2023 COLLECTION

SUSTAINABILITY *factsheets*

CONSUMPTION PATTERNS, IMPACTS & SOLUTIONS

CENTER FOR SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

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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 32 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 an 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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Note on Units

The CSS Factsheets use a wide variety of data sources from around the world. We usually present data in the same units as in the source documents, but we strive to adhere to SI notation for units and order of magnitude prefixes. A common point of confusion occurs in mass units, between the metric ton (or tonne = 1000 kg) and the short ton (2000 lb). In the CSS Factsheets, we use the abbreviation 't' for metric ton (Mt for million metric tons) and 'ton' for short ton.

About the Center for Sustainable Systems

The Center for Sustainable Systems (CSS) was established in March 1999 in the School for Environment and Sustainabilty (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 32 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.

2006 Michigan at a Climate Crossroads report presents the impacts of ten strategies for reducing greenhouse gas emissions to the Michigan State Legislature and Office of the Governor.

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).

2021 30th anniversary of the Center.

CENTER FOR SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

factsheets
Sustainability Indicators

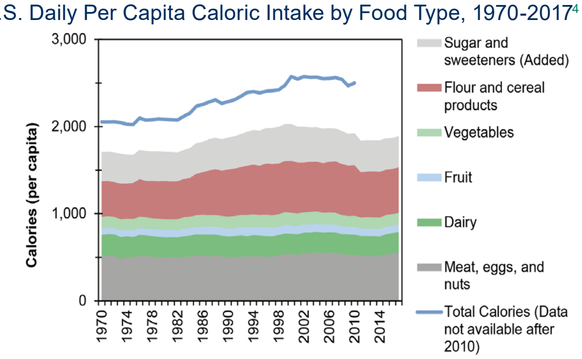
U.S. Environmental Footprint

The U.S. population is expected to grow from 333 million in 2022 to 404 million by 2060.[1,2] 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 just over 5 Earths to support the human population if everyone's consumption patterns were similar to the average American.[3] 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 2,054 in 1970 to 2,501 in 2010.[4]
- In 2003, the average American consumed 46 gallons of soft drinks, a 330% increase since 1947.[5] Between 1970 and 2021, per capita milk consumption decreased 51%, to 10.6 gallons per year.[6]
- The average American consumes about 356 calories of added sugars and sweeteners per day. The American Heart Association recommends limiting added sugars to between 100 and 150 calories daily for an average adult.[4,7]
- U.S. per capita consumption of added fats increased by 66% from 1970 to 2010.[4]
- Approximately 41% of U.S. adults and over 20% of adolescents age 12-19 are obese (BMI > 30).[8]
- In the U.S. between 30-40% of food is wasted. Food waste is the most commonly landfilled and incinerated material in the U.S.[9] The average American wastes 50% more food than in 1970.[10] This waste accounts for roughly 22% of the municipal solid waste stream and represents a loss of $450 per person each year.[10,11]

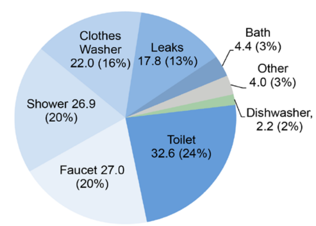
U.S. Daily Per Capita Caloric Intake by Food Type, 1970-2017[4]



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%).[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.[12] Over 50% of water withdrawals occur in 12 states, 9% in California.[12]
- The average North American household uses roughly 240 gallons of water daily for indoor and outdoor uses.[13]
- Households with more efficient fixtures and no leaks can drop their water usage to 40 gallons per person per day.[13]

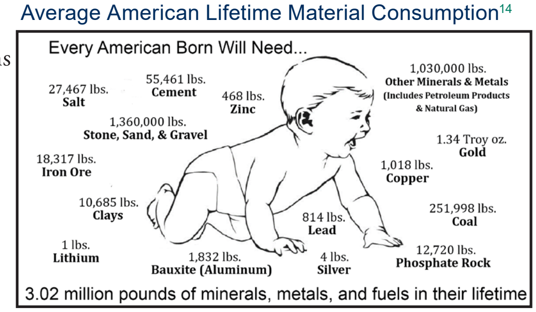
North American Household Water Use[13]
Gallons Per Household Per Day



Material Use and Waste Management

- In 2000, per capita consumption of all materials in the United States was 23.7 metric tons (t), 52% more than the European average.[15]
- In 1900, raw material consumption was less than 2 t per person. At its peak in 2006, it had grown to over 13 t per person.[16,17]
- In 2018, the average American generated 4.9 lbs of municipal solid waste (MSW) each day, with only 1.6 lbs recovered for recycling or composting.[11] For comparison, MSW generation rates (lbs/person/day) were 2.20 in Sweden, 2.98 in the U.K., and 3.71 in Germany.[18]
- In 2018, 32.1% of U.S. MSW was recovered for recycling or composting, diverting 94 million U.S. short tons of material from landfills and incinerators—more than double the value from 1990.[11]
- Only 53% of Americans are automatically enrolled in curbside recycling programs. In 2016, 82% of cities with curbside recycling collect material single-stream, meaning materials such as glass and paper are separated at the recycling plant.[19,20]

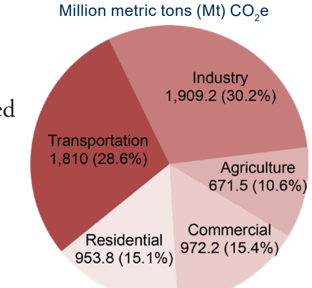
Average American Lifetime Material Consumption[14]



Greenhouse Gases (GHG)

- In 2021, U.S. GHG emissions were 19 t CO2e per person.[21,22]
- From 1990-2019, total annual U.S. GHG emissions increased by 2%. In 2020, due to the COVID-19 pandemic, emissions fell by 9%. In 2021, total annual U.S. GHG emissions increased by 5%, but still remained below 1990 levels. Emissions from electricity generation, 25% of the U.S. total, are included by sector in the figure (at right).[21]
- In 2023, the Intergovernmental Panel on Climate Change (IPCC) concluded that: "human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020."[23]
- 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.

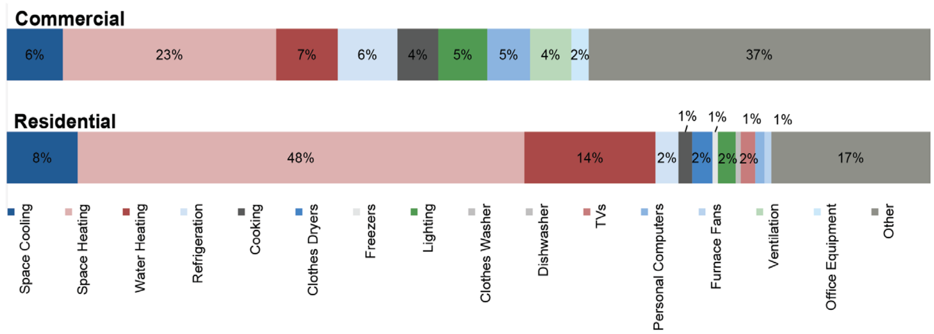
U.S. GHG Emissions, 2021[21]
Million metric tons (Mt) CO_2e



Residential and Commercial Buildings

- Since the 1970s, average residential living trends in the U.S. have been towards bigger houses with fewer occupants:
  - U.S. house size increased 21.4%[24]
  - Number of occupants per house decreased 14%[25]
  - Living space per person increased 41%.[24,25]
- 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 19% from 115,000 Btu/sqft in 1979 to 96,500 Btu/sqft in 2022.[1,26]
- The amount of developed U.S. land increased by 61% from 1982 to 2017, making up 6% of total U.S. surface area in 2017.[27]

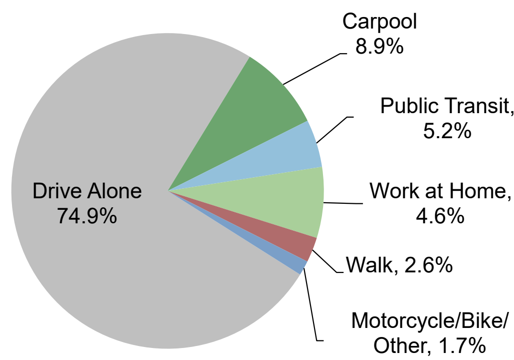
Commerical and Residential Buildings Primary Energy Distribution, 2022[1]



Transportation

- In 2021, the U.S. had 282.4 million vehicles, 49.6 million more than licensed drivers.[28]
- Drivers traveled over 3.1 trillion vehicle-miles in the U.S. in 2021, more than double the amount traveled in 1980.[28] This is equivalent to more than 6 million round-trips to the moon.[29]
- Compared to 1990 models, the average 2022 vehicle's weight increased by 26%, horsepower increased by 101%, and acceleration increased (i.e., 0-60 mph times dropped) by 35%.[30]
- Fuel economy surpassed 1988 levels in 2009 after years of decline.[31]
- The average vehicle occupancy for a passenger car is 1.5, compared to 7.5 for a transit bus and 26.1 for a train.[32]
- Congestion is a worsening urban problem, causing an additional 8.7 billion hours of travel time, 3.5 billion gallons of fuel use, and 68.6 billion pounds of CO_2 emissions by urban Americans in 2019.[33]

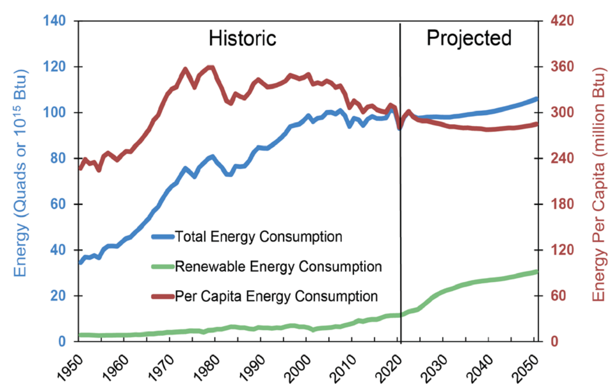
U.S. Modes of Transportation to Work in 2020[33]



Energy

- In 2021, the U.S. spent $1.3 trillion on energy ($3,954 per person), equal to 5.7% of GDP.[35]
- More U.S. energy comes from petroleum than any other source, comprising nearly 35% of consumption.[34]
- Daily U.S. per capita energy consumption includes 2.56 gallons of oil, 8.43 pounds of coal, and 266 cubic feet of natural gas. Residential daily electricity consumption is 12.5 kilowatt-hours (kWh) per person.[1,34]
- With less than 5% of the world's population, the U.S. consumes 16% of the world's energy and accounts for 16% of world GDP. In comparison, the European Union has 6% of the world's population, uses 10% of the world's energy, and accounts for 15% of world GDP; China has 18% of the world's population, consumes 27% of the world's energy, and accounts for 19% of world GDP.[36,37]

U.S. Energy Consumption: Historic and Projected[1,34]



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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "U.S. Environmental Footprint Factsheet." Pub. No. CSS08-08. **August 2023**

