.9,10 More than 14% of households used their primary computer for 10 or more hours per day in 2009.10
- In 2013, U.S. data centers consumed 91 billion kWh of electricity—2.4% of total electricity consumption—at a cost of $13 billion.2,3
- The peak power associated with servers and data centers in 2007 was 7 GW. Existing technologies and efficient design strategies can reduce server energy use by 25% or more, while best management practices and consolidating servers can reduce energy use by 20%.11
- Computers and office equipment consumed 253 billion kWh of electricity in 2012, 24% of the total electricity consumption of office buildings that year.11

Energy and Environmental Impact
- Electricity used for U.S. servers & data centers creates 103 billion lbs CO₂ annually.2,14
- Computer electricity consumption varies greatly with age, hardware, and user habits. An average desktop computer requires 48 W when idle and 2.3 W in sleep mode (285 kWh annually). Laptops require less power on average: 15 W when idle and 1.2 W in sleep mode (89 kWh annually).15
- A 17” light emitting diode (LED) LCD monitor uses about 13 W while on, 0.4 W in standby, and about 0.3 W when off.16
- Every kWh used by office equipment requires an additional 0.2-0.5 kWh of air conditioning.17
- The life cycle energy burden of a typical computer used for 3 years is 4.222 kWh. Only 34% of a computer’s life cycle energy consumption occurs in the 3-year use phase. Production dominates life cycle energy use due to the high energy costs of semiconductors and short use phase.18
- Manufacturing represents 60-85% of life cycle energy demand for a personal computer and 50-60% for mobile phones. Remanufacturing energy is a fraction of manufacturing energy: 5-30% for personal computers and 5% for mobile phones.18
- Some emerging technologies can reduce manufacturing burdens. Globally, 3D printing has the potential to reduce total primary energy use by 2.5-9.3 EJ and CO₂ emissions by 131-526 Mt by 2025.20

Electronic Waste
- In 2016, approximately 45 million metric tons of e-waste were generated worldwide only 20% were recycled properly.22
- U.S. federal hazardous waste regulations allow the export of e-waste, posing a global threat to human health.23,24 An estimated 5-30% of the 40 million computers used in the U.S. were exported to developing countries in 2010.26 In 2016, Basel Action Network found that 34% of the e-waste tracked by GPS trackers in the U.S. moved off shore, almost all to developing countries.26
- In 2010, the U.S. disposed of 52 million computers and 152 million mobile devices, 40% of computers and 11% of mobile devices are recycled.27
- The main constituents of printed circuit boards used in mobile electronics are polymers and copper, with trace amounts of precious metals Ag, Au, and Pb, and toxic metals As, Be, Cr and Pb.28
- One ton of printed circuit boards has a higher concentration of precious metals than one ton of mined ore.29

Paper Industry
- Paper production increased by 2.5% from 2012-2016 globally, but decreased by 4% in Northern America.30 Annual consumption of printing and writing paper is expected to rise from 199 to 274 million metric tons between 2006 and 2060.31
- The U.S. accounts for approximately 18% of global printing and writing paper consumption.30
- Depending on the process, producing one ton of paper consumes 12 to 24 trees.32
- In 2016, GHG emissions of the U.S. pulp and paper manufacturing industry were 37.7 million metric tons CO₂, approximately equivalent to the annual carbon sequestered by 44 million acres of US forests.33,34
Sustainable Alternatives

Technology

- Virtualization enables one physical server to run many independent programs and/or operating systems. This technology reduces the number of physical servers needed and promotes greater utilization of each server. With virtualization, each machine can run at 80% capacity rather than 10%. Virtualization reduces cost, material waste, electricity use, server sprawl, and cooling loads, saving money while reducing the environmental burdens of running a data center.
- Data center energy efficiency can be improved by utilizing combined heat and power systems. Heat recovered from electricity generation in the form of steam or hot water can be used by an on-site chiller to cool the data center.
- Multi-function office equipment can reduce energy consumption and waste. To save money and energy, Energy Star recommends choosing a machine that combines multiple functions, like printing and scanning, instead of purchasing two different machines.
- Video teleconferences can greatly reduce business travel impacts. One study found that a video conference requires 500 times less energy than a business trip including a 1,000 km (663 miles) flight. Telecommuting, in which employees work in distributed locations, is increasing in frequency. One study found full-time telecommuting could prevent 1,700 lbs of CO₂ emissions per employee per year.

Reduce Energy Consumption

- Office equipment energy consumption could be reduced by 23% if all office equipment had and utilized low-power mode. If all desktop computers and printers were turned off for the night, energy consumption would be further reduced by 9%. If every PC in the world were shut off for one night, the energy saved could light the Empire State Building for over 30 years.
- Energy Star certified server computers are, on average, 30% more energy efficient than standard servers. Replacing a conventional server with an Energy Star server could save up to 1000 kWh annually. If all servers sold in the U.S. met Energy Star standards, $800 million per year would be saved in energy use.
- Energy consumed by devices in standby mode accounts for 5-10% of residential energy use, adding up to $100 per year for the average American household. Unplug electronic devices when not in use, or plug them into a power strip and turn the power strip off. Turning off a computer when it is not in use can save $50, 500 kWh, and 571 lbs of CO₂ per computer annually.