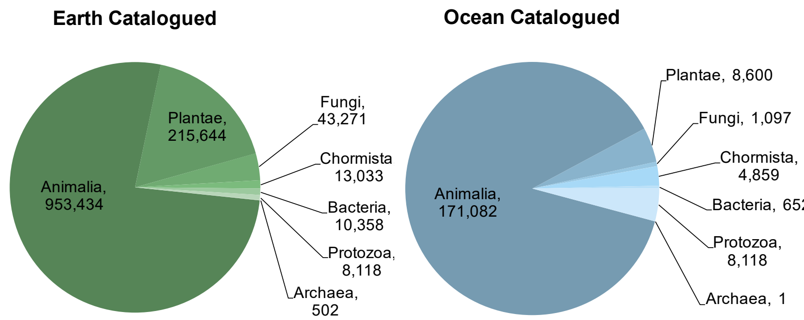
Biodiversity

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, resilience, social relations, and health.[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]
- Of the estimated 8.7 million eukaryotic species (complex cells) on Earth, 86% of land species and 91% of ocean species have not yet been described.[5]
- 1.2 million species have been described globally.[5]
- 55,742 plant and animal species are listed in the U.S.[6]
- 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.[7]
- One study suggests that while tropical reefs have more diverse fish communities, it is polar waters that are hotspots of fish speciation (formation of distinct new species) — contrary to much of the previous thinking about evolution.[8]

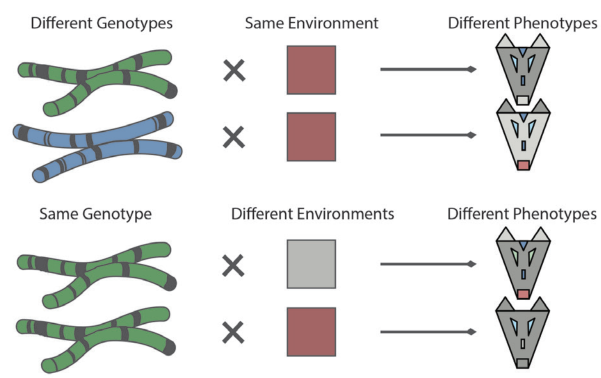
Catalogued Earth and Ocean Species[5]



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 each form (an allele) 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.[3]

Genotype vs. Phenotype[3]



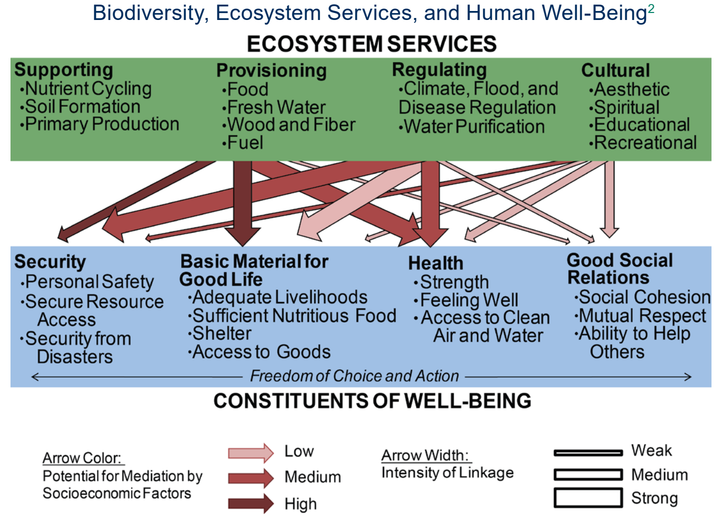
Community/Ecosystem Diversity

- Ecosystem diversity describes the variety of biological communities and their associations with the ecosystem of which they are part.[3]
- Within 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 for a species, its population size becomes restricted.[3]

Goods & Services

- Ecosystem services are the conditions and processes that enable natural ecosystems to sustain human life.[9]
- 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.[9]
- Biodiversity improves 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.[10]
- These services provide us with food, natural fibers, timber, biomass fuels, crop pollination, medicines, psychological health, and more.[11]

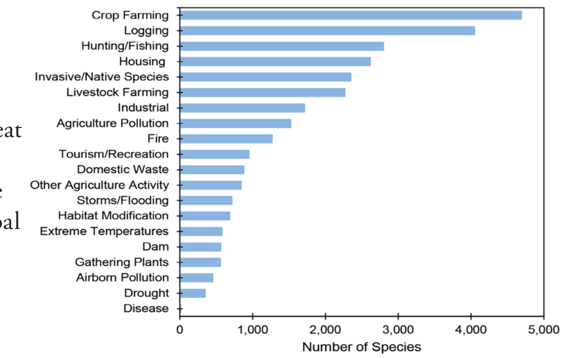
Biodiversity, Ecosystem Services, and Human Well-Being[2]



Loss of Biodiversity

- Since 1955, alteration of biodiversity related to human activities was greater than at any time in human history, driven by habitat loss from agriculture and infrastructure, over-exploitation, pollution, invasive species, and climate change.[2,11]
- Climate change is likely to become the largest threat to biodiversity, in part because it affects areas uninhabited by humans.[11] Impacts on some ecosystems are approaching irreversibility; heat extremes and mass mortality events have resulted in the local loss of hundreds of species.[14]
- Higher temperatures could increase drying, resulting in dieback in the Amazon, which has the highest biodiversity of all forests.[15] Habitat loss increases greenhouse gas emissions; 11% of global emissions result from deforestation and forest degradation.[16]
- Over-fishing and harvesting also contribute to a loss of genetic diversity and relative species abundance of individuals and groups.[17]

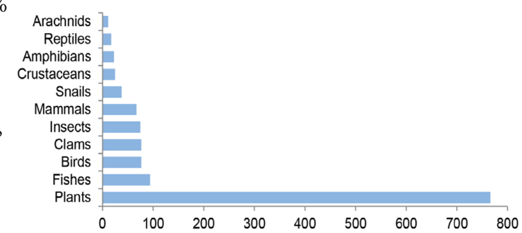
Major Risks to Threatened or Near-Threatened Species[12]



Biodiversity Loss Due to Agriculture

- Seven agricultural commodities (cattle, oil palm, soy, cocoa, rubber, coffee, wood fiber) accounted for 26% of global tree cover lost from 2001-2015, replacing 71.9 Mha of forest.[18]
- Of the 30 mammalian and bird species used extensively for agriculture, half account for over 90% of global livestock production.[19]
- Genetic diversity within breeds is declining, and 24% of 8,803 livestock breeds identified are classified as at risk of disappearing.[20]
- Of 30,000 wild and 7,000 cultivated edible plants, 30 provide 95% of dietary energy. Wheat, rice, and maize provide >50% of plant-derived calories, globally.[21]
- Between 1900 - 2000, around 75% of the genetic diversity of agricultural crops was lost.[22]
- Productivity, stability, ecosystem services, and resilience are positively associated with species diversity in agricultural ecosystems.[23]

Federally Listed Endangered Species by Taxonomic Group[13]



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.[24]
- Globally, 1% or less of the species within most assessed taxa are extinct. However, 20-43% of species in these taxa are labeled as threatened.[24]
- Globally, there has been an average 69% decline in the relative abundance of monitored wildlife populations since 1970.[25]
- As of 2022, 208 plant and animal species have gone extinct in the U.S. and 2,288 are threatened or endangered.[6,26]
- Current extinction rates are higher than those leading to the five mass extinctions and could reach mass extinction magnitude in 300 years.[24]
- Up to 1 million species may be threatened with extinction in coming decades.[27]

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 (CITES) (1973), and the Convention on Biological Diversity (CBD) (1992).[28]
- The Endangered Species Act (ESA) (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.[29]
- As of 2023, 194 countries have National Biodiversity Strategic Action Plans for the conservation and sustainable use of biological diversity.[30]
- Globally, over 238,000 protected areas (such as national parks and reserves) have been established, covering nearly 15% of the land and 7.3% of the sea. The size of protected areas is now more than 19 times larger than it was in 1962.[31]

Global Initiatives

- 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.[32]
- In 2022, the Kunming-Montreal Global Biodiversity Framework was adapted by the Convention on Biological Diversity. It includes 23 targets for reversing habitat and species loss, including protecting 30% of the world's terrestrial and marine areas by 2030 ("30x30").[33]

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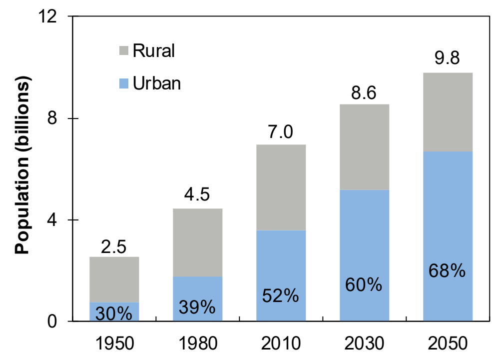
Social Development Indicators

Standards of living are difficult to measure, but indicators of social development are available. A basic measure, per capita Gross Domestic Product (GDP), 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 Gross National Income (GNI). The three highest HDI-ranked countries are Switzerland, Norway, and Iceland.[1] Many of the indicators discussed below are used to measure progress towards the Sustainable Development Goals (SDGs), a set of targets agreed upon by United Nations member states as crucial for global human progress.

Population

World Population, Urban and Rural, 1950 to 2050[3]



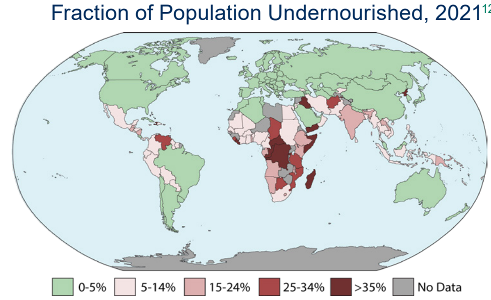
- The 2023 U.S. population is 334 million and world population is over 7.9 billion.[2]
- Global population is projected to reach 9.8 billion by 2050. An estimated 6.7 billion people will be living in urban areas—a 68% increase from 2015.[3]
- The population of Sub-Saharan Africa is growing rapidly and may exceed 3 billion people by 2100. By 2070 it is projected to become the most populated region in the world.[4]
- Significant issues affecting population include shifting mortality and fertility rates, international migration, gender equality, and impacts of the COVID-19 pandemic.[4]
- Fertility rate, or number of births per woman (of child-bearing age), is projected to fall from a global average of 2.3 in 2021 to 2.1 by 2050. Currently, Niger has the highest fertility rate at 7.0; the U.S. fertility rate is 1.8.[4,5]
- Life expectancy averages 64 years in Least Developed Countries (LDC); life expectancy at birth in the U.S. is 76 years.[6]
- Globally, contraceptive use is increasing. In 2020, global contraceptive use was 1.7 times higher than in 1990 and was 6 times higher in LDC than in 1990.[7] However, more than 20% of women of reproductive age in 15 countries still do not have access to contraceptives.[8]

Standard of Living

- For the first time in 20 years, global extreme poverty rose in 2020—a result of the COVID-19 pandemic and Russia's invasion of Ukraine. By the end of 2030, 7% of the world's population (574 million people) will live in extreme poverty.[9]
- In 2021, 11.6% of the U.S. population—37.9 million people—were living in poverty (income under $27,479 for a family of 4 with 2 children).[10] Black, Hispanic, and Native American populations in the U.S. face higher than average levels of poverty (19.5%, 17.1, and 24.2%, respectively).[10]
- According to the Gini Coefficient, Slovakia, Slovenia, and Belarus have among the most equal income distributions in the world. There are over 100 countries a with more even income distribution than the U.S. (Gini coefficient = 41.5).[1]
- More than 582,462 people experienced homelessness at some point in the U.S. in 2022.[11]