Take Action

- Purchase Energy Star certified products, consolidate multiple devices into all-in-one equipment, and turn off devices when not in use.
- The EPA's Electronic Product Environmental Assessment Tool (EPEAT) rates the environmental impacts of computer products across multiple criteria, including energy efficiency, material toxicity, and recyclability.
- Responsible Recycling Practices (R2) and e-Stewards offer third-party certification for electronics recyclers to ensure the proper disposal of used electronics.

5. UN News Center (2013) Deputy UN chief calls for urgent action to tackle global sanitation crisis.
6. International Data Corporation (2013) "Android Rises, Symbian and Windows Phone? Launch as Worldwide Smartphone Shipments Increase 87.2% Year Over Year, According to IDC."
42. Alliance to Save Energy (2009) PC Energy Report, United States, United Kingdom, Germany.
Personal Transportation

In the U.S., the predominant mode of travel is by automobile and light truck, accounting for about 86% of passenger miles traveled in 2016.¹ The U.S. has less than 5% of the world’s population, but has 14% of the world’s cars, compared to 14.6% in China, 6.7% in Japan, 4.9% in Germany, and 4.4% in Russia.²³ The following consumption patterns indicate that the current transportation system is not sustainable.

Patterns of Use

Miles Traveled
• Total U.S. passenger miles traveled in 2016 was 4.58 trillion.¹
• U.S. population increased 30% from 1990 to 2016, while vehicle miles traveled increased 48% over the same time period.¹⁴⁵

Vehicles and Occupancy
• In 1977, the U.S. average vehicle occupancy was 1.87 persons per vehicle.⁶
• By 2015, average vehicle occupancy had decreased to 1.6 persons per vehicle.³
• In 2016, the U.S. had 269 million registered vehicles and 222 million licensed drivers.¹
• In 2009, 23% of U.S. households had three or more vehicles.⁷

Average Fuel Economy
• Light-duty vehicle fuel economy peaked at 22.0 miles per gallon (mpg) in 1987, declined until the early 2000s, then increased again, surpassing 22.0 mpg in 2009.⁸
• The average fuel economy for a light-duty 2017 model year vehicle was 25.2 mpg: 30.0 mpg average for a new passenger car and 22.2 mpg average for a new light truck.⁸
• Even when accounting for recent legislation, the U.S. has some of the lowest required fuel economy standards of any industrialized nation, well below the European Union, China, and Japan.⁹

Vehicle Size
• From 1988 to 2017, average vehicle weight increased 23% (due to growth in SUV market share), horsepower increased by 89%, and acceleration increased (i.e., 0-60 mph times dropped) by 38%.⁸
• The average weight of a passenger car increased 17% from 1988 to 2017, while the average weight of a pickup truck increased by 22%.⁸ Had vehicle weights remained at 1988 levels, model year 2010 cars could have achieved 12% higher fuel economy and trucks a 13% increase.¹⁰
• SUVs and pickups accounted for 50% of new vehicles sold in the U.S. in 2017.⁸

Energy Use
• The transportation sector makes up 29% of total U.S. energy use. From 1973-2017, the percentage of U.S. energy used in the transportation sector increased by 17%.³
• In 2015, American cars and light trucks used 15.1 Quadrillion Btus of energy, representing 15.5% of total U.S. energy consumption.²
• In 2017, 95% of total primary energy used by the transportation sector came from fossil fuels; 92% of total primary energy was from petroleum.¹¹
• The transportation sector accounted for 28.3% of U.S. greenhouse gas emissions in 2016—1,854 million metric tons CO₂e.¹²
• Passenger cars and light-duty trucks were responsible for 772 million metric tons CO₂e and 334 million metric tons CO₂e, respectively, together making up 60% of U.S. transportation emissions and 17% of total U.S. emissions.¹³
Life Cycle Impacts

A typical passenger car is responsible for the following burdens during its lifetime—raw material extraction through end-of-life. Most of these emissions are due to fuel use while driving.

<table>
<thead>
<tr>
<th>Environmental Flow</th>
<th>Lifetime (120,000 miles) Total (kg)</th>
<th>Per Mile (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>61,300</td>
<td>511*</td>
</tr>
<tr>
<td>CO</td>
<td>1,940</td>
<td>16</td>
</tr>
<tr>
<td>SO₂</td>
<td>137</td>
<td>1.1</td>
</tr>
<tr>
<td>NOₓ</td>
<td>256</td>
<td>2.1</td>
</tr>
<tr>
<td>NMHC</td>
<td>259</td>
<td>2.1</td>
</tr>
<tr>
<td>Methane</td>
<td>70</td>
<td>0.58</td>
</tr>
<tr>
<td>Solid Waste</td>
<td>4,380</td>
<td>36.5</td>
</tr>
<tr>
<td>Energy</td>
<td>995 GJ **</td>
<td>8.3 MJ **</td>
</tr>
</tbody>
</table>

* Equivalent to 1.1 lb CO₂/mile ** Equivalent to 163 barrels of oil

Solutions and Sustainable Alternatives

Reduce Vehicle Miles Traveled

- Live closer to work. The average commute was 12.2 miles in 2009 (up from 12.1 in 2001).³
- Consider telecommuting or working from home.
- In 2016, 76.6% of workers in the U.S. commuted by driving alone, and only 9.0% of workers carpooled (a drop from 19.7% in 1980).³ Joining a carpool can help lower household fuel costs, prevent greenhouse gas emissions, and reduce traffic congestion.
- Roughly one-fifth of vehicle trips are shopping-related. Combine errands (trip chaining) to avoid unnecessary driving.³
- Use alternative modes of transportation, such as bikes, buses, or trains. According to the Texas Transportation Institute, public transit saved Americans 865 million hours of travel time and 450 million gallons of gasoline in 2011 by reducing traffic congestion.¹⁴

Promote Fuel Efficiency

- Consider buying a vehicle that is best-in-class for fuel economy. Each year, the U.S. Environmental Protection Agency and Department of Energy jointly publish the Fuel Economy Guide, which ranks the most efficient vehicles in production.¹⁵
- Drive responsibly. Aggressive driving habits can lower fuel efficiency by 10% to 40%, and speeds over 50 mph significantly lower gas mileage.¹⁵
- Gallons per mile (gpm) is a better indicator of fuel efficiency than mpg. For example, upgrading from a 16 mpg to 20 mpg vehicle saves 125 gallons of fuel over 10,000 miles, whereas upgrading from a 34 to 50 mpg vehicle saves 94 gallons over 10,000 miles.¹⁷
- Improvements in information technology related to vehicles promise to reduce energy wasted from drivers stuck in traffic. Currently, about one-third of drivers stuck in traffic in major cities are looking for parking.¹⁸

Encourage Supportive Public Policy

- Dense, mixed-use communities encourage foot and bike traffic while reducing travel time between residences, businesses, and office spaces.
- In 2010, the U.S. EPA and National Highway Traffic Safety Administration (NHTSA) raised Corporate Average Fuel Economy (CAFE) standards to 34.1 miles per gallon by model year 2016. These standards are projected to save 1.8 billion gallons of fuel and prevent 960 million metric tons of CO₂ emissions.¹⁹
- In 2012, the Obama Administration finalized standards increasing fuel economy to 54.5 miles per gallon by model year 2025, a step projected to reduce U.S. oil consumption by 12 billion barrels and save consumers more than $1.7 trillion in fuel costs.²⁰

7. U.S. DOT, FHWA (2011) 2009 National Household Travel Survey.

Cite as: Center for Sustainable Systems, University of Michigan. 2018. “Personal Transportation Factsheet.” Pub. No. CSS01-07. August 2018
Autonomous Vehicles

Autonomous vehicles (AVs) use technology to partially or entirely replace the human driver in navigating a vehicle from an origin to a destination while avoiding road hazards and responding to traffic conditions. Given the broad spectrum of AVs, the National Highway Traffic Safety Administration (NHTSA) has developed a five-level classification scheme based on vehicle capabilities. The Society of Automotive Engineers (SAE) has developed a similar classification with six levels based on human intervention, separating Level 4 NHTSA into two levels.

Levels of Automation

The National Highway Traffic Safety Administration classifies AVs by level of automation:

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Vehicles equipped with no automated features, requiring the driver to be in complete control of the vehicle.</td>
</tr>
<tr>
<td>1</td>
<td>Vehicles equipped with one or more primary automated features such as cruise control.</td>
</tr>
<tr>
<td>2</td>
<td>Vehicles equipped with two or more primary features, such as adaptive cruise control and lane-keeping, that work together to relieve the driver from controlling those functions.</td>
</tr>
<tr>
<td>3</td>
<td>Vehicles equipped with features that allow the driver to relinquish control of the vehicle's safety-critical functions depending on traffic and environmental conditions. The driver is expected to take over control of the vehicle given the constraints of the automated features after an appropriately timed transition period. Google's experimental Lexus RX450h has level 3 automation.</td>
</tr>
<tr>
<td>4</td>
<td>Fully autonomous vehicles that monitor roadway conditions and perform safety-critical tasks throughout the duration of the trip with or without a driver present. This level of automation is appropriate for occupied and unoccupied trips.</td>
</tr>
</tbody>
</table>

Development of Autonomous Vehicles

AV research started in the 1980s when universities began working on two types of AVs: one that required roadway infrastructure and one that did not. The U.S. Defense Advanced Research Projects Agency (DARPA) has held “grand challenges” testing the performance of AVs on a 150-mile off-road course. No vehicles successfully finished the 2004 Grand Challenge, but five completed the course in 2005. In 2007, six teams finished the third DARPA challenge, which consisted of a 60-mile course navigating an urban environment obeying normal traffic laws.

Autonomous Vehicle Technologies

AVs use combinations of technologies and sensors to sense the roadway, other vehicles, and objects on and along the roadway. The key technologies and sensors are described in the figure to the right. Currently, there are no U.S. AV standards requiring specific technologies to be in place.

Current and Projected Market

Market Leaders

- Google has tested their vehicles in six U.S. states and driven in autonomous mode over 7 million miles since 2009 in 25 cities.9
- Tesla has accumulated over 1.2 billion miles in Autopilot mode since Oct. 2015.10
- Other major contributors include Audi, BMW, Daimler, GM, Nissan, Volvo, Bosch, Continental, Delphi Automotive, Mobileye, Valeo, Velodyne, Nvidia, Ford, as well as many other OEMs and technology companies.11,12

Regulations, Liability, and Projected Timeline

- Regulation will directly impact the adoption of AVs. Currently, there are no national standards or guidelines for AVs, allowing states to determine their own.13 As of July 2018, 29 states and D.C. have enacted AV legislation regarding the definition of AVs, permissible usage, and liability.14
- Product liability laws need to assign liability properly when AV crashes occur, as highlighted by the May 2016 Tesla Model S fatality. Liability will depend on multiple factors, especially whether the vehicle was being operated according to its level of automation.15,16
- Although many researchers, OEMs, and industry experts have different projected timelines for AV market penetration and full adoption, the majority predict NHTSA level 4 AVs around 2030.17,18