Food

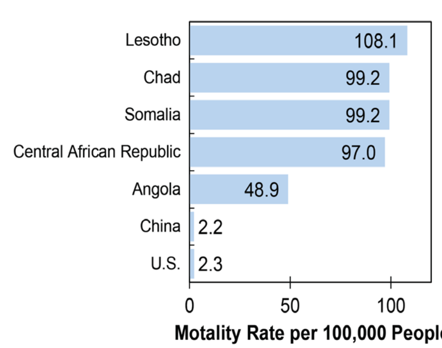
Fraction of Population Undernourished, 2021[12]



- Average expenditures on food as a percentage of income range from 14% in developed countries to 30% in developing countries in 2021.[13,14] On average, Americans spend 7%, while Nigerians spend 59%.[13]
- Globally, 45% of deaths of children under age five are caused by undernutrition.[15]
- The Green Revolution during the second half of the 20th century led to large increases in agricultural yields and helped feed the rapidly growing global population. Sub-Saharan Africa was the only developing region where increased food production was primarily due to increased crop area vs. increased crop yield.[16]
- The United Nations Food and Agriculture Organization publishes a comprehensive set of food security statistics annually.[17]

Water and Sanitation

Deaths from Unsafe Water and Sanitation, 2019[18]

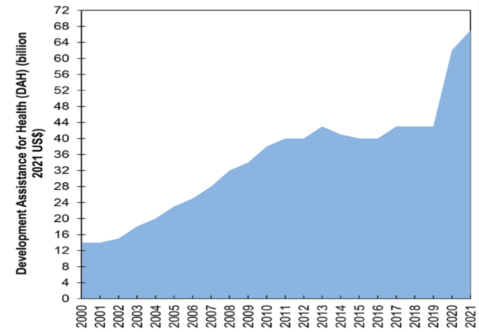


- Approximately 1.7 billion people lack access to proper sanitation. Access is lowest in sub-Saharan Africa, where only one in four people have proper facilities. Worldwide, urban areas have better sanitation coverage—88% have access to proper facilities, compared to 66% in rural areas.[19]
- Only 37% of people in LDCs have access to basic hygiene (soap and water).[19]
- In 2020, 74% of the world population had access to clean drinking water at home, but 282 million people spent more than 30 minutes per round trip to collect safe drinking water. In Oceania and Sub-Saharan Africa only 47% and 49% of the rural populations, respectively, have access to improved water resources.[19]

Healthcare and Disease

- Approximately 26% of deaths in 2019 were caused by communicable diseases.[20]
- Globally, 38 million people were infected with HIV and 680,000 died from AIDS in 2020. Most cases—20.6 million—were in eastern and southern Africa. The number of new infections declined by 31% between 2010 and 2020, but infection rates have increased in northern Africa, the Middle East, and Latin America.[21]
- Diarrheal diseases killed 1.6 million people in 2016 due to inadequate water, sanitation, and hygiene services. Each year 446,000 children die from diarrhea. Greater than 70% and 55% of the infections are due to unsafe drinking water and sanitation, respectively.[22]
- In 2021, there were 247 million cases of malaria worldwide, with 95% occurring in Africa; 619,000 people died and 76% of malaria cases in children under 5 resulted in death.[23] Research shows more populations will be at risk of malaria as climate change expands suitable habitat for disease-carrying mosquitoes.[24] Malaria mortality rates have decreased by more than 50% globally since 2000.[23]
- Indoor air pollution, primarily from smoke while cooking, contributes to 3.2 million premature deaths each year.[25]
- 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.[18]
- COVID-19 has become a leading cause of death. Preliminary WHO estimates suggest at least 6.9 million deaths globally as of 2023.[18] COVID-19 was also responsible for 14.9 million excess deaths and 336.8 million years of life lost globally by the end of 2021.[18]
- In 2015, about 90 million people fell below the poverty line due to out-of-pocket health care costs.[26]

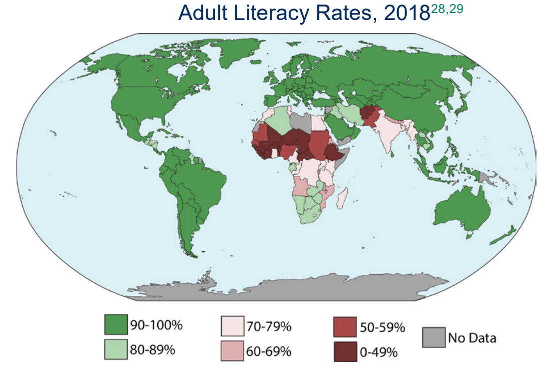
Development Assistance for Health to Developing Nations[27]



Education and Employment

- Global youth literacy has risen from 83% in 1990 to 92% in 2020. The gap in female and male literacy rates is also closing; in 1990, literacy rates were 87% and 80% for boys and girls, respectively. In 2020, the literacy rates were 93% and 91%.[30]
- Marshall Islands spends the highest percentage of its GDP on education, devoting on average 16% annually over the last decade. The U.S. spends around 5% annually.[31]
- Sub-Saharan Africa primary school enrollment increased from 52% to 80% from 1990-2015; the 2015 world average is 91.5%.[32]
- In Low Human Development nations, 25% percent of the population has at least some secondary education. In Very High Human Development nations this metric is 89%.[33]
- Most jobs in developing countries are in agriculture (60%), services (27%), and industry (13%).[34]

Adult Literacy Rates, 2018[28,29]



Environment

- In 2023, the Intergovernmental Panel on Climate Change (IPCC) concluded that anthropogenic greenhouse gas emissions and human activities have unequivocally caused climate change.[35] In the 21st century, climate change will likely result in increasing extinction risk for plant and animal species, more flooding and coastal erosion, extreme heat, droughts, tropical storm intensity, and human health risks associated with malnutrition and water-related and vector-borne diseases. Declines in crop productivity in low latitudes and freshwater availability are likely. Poor communities are especially vulnerable because of their low adaptive capacity and high dependence on local climate (e.g., rain for agriculture).[36]
- A 2019 analysis found that not investing in climate change mitigation would result in an average 7.2% decrease in global GDP by 2100 while adhering to the Paris Agreement could limit this decrease to 1.1%.[37]

Global Initiatives

- In 2015, the UN established seventeen Sustainable Development Goals (SDGs), including eliminating poverty and hunger, reducing inequalities, and improving health and education while ensuring environmental sustainability.[38]
- Through 2019, Denmark, Luxembourg, Norway, Sweden, and the United Kingdom continued to exceed giving 0.7% of their GNI as Official Development Assistance (ODA), an Organization for Economic Cooperation and Development (OECD) program. The U.S. donates a lower percentage of GNI, but the greatest absolute dollar amount of any nation. In 2019, U.S. ODA totaled $34.6 billion.[39]

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Cite as: Center for Sustainable Systems, University of Michigan. 2022. "Social Development Indicators Factsheet." Pub. No. CSS08-15. **September 2022**

Carbon Footprint

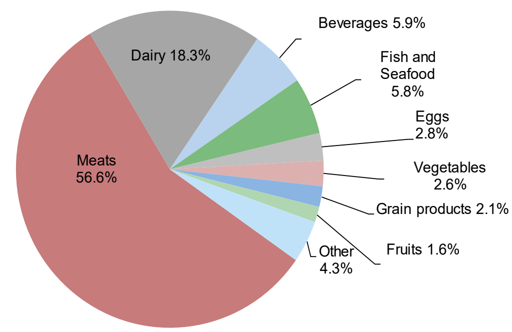
"A carbon footprint is the total greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organization, event or product."[1] It is calculated by summing the emissions resulting from every stage of a product or service's lifetime (material production, manufacturing, use, and end-of-life). Throughout a product's lifetime, or lifecycle, GHGs may be emitted, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), each with a greater or lesser ability to trap heat in the atmosphere. These differences are accounted for by the global warming potential (GWP) of each gas, resulting in a carbon footprint in units of mass of carbon dioxide equivalents (CO_2e). See the Center for Sustainable Systems "Greenhouse Gases Factsheet" for more information on GWP. A typical U.S. household has a carbon footprint of 48 metric tons (t) CO_2e/yr.[2]

Sources of Emissions

Food

- Food accounts for 10-30% of a household's carbon footprint, typically a higher portion in lower-income households.[2] Production accounts for 68% of food emissions, while transportation accounts for 5%.[4]
- Food production emissions consist mainly of CO_2, N_2O, and CH_4, which result primarily from agricultural practices.[5]
- Meat products have larger carbon footprints per calorie than grain or vegetable products because of the inefficient conversion of plant to animal energy and due to CH_4 released from manure management and enteric fermentation in ruminants.[5]
- Livestock emitted 195 million metric tons (Mt) CO2e of methane in 2021 from enteric fermentation, 139 Mt (71%) of it from beef cattle.[6]
- In an average U.S. household, eliminating the transport of food for one year could save the GHG equivalent of driving 1,000 miles, while shifting to a vegetarian meal one day a week could save the equivalent of driving 1,160 miles.[5]
- 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, beef's GHG emissions per kilogram are 7.2 times greater than those of chicken.[7]

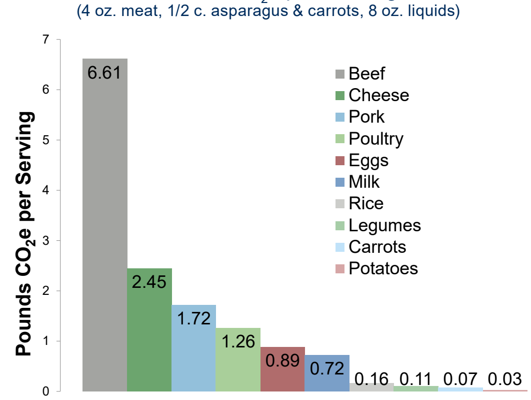
Greenhouse Gases Contribution by Food Type in Average Diet[3]



Household Emissions

- For each kWh generated in the U.S., an average of 0.857 pounds of CO2e is released at the power plant.[8] Coal releases 2.2 pounds, petroleum releases 2.0 pounds, and natural gas releases 0.9 pounds. Nuclear, solar, wind, and hydroelectric release no CO2 when they produce electricity, but emissions are released during upstream production activities (e.g., solar cells, nuclear fuels, cement production).[6,9]
- Residential electricity use in 2021 emitted 578.3 Mt CO2e, 9.1% of the U.S. total.[6]
- Space heating and cooling are estimated to account for 44% of energy in U.S. residential buildings in 2023.[10]
- Refrigerators are one of the largest users of household appliance energy; in 2021, an average of 718 lbs CO2e per household was due to refrigeration.[8,11]
- 26 Mt CO_2e are released in the U.S. each year from washing clothes. Switching to a cold water wash once per week can reduce household GHG emissions by over 70 lbs annually.[12]

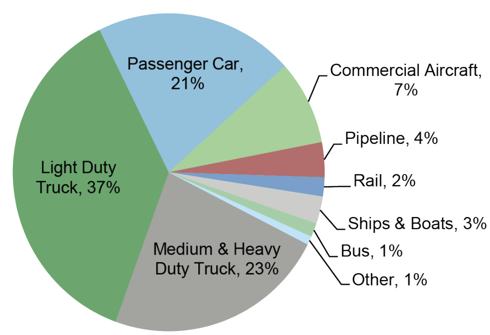
Pounds of CO_2e per Serving[13]
(4 oz. meat, 1/2 c. asparagus & carrots, 8 oz. liquids)