Current Limitations and Barriers

- There are several limitations and barriers that could impede adoption of AVs, including: the need for sufficient consumer demand, assurance of data security, protection against cyberattacks, regulations compatible with driverless operation, resolved liability laws, societal attitude and behavior change regarding distrust and subsequent resistance to AV use, and the development of economically viable AV technologies.19
- Weather can adversely affect sensor performance on AVs, potentially impeding adoption. Ford recognized this barrier and started conducting AV testing in the snow in 2016 at the University of Michigan’s Mcity testing facility, utilizing technologies suited for poor weather conditions.20
Impacts, Solutions, and Sustainability

Although AVs alone are unlikely to have significant direct impacts on energy consumption and GHG emissions, when AVs are effectively paired with other technologies and new transportation models, significant indirect and synergistic effects on economics, the environment, and society are possible.\textsuperscript{1,20} One study found that when eco-driving, platooning, intersection connectivity and faster highway speeds are considered as direct effects of connected and automated vehicles, energy use and GHG emissions can be reduced by 9%-21\%.

### Metrics and Associated Impacts

- **Congestion**: Congestion is predicted to decrease, reducing fuel consumption by 0%-4%. However, decreased congestion is likely to lead to increased vehicle-miles traveled (VMT), limiting the fuel consumption benefit.\textsuperscript{19}
- **Eco-Driving**: Eco-Driving, practices that typically reduce fuel consumption, is predicted to reduce energy consumption by up to 25%.\textsuperscript{21} However, if AV algorithms do not prioritize efficiency, fuel economy may decrease by 3%.\textsuperscript{22}
- **Platooning**: Platooning, a train of detached vehicles that collectively travel closely together, is expected to reduce energy consumption between 3%-25% depending on the number of vehicles, their separation, and characteristics.\textsuperscript{19}
- **De-emphasized Performance**: Vehicle performance, such as fast acceleration, is likely to become de-emphasized when comfort and productivity become travel priorities, potentially leading to a 5%-23% reduction in fuel consumption.\textsuperscript{19}
- **Improved Crash Avoidance**: Due to the increased safety features of AVs, crashes are less likely to occur, allowing for the reduction of vehicle weight and size, decreasing fuel consumption between 5%-23%.\textsuperscript{19}
- **Vehicle Right-Sizing**: The ability to match the utility of a vehicle to a given need. Vehicle right-sizing has the potential to decrease energy consumption between 21%-45%, though the full benefits are only likely when paired with a ride-sharing on-demand model.\textsuperscript{19}
- **Higher Highway Speeds**: Increased highway speeds are likely due to improved safety, increasing fuel consumption by 7%-30%.\textsuperscript{19,23}
- **Travel Cost Reduction**: AVs are predicted to reduce the cost of traveling due to decreased insurance cost and cost of time due to improvements in productivity and driving comfort. These benefits could result in increased travel potentially increasing energy consumption by 4% to 60%.\textsuperscript{19}
- **New User Groups**: AVs are likely to increase VMT, especially for elderly and disabled users. Fuel consumption is anticipated to increase between 2%-10% from new user groups.\textsuperscript{19}
- **Changed Mobility Services**: Ride-sharing on-demand business models are likely to utilize AVs due to the significant reduction of labor costs.\textsuperscript{24} The adoption of a ride-sharing model is estimated to reduce energy consumption by 0%-20%.\textsuperscript{19}
- **Although an accurate assessment of these interconnected impacts cannot currently be made, several scenarios have been projected. One study evaluated the potential impacts of four scenarios, each with unknown likelihoods. The most optimistic scenario projected a 40% decrease in total road transport energy and the most pessimistic scenario projected a 105% increase in total road transport energy.**\textsuperscript{19}

### Potential Benefits and Costs

- **In 2016, U.S. annual vehicular fatality rate was 37,461; 94% of crashes are due to human error. AVs have the potential to remove/reduce human error and decrease deaths.\textsuperscript{25,26}** Depending on adoption and vehicle characteristics, AVs have the potential to reduce crashes by 90%, potentially saving approximately $910 billion per year.\textsuperscript{27,28}
- **Potential benefits include improvements in safety and public health; increased productivity, quality of life, mobility, accessibility, and travel, especially for disabled and elderly; reduction of energy use, environmental impacts, congestion, and public and private costs associated with transportation; and increased adoption of car sharing.\textsuperscript{13,29,30}**
- **Potential costs include increased congestion, VMT, urban sprawl, total time spent traveling, and upfront costs of private car ownership leading to social equity issues; usage impact on other modes of transportation; and increased concern with security, safety, and public health.\textsuperscript{13,23,30}**

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6. Adapted from The Economist (2013) How does a self-driving car work?

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Greenhouse Gases

The Greenhouse Effect
The greenhouse effect is a natural phenomenon that insulates the Earth from the cold of space. As incoming solar radiation is absorbed and re-emitted back from the Earth’s surface as infrared energy, greenhouse gases (GHGs) in the atmosphere prevent some of this heat from escaping into space, instead reflecting the energy back to further warm the surface. Human activities that produce GHGs (anthropogenic) amplify the greenhouse effect. Anthropogenic GHG emissions are modifying the Earth’s energy balance between incoming solar radiation and the heat released back into space, resulting in climate change.