Personal Transportation

- U.S. fuel economy (mpg) declined by 12% from 1988-2004, then improved by 32% from 2004-2021, reaching an average of 25.4 mpg in 2021.[14] Annual per capita miles driven increased 9% since 1995 to 9,937 miles in 2019.[15]
- Cars and light trucks emitted 1.05 billion metric tons (Gt) CO2e or 16.5% of the total U.S. GHG emissions in 2021.[6]
- Of the roughly 66,000 lbs CO_2e emitted over the lifetime of an internal combustion engine car (assuming 93,000 miles driven), 84% come from the use phase.[16]
- Gasoline releases 19.4 pounds of CO2 per gallon when burned, compared to 22.5 pounds per gallon for diesel.[17] However, diesel has 11% more BTU per gallon, which improves its fuel economy.[18]
- The average passenger car emits 0.77 pounds of CO_2 per mile driven.[14]
- 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 $0.25-$0.50 per gallon.[19]

Transportation Greenhouse Gases, 2021[6]

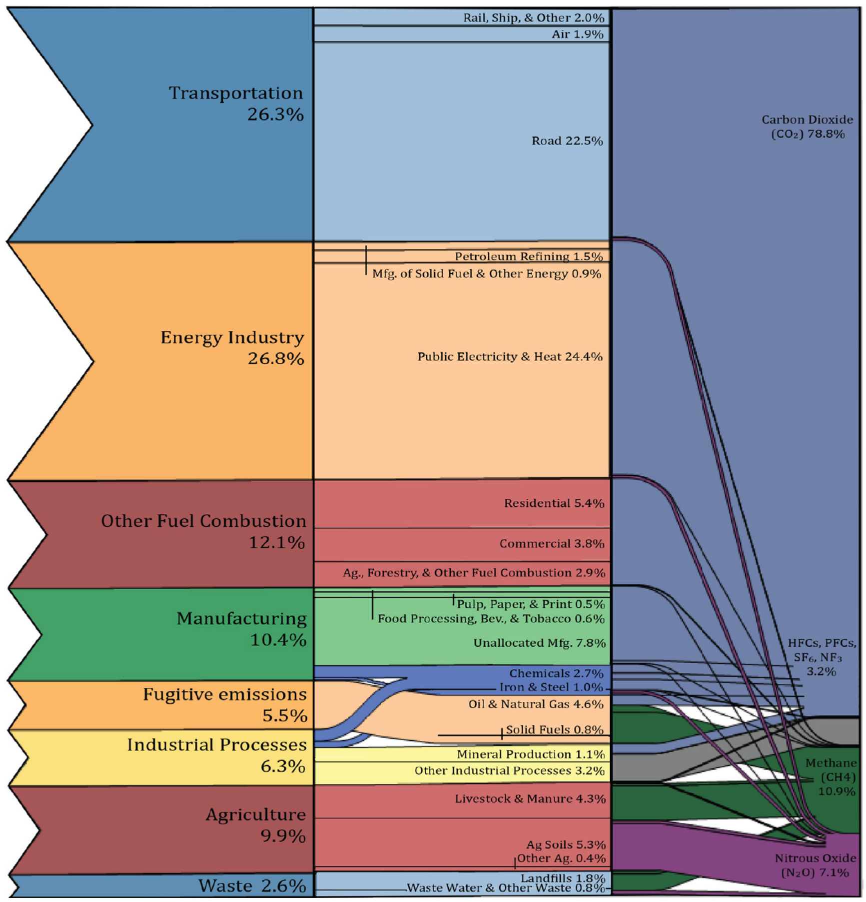


- Commercial aircraft GHG emissions vary according to aircraft type, trip length, occupancy, and passenger and cargo weight, and totaled 120 Mt CO2e in 2021.[6] In 2021, the average domestic commercial flight emitted 0.75 pounds of CO2e per passenger mile.[6,20]
- Domestic air travel fuel efficiency (passenger miles/gallon) had increased 115% from 1990-2019 largely due to increased occupancy. The Covid-19 pandemic decreased this improvement to a 20% increase in fuel efficiency from 1990-2021.[20] Emissions per domestic passenger-mile decreased 44% from 1990-2019, but increased 47% from 2019-2021 due to Covid restrictions.[6,20]
- In 2021, rail transportation emitted 35.2 Mt CO2e, accounting for 2% of transportation emissions in the U.S.[6]

Solutions and Sustainable Actions

Ways to Reduce Carbon Footprint

U.S. Greenhouse Gas Emissions, 2020[29]



- Reduce meat in your diet and avoid wasting food.
- Walk, bike, carpool, use mass transit, or drive a best-in-class vehicle.
- Ensure car tires are properly inflated. Fuel efficiency decreases by 0.2% for each 1 PSI decrease.[21]
- Smaller houses use less energy. Average household energy use is highest in single-family houses (80.85 million BTU), followed by mobile homes (61.3 million BTU), apartments with 2-4 units (53.5 million BTU), and apartments with 5+ units in the building (33.7 million BTU).[11]
- Whether you hand wash dishes or use a dishwasher, follow recommended practices to decrease water and energy use and reduce emissions.[22]
- 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.[23]
- Choose energy-efficient lighting. Switching from incandescent to LED light bulbs saves an average household more than $200/year.[24,25]
- Reduce what you send to a landfill by recycling, composting, and buying products with minimal packaging.
- Purchase items with a comparatively low carbon footprint. Some manufacturers have begun assessing and publishing their products' carbon footprints.
- Covering 80% of roof area on commercial buildings in the U.S. with solar reflective material would conserve energy and offset 125 Mt CO_2 over the structures' lifetime, equivalent to turning off 34 coal power plants for one year.[26,27]
- Replacing the global fleet of shipping containers' roof and wall panels with aluminum would save $28 billion in fuel.[28]

Carbon Footprint Calculator

Estimate your personal or household greenhouse gas emissions and explore the impact of different techniques to lower those emissions:

- U.S. Environmental Protection Agency: www3.epa.gov/carbon-footprint-calculator/
- The Nature Conservancy: www.nature.org/greenliving/carboncalculator/
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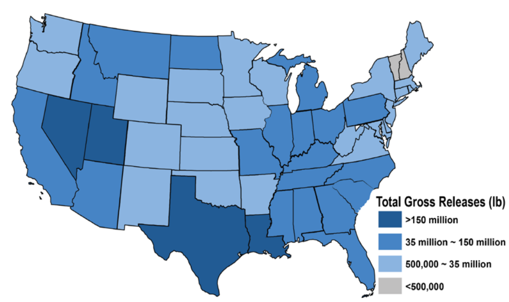
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Carbon Footprint Factsheet." Pub. No. CSS09-05. **August 2023**

Environmental Justice

Environmental Justice (EJ) is defined as the equal treatment and involvement of all people in environmental decision making.[1] Inspired by the Civil Rights movement, EJ became widespread in the 1980s at the intersection of environmentalism and social justice.[2] 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.[3] EJ and sustainability are interdependent and both necessary to create an equitable environment for all.[4]

Built Environment

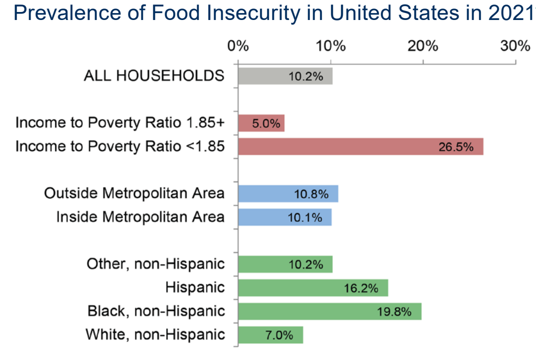
Total Toxic Releases by State, 2021[6]



- 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.[3]
- When urban areas were developing across the U.S., 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.[3]
- Residents of environmentally degraded areas do not or cannot move because of a lack of financial resources, ownership of current land, and sense of place.[3]
- 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.[5]
- On average, people of color make up 56% of the population living in neighborhoods with TRI facilities, compared to 30% elsewhere.[7]
- Negative environmental factors can compound social and economic conditions and lead to higher levels of chronic health problems such as asthma, diabetes, and hypertension for minorities and low-income communities.[8] Due to long-standing inequalities in living, working, health, and social conditions, minorities in the U.S. have an increased risk for infection, hospitalization, and death from COVID-19 compared to non-Hispanic white persons.[9]
- Availability of cheap land in disadvantaged 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.[3,10]
- 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.[11]
- 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.[12]

Food

Prevalence of Food Insecurity in United States in 2021[13]



- In 2021, 10.2% of U.S. households experienced food insecurity at some point during the year — reducing their access to adequate food for an active, healthy lifestyle.[13]
- In 2021, rates of food insecurity for Black and Hispanic households were higher than the national average and higher in rural versus urban areas.[13]
- Food prices are higher and quality is lower in high poverty areas.[14] In 2021, the average U.S. household spent 12% of income on food; low-income families spent over 30%.[15]
- Hispanic and Black children have higher obesity rates than White and Asian children.[16]
- About 53.6 million people (17.4% of total U.S. population) have low access to a supermarket due to limited transportation and uneven distribution of supermarkets.[17]
- A case study in Detroit found that households in poor Black communities were on average 1.1 miles farther from a supermarket than in the poorest White neighborhoods.[14]

Energy

- The presence of power plants and fuel resource extraction operations place 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.[18]
- The average income of residents living within three miles of a coal power plant in 2000 was over $3,000 less than the national average.[19]

Hydropower and Dams

- Dams threaten vulnerable populations through food insecurity, increased morbidity, and the loss of land and water access, jobs, and homes.[20]
- Dam construction often displaces low income communities because of financial pressure from wealthier groups or private investors.[20]
- Environmental concerns associated with hydropower include fish mortality, water quality impairment, alteration of natural landscapes and destruction of sacred Indigenous sites.[21]

Energy Poverty

- Nearly 37 million American homes suffer from energy poverty, the inability to meet a household's energy needs.[22] This makes them vulnerable to detrimental health effects during periods of intense heat or cold.[23]
- Energy poverty results from income inequality and inequalities in energy prices, housing, and energy efficiency.[23]

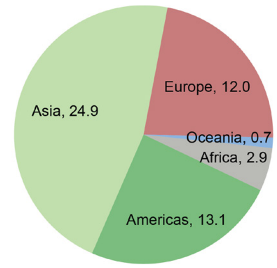
- Low-income households spend three times as much of their income on energy than non-low-income households, despite consuming less energy.[22]
- A case study found that energy-efficient light bulbs are less available and more expensive in higher poverty urban areas.[24]

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.[3]
- The U.S. imports more than 90% of the elements critical to advanced energy generation, transmission, and storage.[25]
- Artisanal and small scale mining (ASM) accounts for 15-20% of global mineral and metal production. ASM often has unsafe working conditions (e.g., child labor) and bad environmental practices (e.g., high mercury emissions).[26]

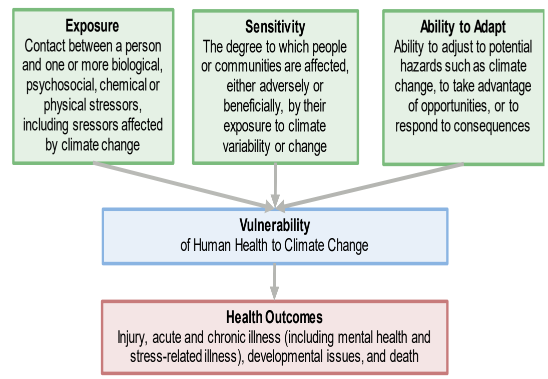
Global E-Waste Generation (t), 2019[27]



Electronic Waste

- In 2019, 53.6 metric tons (t) of e-waste were generated, with Asia being the largest contributor.[27]
- Improper recycling and recovery procedures can lead to exposure to carcinogenic and toxic materials, which often occurs in developing nations where recycling regulations to limit worker exposure are lax or nonexistent.[28]
- A review conducted by researchers found increased DNA damage in those living in e-waste recycling towns, along with increases in still and premature births.[29]
- An estimated 6-29% of the 40 million computers retired in the U.S. were exported in 2010.[30] The International Trade Commission found that the U.S. exported 7% of its used electronics by value in 2011.[31]

Vulnerability to Climate Change[32]



Climate

- The World Health Organization estimates that climate change will cause an additional 250,000 deaths per year between 2030 and 2050.[33]
- Though wealthy, developed nations like the U.S. emit larger amounts 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.[4,32]
- 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.[32] 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.[32]
- Indigenous populations that rely on subsistence farming practices for food have limited options for adapting to climate change threats.[32]
- Areas with poor healthcare infrastructure - common in developing nations - 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.[33]

Solutions

- Launched in 2015, EJSCREEN makes data on environmental and demographic characteristics in the U.S. accessible to the public. It assists federal agencies by displaying existing environmental injustice impacts on areas open to development.[34]
- As of 2023, the EPA's EJ program has granted over $37 million to community projects and organizations in over 1,500 communities focusing on clean air, healthy water, land revitalization, and environmental health.[35]
- The Justice40 Initiative, established by executive order in 2021, set a national goal that disadvantaged communities will receive 40% of the benefits provided by Federal investments into areas like climate change and clean energy.[36]
- The Inflation Reduction Act provides resources for disadvantaged and minority communities to reduce pollution, improve clean transit, make clean energy more affordable and accessible, and strengthen resilience to climate change.[37]
- Use the Environmental Justice Atlas website to learn about and spread awareness on an expanse of EJ issues.[38]
- Engage in and support bottom-up models of research that are responsive to the environmental concerns of communities rather than the interests of large, corporate funders. Advocate for the inclusion of local knowledge in research in addition to observations obtained from scientific methods.[18]

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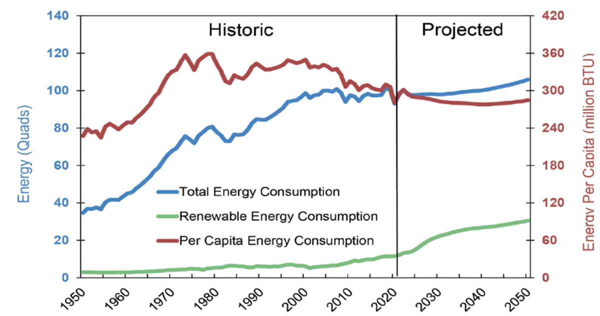
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Environmental Justice Factsheet." Pub. No. CSS17-16. **August 2023**

U.S. Energy System

Energy plays a vital role in modern society, enabling systems that meet human needs such as sustenance, shelter, employment, and transportation. In 2021, the U.S. spent $1.3 trillion on energy, or 5.7% of Gross Domestic Product (GDP).[1] On a per capita basis, annual energy costs were $3,967 per person.[1] 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.[2] The nation's heavy reliance on fossil fuels (primarily imported crude oil) poses major concerns for energy security. Potential gains in energy efficiency in all sectors may be offset by increases in consumption, a phenomenon called the rebound effect.[3]

U.S. Energy Consumption: Historic and Projected Values[4,5]

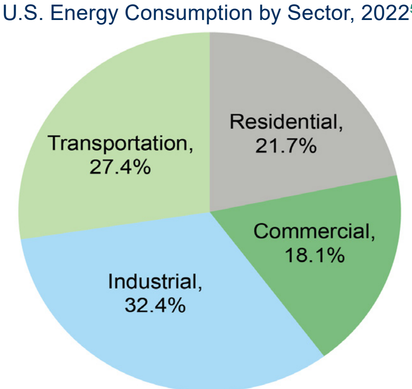


Patterns of Use

Demand

- With less than 5% of the world's population, the U.S. consumes 16% of the world's energy and accounts for 16% of world GDP. In comparison, the European Union has 6% of the world's population, uses 10% of its energy, and accounts for 15% of its GDP, while China has 18% of the world's population, consumes 27% of its energy, and accounts for 19% of its GDP.[6,7]
- Each day, U.S. per capita energy consumption includes 2.5 gallons of oil, 8.27 pounds of coal, and 261 cubic feet of natural gas.[5,6]
- Residential daily consumption of electricity is 12 kilowatt-hours (kWh) per person.[5,6]
- In 2022, total U.S. energy consumption decreased around 1% from 2018 peak levels.[5]

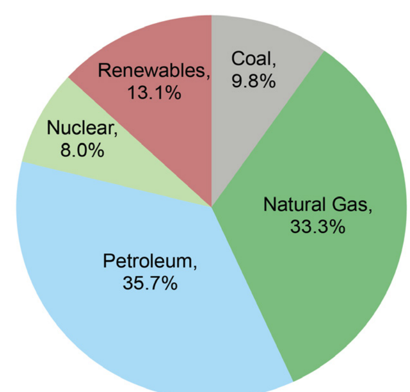
U.S. Energy Consumption by Sector, 2022[5]



Supply

- By current DOE estimates, 66% of U.S. energy will come from fossil fuels in 2050, which is inconsistent with meeting IPCC carbon reduction goals.[4,8]
- Renewable energy consumption is projected to increase annually at an average rate of 3.1% between 2022 and 2050, compared to 0.2% growth in total energy use. Residential photovoltaics are projected to grow annually by 6.5%. At these rates, renewables would provide 29% of U.S. energy consumption in 2050, compared to 13.1% today.[4,5]
- In 2022, for the third time since tracking began, the U.S. exported more oil (9.58 million barrels per day) than was imported (8.32 million barrels per day), and is also expected to be a net exporter in 2050.[4,5]
- Canada, Mexico, and Saudi Arabia are the three largest suppliers of U.S. oil imports.[9] The Persian Gulf region accounted for 12% of U.S. imports in 2022.[9] Oil from OPEC countries was 15% of U.S. imports in 2022.[5] The Persian Gulf contains almost 50% of the world oil reserves, and 15% of world reserves lie in Saudi Arabia.[7]

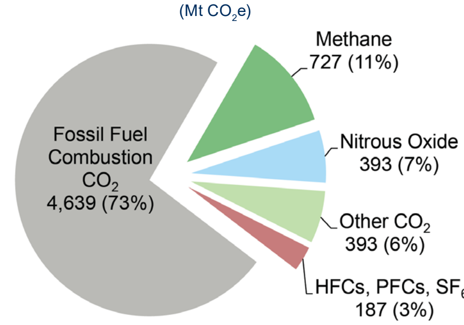
U.S. Energy Consumption by Source, 2022[5]



Life Cycle Impacts

- Air emissions from the combustion of fossil fuels are the primary environmental impact of the U.S. energy system. Such emissions include carbon dioxide (CO_2), nitrogen oxides, sulfur dioxide, volatile organic compounds, particulate matter, and mercury.
- Methane leakage from the oil and natural gas supply chain (fracking wells, pipelines, etc.) is estimated to be 13 million metric tons (Mt) per year, equivalent to 2.3% of U.S. annual gross natural gas production. With a global warming potential of almost 30, this methane leakage is equivalent to 387 Mt of CO2, or 6.1% of total U.S. CO2e emissions in 2021.[10,11,12]
- U.S. greenhouse gas (GHG) emissions in 2021 were 2.1% less than 1990 values. 73% of total U.S. GHG emissions came from burning fossil fuels in 2021.[10]
- 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 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.[13]

U.S. GHG Emissions, 2021[10]
(Mt CO_2e)



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 use. See CSS factsheets on personal transportation and residential buildings for additional ways to trim energy consumption.

Increase Efficiency

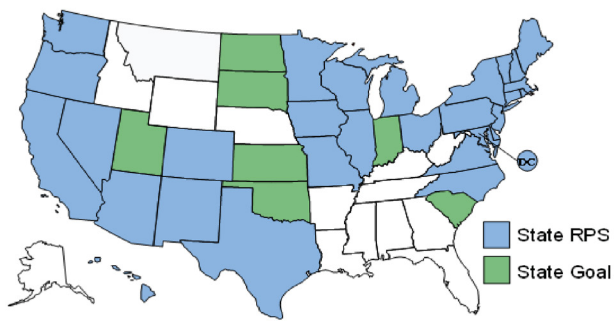
- An aggressive commitment to energy efficiency could reduce U.S. carbon emissions by 57% (2,500 Mt) by 2050.[14]
- Additional information on energy efficiency can be found at the following organizations' websites:
  - General: U.S. DOE Energy Efficiency and Renewable Energy, http://energy.gov/eere/office-energy-efficiency-renewable-energy
  - Residential & Commercial: U.S. EPA Energy Star, https://www.energystar.gov/
  - Transportation: U.S. DOE and EPA Fuel Economy Guide, https://www.fueleconomy.gov/
  - Industrial: U.S. EPA Energy Star, https://www.energystar.gov/buildings/facility-owners-and-managers/industrial-plants/industrial_resources

Increase Renewables

- Installed wind capacity in the U.S. grew 11% in 2021, expanding to nearly 136 GW.[15,16] If 224 GW of wind capacity were installed by 2030, an amount determined feasible by the U.S. DOE, wind would satisfy 20% of projected electricity demand.[17]
- Solar photovoltaic modules covering 0.6% of the land in the U.S. could supply all of the nation's electricity.[18]

Encourage Supportive Public Policy

States with Renewable Energy Portfolio Standards[30]