Greenhouse Gases
- There are ten primary GHGs; of these, water vapor (H₂O), carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are naturally occurring. Perfluorocarbons (CF₃, C₂F₆), hydrofluorocarbons (CHF₃, CFCH₂F, CH₂CHF₂), and sulfur hexafluoride (SF₆) are only present in the atmosphere due to industrial processes.
- Water vapor is the most abundant and dominant GHG in the atmosphere. Its concentration depends on temperature and other meteorological conditions, and not directly upon human activities.
- CO₂ is the primary anthropogenic greenhouse gas, accounting for 78% of the human contribution to the greenhouse effect in 2010.
- Global Warming Potentials (GWP) indicate the relative effectiveness of GHGs in trapping the Earth’s heat over a certain time horizon. CO₂ is typically used as the reference gas and has a GWP of one. For example, the 100-year GWP of SF₆ is 22,800, indicating that its radiative effect on a mass basis is 22,800 times as powerful as CO₂ over the same time horizon.
- GHG emissions are typically discussed in terms of mass of carbon equivalents or carbon dioxide equivalents (CO₂e), which are calculated by multiplying the mass of emissions by the GWP of the gas.

Atmospheric Greenhouse Gas Emissions
- From 10,000 years ago until 250 years ago, atmospheric concentrations of N₂O, CO₂, and CH₄ were relatively stable. During the last 250 years, concentrations of N₂O, CO₂, and CH₄ increased by 20%, 40% and 150%, respectively.
- Pre-Industrial Revolution, the concentration of CO₂ remained around 280 parts per million (ppm) by volume. In April 2018, the global monthly average concentration increased to 408.96 ppm, which is about 2.6 ppm higher than in April 2017.

Sources of Greenhouse Gas Emissions
- Anthropogenic CO₂ is emitted primarily from fossil fuel combustion. Iron and steel production, natural gas systems, and cement production are other significant sources of CO₂ emissions.
- The U.S. oil and gas industry emits 2.3% of its gross gas production, equivalent to 13 million metric tons of methane each year—nearly 60 percent higher than EPA reports.
- CH₄ and N₂O are emitted from both natural and anthropogenic sources. Domestic livestock, landfills, and natural gas systems are the primary anthropogenic sources of CH₄. Agricultural soil management (fertilizer) contributes 77% of anthropogenic N₂O. Other significant sources include mobile and stationary combustion, and livestock.
- Hydrofluorocarbons (HFCs) are now used in refrigeration, cooling, and as solvents in place of ozone-depleting chlorofluorocarbons (CFCs).
- Perfluorocarbons (PFCs) are used primarily for aluminum production, and SF₆ is used as an insulator in electricity distribution equipment.

Emissions and Trends
Global
- In 2010, total global anthropogenic GHG emissions were 49 Gt CO₂e. Since 1970, annual anthropogenic GHG emissions increased by 81%. GHG emissions increased by 1.0 Gt CO₂e per year from 2000 to 2010. For comparison, emissions averaged an increase of 0.4 Gt CO₂e per year from 1970-2000.
- Emissions from fossil fuel combustion account for a majority (65%) of global anthropogenic CO₂ emissions. In 2015, global emissions of CO₂ from energy use totaled 32.7 Gt CO₂.
- From 2000 to 2015, global CO₂ emissions from energy use increased 36%.
- Since 2006, China has been the world’s largest contributor of CO₂ emissions, surpassing the U.S.
United States
- The U.S. represents less than 5% of the world’s total population but was responsible for 15% of total anthropogenic GHG emissions in 2016.\(^9,10\)
- From 1990 to 2016, U.S. GHG emissions increased by 2.5%, at an average annual growth rate of 0.1%.\(^4\)
- Fossil fuel combustion is the largest source of U.S. GHGs, currently accounting for 76% of total emissions. Since 1990, fossil fuel consumption has grown at a rate of 0.4%. However, both GHG emissions and fossil fuel consumption have decreased since 2005 while GDP kept growing.\(^4\)
- CO\(_2\) emissions accounted for 82% of total U.S. GWP-weighted emissions in 2016 and were 3.7% higher than in 1990.\(^4\)
- The electric power industry accounts for about one-third of total U.S. GHGs.\(^4\)
- In 2016, the residential, commercial, and industrial sectors each used approximately a third of the electricity generated.\(^4\)
- Transportation is the largest contributor of U.S. GHG emissions, responsible for 28.5% of total emissions in 2016 (22% higher than the 1990 level). Passenger cars and light-duty trucks accounted for 772 and 334 million metric tons CO\(_2\)e, respectively, together making up 60% of U.S. transportation emissions and 17% of total U.S. emissions.\(^4\)
- Urban sprawl, increased travel demand, and an increase in the number of vehicles are driving the growth of transportation GHG emissions.\(^4\)
- Land use and forestry in the U.S. sequester a portion of CO\(_2\), removing 11% of the GHGs emitted by the U.S. in 2016.\(^4\)
- As a result of 2008 federal legislation, sources that emit over 25,000 metric tons CO\(_2\)e in the U.S. are required to report emissions to the U.S. Environmental Protection Agency (EPA).\(^1^9\)

**Emissions by Activity**

- Use of a 100W light bulb for 10 hours: \(1.05\) lbs CO\(_2\)\(e\)\(^1^3\)
- 1 mile driven in a car (29.1 mpg): 0.67 lbs CO\(_2\)\(e\)\(^1^4\)
- 1 mile driven in a light-duty vehicle (21.2 mpg): 0.93 lbs CO\(_2\)\(e\)\(^1^4\)