- The U.S. currently produces 14% of the world's energy-related CO_2 emissions. U.S. emissions are projected to decrease 20% by 2035 from 2022 levels.[4,19] The Climate Action Now Act, passed by the House in May 2019, would require an annual plan to ensure the United States meets its stated goals under the Paris Agreement of reducing greenhouse gas emissions by 26-28% by 2025.[20] The Act has not yet been brought to a vote in the Senate.[21] In comparison, the United Kingdom passed into law a goal of having net-zero greenhouse gas emissions by 2050.[22]
- In 2012, new auto manufacturing standards for model years 2017-2025 were set, raising corporate average fuel economy (CAFE) standards to 54.5 miles per gallon for new light-duty vehicles in 2025. In 2020, the Safer Affordable Fuel-Efficient (SAFE) Vehicle Rule significantly weakened these CAFE standards.[23,24] In 2022, NHTSA revised the SAFE standards to align with the Energy Policy and Conservation Act (EPCA). The final rule set the CAFE standards to approximately 49 mpg for passenger cars and light trucks by 2026.[25] These new CAFE standards are projected to reduce fuel use by more than 200 billion gallons by 2050, saving Americans money and cutting CO_2 emissions by 2,500 Mt.[26]
- The growth of biomass, geothermal, and wind was spurred by a 2.5¢/kWh Federal Production Tax Credit (PTC), as well as state Renewable Portfolio Standards (RPS) that require a certain percentage of electricity be derived from renewable sources.[27] The 2022 Inflation Reduction Act (IRA) extended and increased the PTC and the Investment Tax Credit (ITC) through 2024.[28] The IRA provides resources to organizations including businesses, NGOs, and state, local, and tribal governments to accelerate the clean energy transition.[29] Thirty-six states, the District of Columbia, and four U.S. territories had renewable portfolio standards or goals in place as of November 2022.[30]
- A federal tax credit of up to $7,500 is available for new electric, plug-in hybrid, and fuel cell electric vehicles purchased in 2023.[31]
- Homeowners can receive tax credits and rebates for the costs of renewable energy systems and appliance and building efficiency improvements. Eligible technologies include heat pumps, solar water heaters, PV panels, small wind turbines, and building insulation.[32,33]

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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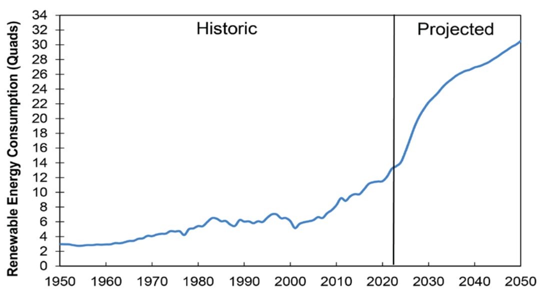
factsheets
Energy

U.S. Renewable Energy

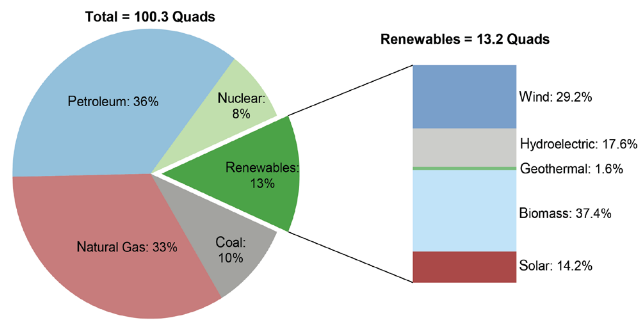
Patterns of Use

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 use, 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 79% of the nation's energy comes from fossil fuels, 8.0% from nuclear, and 13.1% from renewable sources. In 2019, renewables surpassed coal in the amount of energy provided to the U.S. and this trend has continued through 2022. Wind and solar are the fastest growing renewable sources, but contribute just 6% of total energy used in the U.S.[1]

U.S. Renewable Energy Consumption: Historic and Projected[1,2]



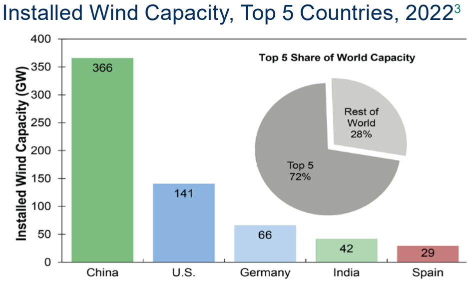
U.S. Total and Renewable Energy Consumption by Source, 2022[1]



Major Renewable Sources

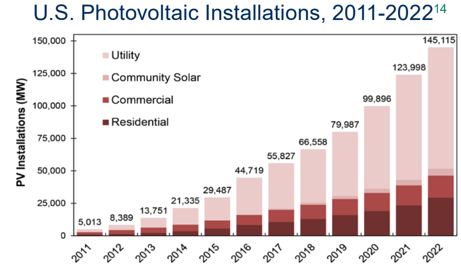
Wind

Installed Wind Capacity, Top 5 Countries, 2022[3]



- U.S. onshore wind resources have a potential capacity of almost 11,000 GW and current installed capacity of 140.9 GW.[3,4] Offshore wind resources are potentially 4,200 GW, current capacity is 42 MW, and the development pipeline contained over 40,000 MW of capacity of projects in 2022.[4,5]
- Over 13 GW of wind capacity was installed in the U.S. in 2021 and over 16 GW in 2020.[6,7,8]
- The federal production tax credit (PTC) significantly influences wind development, but cycles of enactment and expiration lead to year-to-year changes in investment.[9] The Inflation Reduction Act (IRA) of 2022 extended and increased the PTC through 2024 for wind projects beginning construction before 2025 with a PTC up to 2.6¢/kWh for 10 years of electricity output.[10]
- Based on the average U.S. electricity fuel mix, a 1.82 MW wind turbine (U.S. average size in 2021) displaces 3,596 metric tons (t) of CO2 emissions per year.[11] By 2050, 404 GW of wind capacity would meet an estimated 35% of U.S. electricity demand and result in 12.3 gigatons (Gt) of avoided CO_2 emissions, a 14% reduction when compared to 2013.[12]
- Wind turbines generate no emissions and use no water when producing electricity, but concerns include bat and bird mortality, land use, noise, and aesthetics.[13]

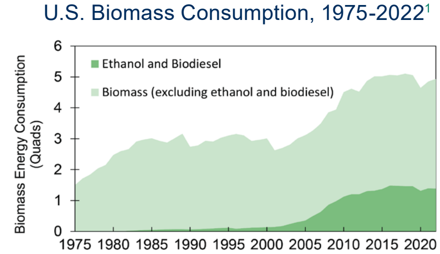
U.S. Photovoltaic Installations, 2011-2022[14]



Solar

- Assuming intermediate efficiency, solar photovoltaic (PV) modules covering 0.6% of U.S. land area could meet national electricity demand.[15]
- PV module prices have declined to an average of $0.36/Watt.[16] The U.S. manufactured 1% of PV cells and 2.7% of PV modules globally in 2021.[17]
- Solar capacity has grown at an average of 24% annually over the last decade. Total installed capacity increased to almost 150 GW in 2022.[14] Solar has added the most generating capacity to the grid for the last four years. It accounted for 54% of new generating capacity in Q1 of 2023. Nearly 30 GW of solar installations are projected to take place in 2023.[14]
- The IRA provides tax incentives that will increase the demand for solar; PV deployment is expected to nearly triple in cumulative capacity by 2028.[14]
- The U.S. Department of Energy's SunShot Initiative aims to reduce the price of solar energy 50% by 2030, which is projected to lead to 33% of U.S. electricity demand met by solar and a 18% decrease in electricity sector greenhouse gas emissions by 2050.[18]
- While solar PV modules produce no emissions during operation, toxic substances (e.g., cadmium and selenium) are used in some technologies.[15]

U.S. Biomass Consumption, 1975-2022[1]



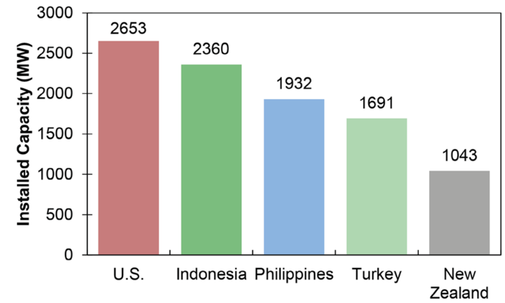
Biomass

- Wood—mostly as pulp, paper, and paperboard industry waste products—accounts for 43% of total biomass energy consumption. Waste—municipal solid waste, landfill gas, sludge, tires, and agricultural by-products—accounts for an additional 8%.[1]
- Biomass has low net CO_2 emissions compared to fossil fuels. At combustion, it releases CO_2 previously removed from the atmosphere. Further emissions are associated with processing and growth of biomass, which can require large areas of land. Willow biomass requires 121 acres of land to generate one GWh of electricity per year, more land than other renewable sources.[19]
- U.S. ethanol production is projected to reach 47 million gallons per day in 2050.[2]

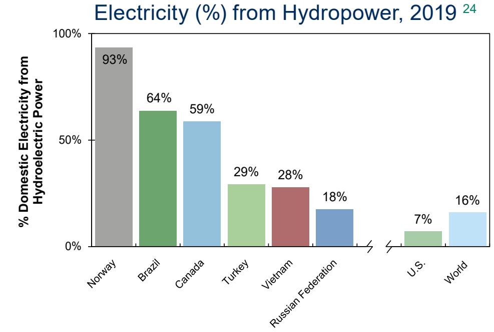
Geothermal

- 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]
- Each year, electricity from hydrothermal sources offsets the emission of 4.1 million U.S. short tons (tons) of CO_2, 80 thousand tons of nitrogen oxides, and 110 thousand tons of particulate matter from coal-powered plants.[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.[21]
- Electricity generated from geothermal power plants is projected to increase from 15.6 billion kWh in 2022 to 37.2 billion kWh in 2050. Geothermal electricity generation has the potential to exceed 500 GW, which is half of the current U.S. capacity.[2,23]

Geothermal Installed Capacity, Top 5 Countries, 2021[20]



Electricity (%) from Hydropower, 2019[24]



Hydroelectric

- In the U.S., net electricity generation from conventional hydropower peaked in 1997 at 356 TWh/yr. Currently, the U.S. gets 262 TWh/yr of electricity from hydropower.[1]
- While electricity generated from hydropower is virtually emission free, significant levels of methane and CO_2 may be emitted through the decomposition of vegetation in the reservoir.[25] 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.[26]

Advancing Renewable Energy

Encourage Supportive Public Policy

- Lawrence Berkeley National Laboratory estimates that 45% of renewable energy growth in the U.S. can be attributed to state Renewable Portfolio Standards (RPS) that require a percentage of electricity be derived from renewable sources.[27] Clean Energy Standards (CES) that mandate certain levels of carbon-free generation can include some non-renewables such as nuclear fuels.[28] Thirty-six states, the District of Columbia, and four U.S. territories had renewable portfolio standards or goals in place as of November 2022.[29] State standards are projected to support an additional 90 GW of renewable electricity projects by 2030.[27]
- Renewable energy growth is also driven by important federal incentives such as the Investment Tax Credit, which offsets upfront costs, as well as state incentives such as tax credits, grants, and rebates. [30]
- Eliminating subsidies for fossil and nuclear energy would encourage renewable energy. Congress allocated over $5.7 billion in tax relief to the oil and gas industries for fiscal years 2020-2024.[31] Studies estimate that the Price-Anderson Act, which limits the liability of U.S. nuclear power plants in the case of an accident, amounts to a subsidy of $366 million to $3.5 billion annually.[32]
- 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-nine states, the District of Columbia, and four U.S. territories have some form of net metering program.[33]

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.[34] Around 850 utilities in the U.S. offer consumers the option to purchase renewable energy, or "green power."[35]
- Many companies purchase renewable energy as part of their environmental programs. Google, Microsoft, T-Mobile, Walmart, and The Proctor & Gamble Company were the top five users of renewable energy as of April 2023.[36]

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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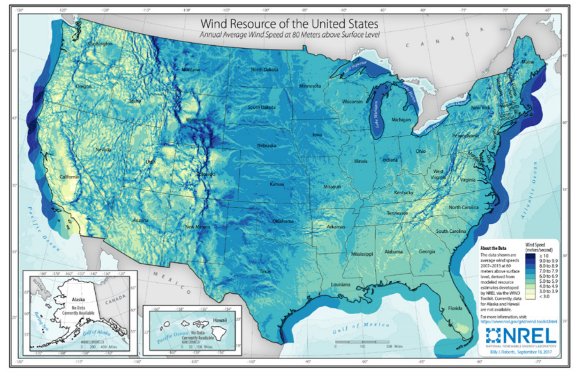
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "U.S. Renewable Energy Factsheet." Pub. No. CSS03-12. **July 2023**

Wind Energy

Wind Resource and Potential

U.S. Wind Resources, Onshore and Offshore[2]
(80 meter height)



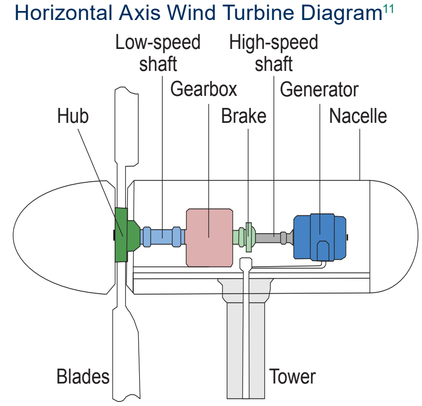
Approximately 2% of the solar energy striking the Earth's surface is converted into kinetic energy in wind. Wind turbines convert the wind's kinetic energy to electricity without emissions.[1] The distribution of wind energy is heterogeneous, both across the surface of the Earth and vertically through the atmosphere. Average annual wind speeds of 6.5m/s or greater at 80m are generally considered commercially viable. New technologies, however, are expanding the wind resources accessible for commercial projects.[3] In 2022, 10.2% of U.S. electricity was generated from wind energy, but wind capacity is increasing rapidly.[4]

- High wind speeds yield more power because wind power is proportional to the cube of wind speed.[5]
- Wind speeds are slower close to the Earth's surface and faster at higher altitudes. The average hub height of modern wind turbines is 94 meters.[6]
- Global onshore and offshore wind generation potential at 90m turbine hub heights could provide 872,000 TWh of electricity annually.[7] Total global electricity consumption from all sources in 2020 was about 23,966 TWh.[8]
- Similarly, the annual continental U.S. wind potential of 43,000 TWh greatly exceeds 2022 U.S. electricity consumption of 4,048 TWh.[4,7]
- 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.[9]
- Five of the eight Great Lakes states have lake-based wind energy resource potentials that exceed the state's annual electricity consumption (MI, WI, NY, OH, MN). Michigan's Great Lakes resource potential could supply over 18 times its 2020 electricity demand.[10]

Wind Technology and Impact

Horizontal Axis Wind Turbines

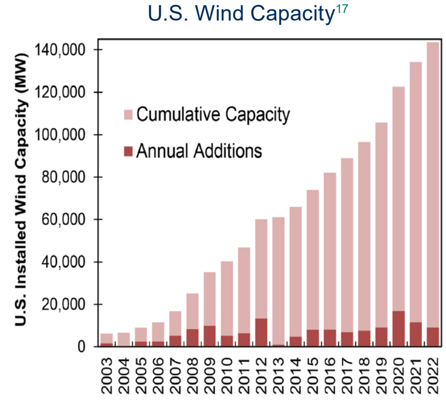
Horizontal Axis Wind Turbine Diagram[11]



- 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 generator. The nacelle houses these components atop a tower.[11]
- HAWT come in a variety of sizes, ranging from 2.5 meters in diameter and 1 kW for residential applications to 100+ meters in diameter and 10+ MW for offshore applications.
- The theoretical maximum efficiency of a turbine is ~59%, also known as the Betz Limit. Most turbines extract ~50% of the energy from the wind that passes through the rotor area.[9]
- The capacity factor of a wind turbine is its average power output divided by its maximum power capability.[9] Capacity factor of land based wind in the U.S. ranges from 21% to 52% and averages 35%.[6]
- Offshore winds are generally stronger than on land, and capacity factors are higher on average (expected to reach 60% by 2050 for new projects), but offshore wind farms are more expensive to build and maintain.[13,14] Offshore turbines are currently placed in depths up to 40-50m (about 131-164ft), but floating offshore wind technologies could greatly expand generation potential as 58% of the total technical wind resource in the U.S. lies over waters greater than 60m.[15,16]

Installation, Manufacturing, and Cost

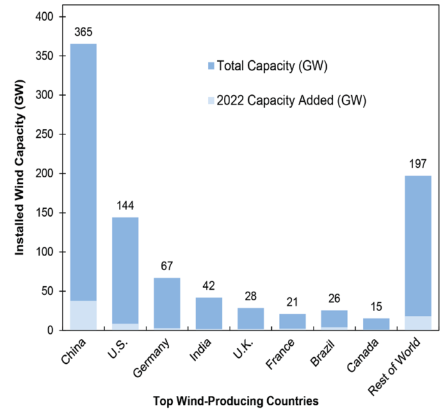
U.S. Wind Capacity[17]



- The U.S. has a cumulative capacity of 142 GW with more than 72,000 installed utility-scale wind turbines. U.S. wind capacity grew from 40 GW in 2010 to 142 GW in 2022, a 11% average annual increase.[17,18] Global wind capacity increased by 12% annually, on average, from 2012 to 2022, reaching 906 GW in 2022.[19]
- U.S. average turbine size was 3.0 MW in 2021, up 18% from 2.55 MW in 2019.[6]
- Average capacity factor has increased from 19% for projects installed from 1998 to 2001 to 39% for projects built between 2014 and 2020.[6]
- On a capacity-weighted average basis, wind project costs declined by roughly $3,303/ kW between 1983 and 2021, when costs were $1,500/kW.[6]
- The average installed cost of a small (<100 kW) turbine was approximately $5,120 per kW in 2021.[20]
- In 2020-21, new wind energy purchase contracts averaged 2.5¢/kWh, while the average residential electricity price was 15.1¢/kWh in 2021.[4,6]
- Minnesota (17,558 MW), Texas (17,167 MW), and California (16,385 MW) are the leading states in total installed wind capacity.[17]
- Iowa generated 62% of its electricity from wind and had the second highest annual electricity generation from wind of any U.S. state in 2022.[21]

- In 2021, there were more than 120,000 full-time workers in the U.S. wind industry and turbines and components were manufactured at over 500 facilities.[22]
- Large (>20 MW) wind projects require ~85 acres of land area per MW of installed capacity, but 1% or less of this area is occupied by roads, foundations, or equipment; the remainder is available for other uses.[9]
- 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.[9]

Global Wind Capacity, 2022[19]



Energy Performance and Environmental Impacts

- Wind turbines can reduce the impacts associated with conventional electricity generation. The U.S. wind capacity avoids an estimated 340 million metric tons (Mt) of CO2 emissions annually.[22]
- 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 510 billion kg of CO_2 emissions annually, or 12.3 trillion kg cumulatively from 2013, and decreasing water use by 15%.[9]
- A 2013 study found energy return on investment (EROI) (energy delivered/energy invested) for wind power between 18:1 and 20:1.[23]
- Annual avian mortality from collisions with turbines is 0.2 million, compared with 130 million mortalities due to power lines and 300-1,000 million from buildings. The best way to minimize mortality is careful siting.[9] Bat mortality due to wind turbines is less well studied. Research shows that a large percentage of bat collisions occur in migratory species during summer and fall months when they are most active.[9,24] The wind industry has been testing methods that potentially reduce bat mortality by more than 50%.[9]
- Noise 350m from a typical wind farm is 35-45 dB. For comparison, a quiet bedroom is 35 dB and a 40 mph car 100m away is 55 dB.[25]
- As of 2013, several studies have conclusively determined that sound generated by wind turbines has no impact on human health.[9]
- Offshore turbine foundations and transmission cables alter benthic habitats, but foundations can create pelagic habitats. Appropriate siting of offshore wind farms is the most effective way to avoid conflicts.[26]

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.

- Renewable Portfolio Standards (RPS) require electricity providers to obtain a minimum fraction of energy from renewable resources.[27]
- Feed-in tariffs set a minimum price per kWh paid to renewable electricity generators by retail electricity distributors.[27]
- Net metering — offered in 39 states, D.C., and four U.S. territories — allows customers to sell excess electricity back to the grid.[28]
- Capacity rebates are one-time, up-front payments for building renewable energy projects, based on the capacity (in watts) installed.
- The 2022 Inflation Reduction Act (IRA) extended and increased the production tax credit (PTC) and investment tax credit (ITC) through 2024 for wind energy projects that begin construction before 2025. The PTC provides up to 2.6¢/kWh of electricity generated and the ITC provides up to 30% of the project's initial investment cost.[29] These tax credits are dependent on the size of the project, construction start date, and in some cases whether certain wage and apprenticeship requirements have been satisfied.[30]
- Section 9006 of the Farm Bill is the Rural Energy for America Program (REAP) that funds grants and loan guarantees for agricultural producers and rural small businesses to purchase and install renewable energy systems.[31]
- System benefits charges are paid by all utility customers to create a fund for low-income support, renewables, efficiency, and R&D projects that are unlikely to be provided by a competitive market.[32]
- The first U.S. commercial offshore wind farm began delivering electricity in 2016. In 2020, a second offshore wind farm completed installation. As of May 2022, 9 states have offshore wind projects seeking leasing status.[33]

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). RECs are sold by renewable energy producers for a few cents per kilowatt hour, customers can purchase RECs to "offset" their electricity usage and help renewable energy become more competitive.[27]
- Consider installing your own wind system, especially if you live in a state that provides financial incentives or has net metering.

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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Wind Energy Factsheet." Pub. No. CSS07-09. **August 2023**

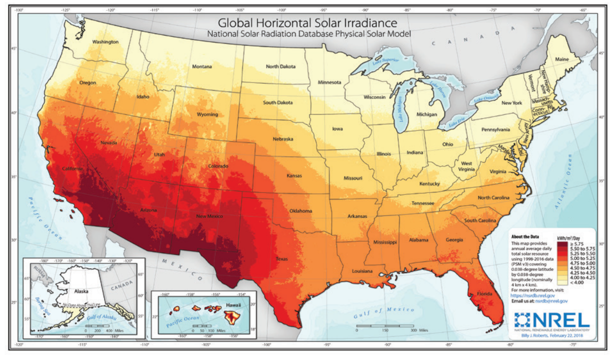
Photovoltaic Energy

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 generate electricity directly from sunlight. Solar technologies generated 3.4% of U.S. electricity in 2022.[1]

Solar Resource and Potential

- On average, 1.73×10^5 terawatts (TW) of solar radiation continuously strike the Earth, while global electricity demand averages 2.9 TW.[3,4]
- Electricity demand varies throughout the day. Energy storage and demand forecasting will help to match PV generation with demand.[5]
- If co-located with demand, solar PV can be used to reduce stress on electricity distribution networks, especially during demand peaks.[6]
- PV conversion efficiency is the percentage of incident solar energy that is converted to electricity.[7]
- Though most commercial panels have efficiencies from 17% to 20%, researchers have developed PV cells with efficiencies approaching 50%.[8,9]
- Assuming intermediate efficiency, PV covering 0.6% of U.S. land area would generate enough electricity to meet national demand.[10]
- In 2011, the U.S. Department of Energy (DOE) announced the SunShot Initiative. Its aim was to reduce the cost of solar energy by 75%, making it cost competitive with other energy options. In 2017, DOE announced that the 2020 goal of utility-scale solar for $0.06/kWh had been achieved three years early. The 2030 goal includes reducing utility-scale solar energy to $0.03/kWh, cheaper than electricity from fossil fuel energy resources.[11]