**Future Scenarios and Targets**
- Stabilizing atmospheric CO\(_2\) concentration requires more than just slowing the growth rate of emissions; it requires absolute emissions reduction.\(^2^6\)
- Based on current climate regulations, global energy-related CO\(_2\) emissions are anticipated to increase by 26% from 2015 to 2050.\(^1^6\)
- Non-OECD countries’ CO\(_2\) emissions are expected to increase by 1.4% annually, significantly faster than OECD countries at 0.4% annually. Despite these increases, OECD countries will have per capita emissions 2.5 times higher than non-OECD countries in 2050.\(^1^0\)
- Under the Kyoto Protocol, developed countries agreed to reduce their GHG emissions on average by 7% below 1990 levels by 2012. Had the U.S. ratified the Kyoto Protocol, its reduction requirement would have been to reduce its emissions by 7%.\(^7\)
- When the first commitment period ended in 2012, the Protocol was amended for a second commitment period; the new overall reduction target would be 88% below 1990 levels by 2020.\(^1^0\)
- Global CO\(_2\) emissions must be reduced by 50-85% below 2000 levels by 2050 in order to stabilize the average CO\(_2\) concentration below 400 ppm.\(^1^0\)

\[1\text{ Teragram (Tg) = 1000 Giga grams (Gg) = 1 million metric tons = 0.001 Giga tons (Gt) = 2.2 billion pounds (lbs)}\]

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17. UN Environment Programme (UNEP) and UN Framework Convention on Climate Change (UNFCCC) (2008) Climate Change Information Kit.
Climate Change: Science and Impacts

The Earth’s Climate
Climate change is altering temperature, precipitation, and sea levels, and will adversely impact humans and natural systems, including water resources, human health, human settlements, ecosystems, and biodiversity. The unprecedented acceleration of climate change over the last 50 years and the increasing confidence in global climate models add to the compelling evidence that climate is being affected by greenhouse gas (GHG) emissions from human activities. Changes in climate should not be confused with changes in weather. Weather is observed at a particular location on a time scale of hours or days, and exhibits a high degree of variability, whereas climate is the long-term average of short-term weather patterns, such as the annual average temperature or rainfall at a given location. Under a stable climate, there is an energy balance between incoming solar radiation (short wave) and outgoing infrared radiation (long wave). Solar radiation passes through the atmosphere and most is absorbed by the Earth’s surface. The surface then re-emits some energy as infrared radiation, a portion of which radiates into space. Increases in the concentrations of greenhouse gases in the atmosphere reduce the efficiency with which the Earth’s surface radiates energy to space, thus warming the planet.

Climate Forcings
• Any disturbance of the Earth’s balance of incoming and outgoing energy is referred to as a positive or a negative climate forcing. Positive forcings, such as GHGs, exert a warming influence on the Earth, while negative forcings, such as sulfate aerosols, exert a cooling influence.
• Increased concentrations of GHGs from anthropogenic sources have increased the absorption and emission of infrared radiation, enhancing the natural greenhouse effect. Methane and other GHGs are more potent, but CO$_2$ contributes most to warming because of its prevalence.
• Anthropogenic GHG emissions, to date, amount to a climate forcing roughly equal to 1% of the net incoming solar energy, or the energy equivalent of burning 13 million barrels of oil every minute.

Climate Feedbacks and Inertia
• Climate change is also affected by the Earth’s responses to forcings, known as climate feedbacks. For example, the increase in water vapor that occurs with warming increases the climate’s sensitivity to CO$_2$ by a factor of two.
• The depth of the ocean creates a large thermal inertia that slows the response of climate change to forcings; energy balance changes result in delayed climate response with high momentum.
• As polar ice melts, less sunlight is reflected and the oceans absorb even more heat.
• Due to global warming, large reserves of organic matter frozen in subarctic permafrost will thaw and decay, releasing additional CO$_2$ and methane to the atmosphere.
• If GHG emissions were completely eliminated today, climate change impacts would still continue for centuries. The Earth’s temperature requires 25 to 50 years to reach 60% of its equilibrium response.
• Today’s emissions will affect future generations; CO$_2$ persists in the atmosphere for hundreds of years.

Human Influence on Climate
• Separately, neither natural forcings (i.e., volcanic activity and solar variation) nor anthropogenic forcings (i.e., GHGs and aerosols) can fully explain the warming experienced since 1850.
• Climate models most closely match the observed temperature trend only when the effects of natural and anthropogenic forcings are considered together.
• In 2013, the Intergovernmental Panel on Climate Change (IPCC) concluded that: “It is extremely likely (>95% certainty) that human influence has been the dominant cause of the observed warming since the mid-20th century.”
Observed Impacts

Physical Systems

- Average surface temperatures have risen at least 0.8-1.4°C (1.4-2.5°F) since the mid 1800s.13
- 2016 was the warmest year on record since records began in 1880. 2016 global average ocean temperatures also experienced a record high. The year 2017 was the third warmest year on record, the warmest year without an El Niño present in the tropical Pacific Ocean, and also marks the 41th consecutive year that annual global temperatures were above average.13
- During the 20th century, winter temperatures in Alaska and western Canada increased by 3.4-7.2°F, and Arctic sea-ice thickness declined by about 40% during the late summer and early autumn in the last three decades.14 In 2017, the annual Arctic sea ice extent averaged 4.01 million square miles, which was the second smallest annual ice extent on record.15
- U.S. average annual precipitation has increased by 7% over the past 50 years. Most of the increase has come in the form of fewer, more extreme precipitation events, with 20% more rainfall in the heaviest events.2
- In the 20th century, global mean sea level rose between 17 and 21 cm, after having been quite stable over the previous several thousand years.3
- Snow cover has noticeably decreased in the Northern Hemisphere. From 1967-2012, snow cover extent very likely decreased by 53% in June, and around 7% in March and April.6

Biological Systems

- Warming that has already occurred is affecting the biological timing (phenology) and geographic range of plant and animal communities.17 Relationships such as predator-prey interactions are affected by these shifts, especially when changes do not occur evenly among species.18
- Since the start of the 20th century, the average growing season in the U.S. has lengthened by nearly two weeks.19

Predicted Changes

Increased Temperature

- Between now and 2035, the IPCC predicts that the temperature will rise between 0.3-0.7°C (0.5-1.3°F). In the long term, global mean surface temperatures are predicted to rise 0.4-2.6°C (0.7-4.7°F) from 2045-2065 and 0.3-4.8°C (0.5-8.6°F) from 2081-2100, relative to the reference period of 1986-2005. In the past, a change of 5°C (9°F) most often occurred over thousands of years.6
- A warming planet does not simply result in higher average daytime temperatures. The frequency of very hot days increases, while the frequency of very cold days decreases.6

Ocean Impacts

- By 2100, the average sea level is anticipated to rise between 26 and 82 cm. The rise will be a result of thermal expansion from warming oceans and additional water added to the oceans by melting glaciers and ice sheets.7
- The oceans absorb about 27% of anthropogenic CO₂ emissions, resulting in increased acidity. Even under conservative projections, coral reefs will be severely impacted.20

Implications for Human and Natural Systems

- Impacts of climate change will vary regionally but are very likely to impose costs which will increase as global temperatures increase.9
- This century, an unprecedented combination of climate change, associated disturbances, and other global change drivers will likely exceed many ecosystems’ capacities for resilience.25 Species extinction, food insecurity, human activity constraints, and limited adaptability are risks associated with warming at or above predicted temperatures for the year 2100 (4°C or 7°F above pre-industrial levels).9
- With an increase in average global temperatures of 2°C, nearly every summer would be warmer than the hottest 5% of recent summers,22
- A 2-foot rise in sea level would cause relative increases of 2.3 feet in New York City and 3.5 feet in Galveston, TX.2
- Increased temperatures and changes in precipitation and climate variability would alter the geographic ranges and seasonality of diseases spread by organisms like mosquitoes.22
- Although higher CO₂ concentrations and slight temperature increases can boost crop yields, the negative effects of warming on plant health and soil moisture lead to lower yields at higher temperatures. Intensified soil and water resource degradation resulting from changes in temperature and precipitation will further stress agriculture in certain regions.22

1. Adapted from image by W. Elder, National Park Service.
5. CSS calculation based on data from UNEP and UN Framework Convention on Climate Change (UNFCCC) (2008) Climate Change Information Kit.
16. Photo courtesy of the National Snow and Ice Data Center/World Data Center for Glaciology.
Climate Change: Policy and Mitigation

The Challenge
Climate change is a global problem that will require global cooperation to address. The objective of the United Nations Framework Convention on Climate Change (UNFCCC), which virtually all nations, including the U.S., have ratified, is to stabilize greenhouse gas (GHG) concentrations at a level that will not cause “dangerous anthropogenic (human-induced) interference with the climate system.”

Due to the persistence of the increased concentrations of GHGs, significant emissions reductions must be achieved in coming decades to meet the UNFCCC objective. Unrestricted growth in global emissions is projected to lead to a 5% increase in CO$_2$ concentration levels from 2011 to 2030 and between a 74-202% increase by 2100. Stabilizing CO$_2$ at 450 parts per million (ppm) in the atmosphere by the year 2100 (which will likely keep temperature change below 2°C relative to pre-industrial levels) will require lowering global CO$_2$ emissions in 2050 by 40-70% compared to 2010, and will require emissions levels near zero GtCO$_2$e in 2100. Stabilization at 500 ppm, almost double the pre-industrial concentration, could be achieved by holding GHG emissions constant for 50 years and then reducing emissions by two-thirds over the following 50 years. In 2016, U.S. GHG emissions were 6.5 GtCO$_2$e.

General Policies

Market-Based Instruments
- Market-based approaches include carbon taxes, subsidies, cap-and-trade programs, and emissions standards.
- In a tradable carbon permit system, permits equal to an allowed level of emissions are distributed to each party. Parties with emissions below their allowance are able to sell their excess permits to other parties that have exceeded their emissions allowance.
- Market-based instruments are recognized for their potential to cost-effectively reduce emissions by allowing for flexibility and ingenuity in the private sector.

Regulatory Instruments
- Regulatory approaches include non-tradable permits, technology and performance standards, product bans, and government investment.
- In 2007, the U.S. Supreme Court ruled that the Environmental Protection Agency (EPA) can regulate CO$_2$ emissions from mobile sources under the Clean Air Act. In 2012, after several appeals, the U.S. Court of Appeals upheld the original ruling.
- In the U.S., Corporate Average Fuel Economy (CAFE) standards for vehicles, administered by the National Highway Traffic Safety Administration (NHTSA), are intended to decrease carbon emissions by reducing gasoline consumption. In 2012, the EPA and the NHTSA finalized CAFE and EPA GHG emission standards requiring new vehicles to meet an average emissions level of 163 grams of CO$_2$ per mile, or 54.5 miles per gallon, by model year 2025.

Voluntary Agreements
- Voluntary agreements take many forms, but, in general, are an agreement between a government agency and one or more private parties to “achieve environmental objectives or to improve environmental performance beyond compliance.”
- The EPA partners with the public and private sectors to oversee a variety of voluntary initiatives, including GHG emissions reductions, clean energy, and climate change adaptation.

The Kyoto Protocol
The Kyoto Protocol came into force on February 16, 2005. The Protocol established mandatory, enforceable targets for GHG emissions. Initial emissions reductions for participating countries ranged from –8% to +10% of 1990 levels, while the overall reduction goal was 5% below the 1990 level from 2008 to 2012. When the first commitment period ended in 2012, the Protocol was amended for a second commitment period; the new overall reduction goal would be 18% below 1990 levels by 2020.
- The Protocol is based on three GHG emission reduction mechanisms: Joint Implementation (JI), Clean Development Mechanism (CDM), and International Emissions Trading.

The Paris Agreement
In December of 2015, all Parties of the UNFCCC reached a climate change mitigation and adaptation agreement, called The Paris Agreement, in order to keep global temperatures below a 2°C increase above pre-industrial temperatures. The agreement will be enforced 30 days after 55 countries ratify the agreement. The 55 countries must account for at least 55% of the global emissions.
- The Paris Agreement entered into force on November 4, 2016. As of July 24, 2018, The Paris Agreement had 197 signatories of which 179 parties have ratified the agreement accounting for 55% of global emissions.
Government Action in the U.S.

Federal Policy

- According to the U.S. Senate, “…Congress should enact a comprehensive and effective national program of mandatory, market-based limits and incentives on emissions of greenhouse gases that slow, stop, and reverse the growth of such emissions at a rate and in a manner that will not significantly harm the United States economy and will encourage comparable action by other nations…”
- In 2015, the Clean Power Plan was proposed that sets a national limit for CO₂ emissions from power plants. On February 9, 2016, the plan was stayed by the Supreme Court due to several lawsuits against it. In October 2017, the EPA proposed to repeal the Clean Power Plan.
- Due to the Consolidated Appropriations Act of 2008, large emitters of GHGs in the U.S. must report emissions to the EPA.

State Policy

- Climate change action plans have been enacted by 34 states and D.C.
- Twenty states and D.C. have greenhouse gas emission reduction targets. For example, California has established targets to reduce emissions to 1990 levels by 2020 and 80% below 1990 levels by 2050.
- Twenty-nine states, D.C., and three U.S. territories have Renewable Portfolio Standards, which specify that a certain percentage of electricity be generated from renewable sources by a certain date.

Mitigation Strategies

Stabilizing atmosphere CO₂ concentrations cannot be accomplished without significant changes in energy production and use. Effective mitigation cannot be achieved without individual agencies working collectively towards reduction goals. Stabilization wedges are one method of illustrating GHG reduction strategies; each wedge represents 1 billion tons of carbon avoided per year over 50 years.

- **Energy Savings:** Many energy efficiency efforts require an initial capital investment, but the payback period is often only a few years. In 2009, the Washington Suburban Sanitary Commission entered a 10-year agreement to purchase 28% of their electricity from a local wind energy provider, saving $1.2 million over the first four years.
- **Fuel Switching:** Switching power plants and vehicles to less carbon-intensive fuels can achieve emission reductions in the short-term. For instance, switching from an average coal plant to a natural gas combined cycle (NGCC) plant can reduce CO₂ emissions by approximately 50%.
- **Capturing and Storing Emissions:** CO₂ can be captured from large point sources during both pre- and post-combustion of fossil fuels. Once CO₂ is separated, it can be stored underground. Alternatively through climate intervention strategies, existing CO₂ can be removed from the atmosphere through various Carbon Dioxide Removal (CDR) technologies and methodologies such as direct air capture and sequestration, bioenergy with carbon capture and sequestration, land management strategies, as well as many other methods.

**Individual Action**

- In the U.S., residential homes and personal vehicles are responsible for 32% of total GHG emissions. There are many actions that individuals can take to reduce their daily GHG emissions; many involve energy conservation and can also save money.
- Choose a fuel-efficient vehicle and keep your car well maintained, including properly inflated tires.
- Decrease the amount you drive by using public transportation, walking, riding a bike, telecommuting, or living closer to your work. Leaving your car at home for two days a week can prevent 4,000 lbs of CO₂ emissions per year.
- Curb aggressive driving habits. During highway driving, aggressive acceleration lowers gas mileage by 10%-40% over smooth acceleration.
- Ask your energy supplier about options for purchasing energy from renewable sources.
- When purchasing appliances, look for the Energy Star label and choose the most energy efficient model.
- Energy Star qualified light bulbs use 70-90% less energy than a typical incandescent bulb and last 10-25 times longer.
- Turn off lights and appliances when they are not in use.
- Space heating is the largest user of household energy (24%). Ensure that your home is properly sealed by reducing air leaks, installing the recommended level of insulation, and choosing Energy Star qualified windows.

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13. UNFCCC (2016) Summary of the Paris Agreement.