Annual Average Solar Radiation[2]



PV Technology Types and Efficiencies[9,12]

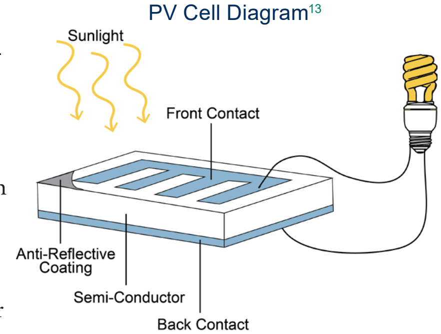
PV Technology		Conversion Efficiency	
		Cell	Module
Crystalline	Monocrystalline silicon (Si)	27.6%	24.4%
	Multicrystalline Si	23.3%	20.4%
	Multi-junction Gallium arsenide (GaAs)	47.6%	38.9%
Thin film	Cadmium telluride (CdTe)	22.3%	19.5%
	CIGS	23.6%	19.2%
Emerging	Perovskite/Si tandem	33.7%	-
	Perovskite	26.0%	17.9%
	Organic	19.2%	13.1%

PV Technology and Impacts

PV Cells

- PV cells are made from semiconductor materials that free electrons when light strikes the surface, producing an electrical current.[15]
- Most PV cells are small, rectangular, and produce a few watts of direct current (DC) electricity.[16]
- PV cells also include electrical contacts that allow electrons to flow to the load and surface coatings that reduce light reflection.[15]
- A variety of semiconductor materials can be used for PVs, including silicon, copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), perovskites, and even some organic compounds (OPV).[15] Although PV conversion efficiency is an important metric, cost efficiency—the cost per watt of power—is more important for most applications.

PV Cell Diagram[13]



PV Modules and Balance of System (BOS)

- PV modules typically comprise a rectangular grid of 60 to 72 cells, laminated between a transparent front surface and a structural back surface. They usually have metal frames and weigh 34 to 62 pounds.[17]
- A PV array is a group of modules, connected electrically and fastened to a rigid structure.[18]
- BOS components include any elements necessary in addition to the actual PV panels, such as wires that connect modules, junction boxes to merge the circuits, mounting hardware, and power electronics that manage the PV array's output.[18]
- An inverter is a power electronic device that converts electricity generated by PV systems from DC to alternating current (AC).[18]
- A charge controller is a power electronic device used to manage energy storage in batteries, which themselves are BOS components.[18]
- In contrast to a rack-mounted PV array, Building Integrated PV (BIPV) replaces building materials such as shingles and improves PV aesthetics.[19]
- Some ground-mount PV arrays employ a solar tracker. This technology can increase energy output by up to 100%.[20]

Residential PV System[14]

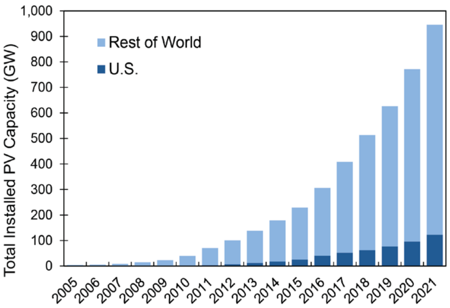
PV Installation, Manufacturing, and Cost

- In 2022, global PV power capacity grew by 239 GW and reached almost 1,200 GW, or 1.2 Terawatt (TW). Solar PV capacity has grown by nearly 750 times since 2000.[23]
- Top installers in 2022 were China (94.7 GW), the U.S. (21.9 GW), and India (17.4 GW).[23]
- New PV installations grew by 45% in 2022 and accounted for 66% of global renewable capacity

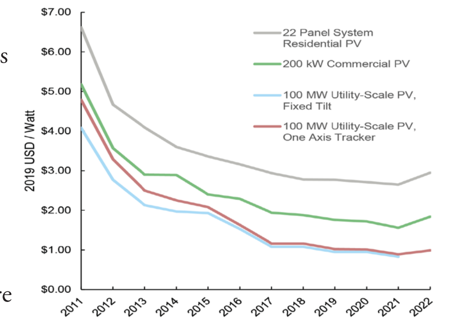
additions. Even with this significant growth, solar power only accounts for 4.5% of global power generation.[23]

- The cost of solar power has dropped over 80% since 2009. Various contracts have been signed around the world with solar power prices as low as 1-2¢/kWh; this is much cheaper than conventional power sources.[24] In comparison, U.S. retail electricity averaged 12.49¢/kWh for all sectors and 15.12¢/kWh for residential users in 2022.[1]
- In 2023, global investment in solar power is estimated to be $380 billion. This accounts for 14% of the total amount invested in energy worldwide.[25]
- Including sectors such as manufacturing, sales, distribution, and installation, there are over 231,000 U.S. solar jobs.[18]

World Cumulative Installed PV Capacity[21]



Median Installed Price, Residential, Commercial, and Utility-Scale PV Systems[22]



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 showed that amorphous silicon PVs generate 3 to 6 times more energy than are required to produce them.[26]
- Reusing multi-crystalline cells can reduce manufacturing energy by 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 CO_2e per kWh delivered, far below electricity sources such as coal (1,001 g CO_2e/kWh).[28,29]
- PVs on average consume less water to generate electricity (26 gallons per MWh), compared to non-renewable technologies such as coal (687 gallons per MWh).[30]

Solutions, Sustainable Actions, and Future Technology

Policies Promoting Renewables

- Consumers that do not have roof space for PV panels can join community solar programs, which are local solar projects that community members can share and receive credit on their electricity bills.[31] Property assessed clean energy (PACE) programs allow property owners to finance the upfront costs of a solar installation through a voluntary assessment on annual property taxes.[32] Green banks and other lending institutions are being developed to specifically fund and support clean energy projects on local, regional, and national scales.[33]
- Carbon cap-and-trade policies would work in favor of PVs by increasing the cost of fossil fuel energy generation.[34]
- The Inflation Reduction Act of 2022 expanded the federal Investment Tax Credit (ITC) to 30% until 2032 for the installation of a solar PV system, a savings of over $7,500 for an average system.[35]
- PV policy incentives include renewable portfolio standards (RPS), feed-in tariffs (FIT), capacity rebates, and net metering.
  - An RPS requires electricity providers to obtain a minimum fraction of energy from renewable resources.[36]
  - A FIT sets a minimum per kWh price that retail electricity providers must pay renewable electricity generators.[37]
  - Capacity rebates are one-time, up-front payments for building renewable energy projects, based on installed capacity (in watts).[37]
  - With net metering, PV owners get credit from the utility (up to their annual energy use) for energy returned to the grid.[37]

What You Can Do

- "Green pricing" allows customers to pay a premium for electricity that supports investment in renewable technologies. Renewable Energy Certificates (RECs) can be purchased to "offset" commodity electricity usage and help renewable energy become more competitive.[38]

Future Technology

- Emerging PV technologies include perovskites, bifacial PV modules, and concentrator PV (CPV) technology. Perovskite solar cells have a high conversion efficiency (over 25%) and low production cost. Bifacial modules are able to collect light on both sides of the PV cells. CPV utilizes low-cost optics to concentrate light onto a small solar cell.[39,40,41]
- Designing for end-of-life could improve the current 10% rate of PV module recycling.[42]

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factsheets
Energy

Biofuels

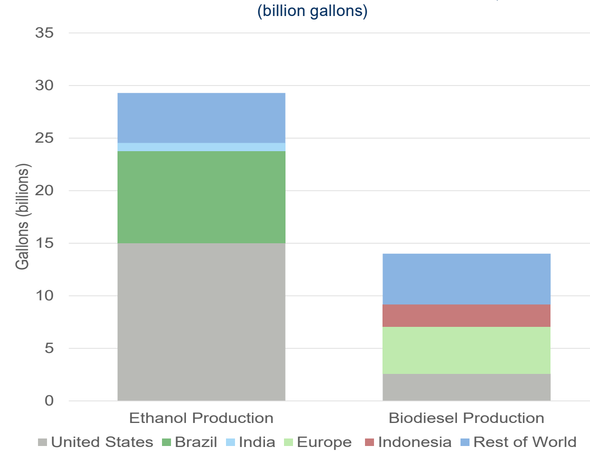
Biofuels have the potential to reduce the energy and greenhouse gas emission intensities associated with transportation, but can have other significant effects on society and the environment. Depending on demand, crop growing conditions, and technology, they may require significant increases in cropland area 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. 94% of U.S. ethanol is derived from corn, while Brazil uses sugar cane as the primary feedstock.[1,2]
- The U.S. and Brazil produced about 81% of the world's ethanol in 2021.[3]
- In the 2021/22 season, 5.3 billion bushels of corn, 36% of the U.S. supply, became ethanol feedstock.[4]
- 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 cellulose does not break down into sugars as easily.[5]
- Biodiesel can be made from animal fats, grease, vegetable oils, and algae. In the U.S., soybean oil, corn oil, and recycled cooking oils are common feedstocks.[6]
- Biodiesel from algae is an area of ongoing research. Algae could potentially produce 10 to 100 times more fuel per acre than other crops.[7]

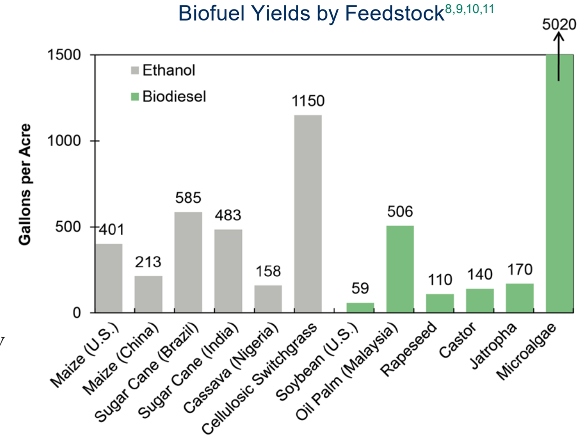
World Fuel Ethanol and Biodiesel Production, 2021[3]
(billion gallons)



Consumption and Demand

- In 2022, for the third time since tracking began, the U.S. exported more oil than it imported. The average U.S. petroleum consumption was 20.28 million barrels per day.[12] In 2022, there were 192 ethanol refineries and 72 biodiesel production plants in the U.S.[13,14]
- U.S. biodiesel production facilities operated at 72% capacity in 2022.[12,14]
- Many biodiesel producers are reliant on federal tax credits and remain sensitive to feedstock (soybean oil) and energy (petroleum) prices. The Inflaction Reduction Act (IRA) reinstated and extended several biofuel tax incentives through 2024.[15,16]
- In 2022, 10% of U.S. vehicle fuel consumption (by volume) was ethanol and over 98% of U.S. gasoline contains ethanol.[2,12]
- E85 sells for less than regular gasoline, but contains less energy per gallon. Flex-fuel vehicles using E85 see a 15-27% reduction in fuel economy.[17]
- By 2024 the global demand for biofuels is expected to increase by 11%.[16]

Biofuel Yields by Feedstock[8,9,10,11]

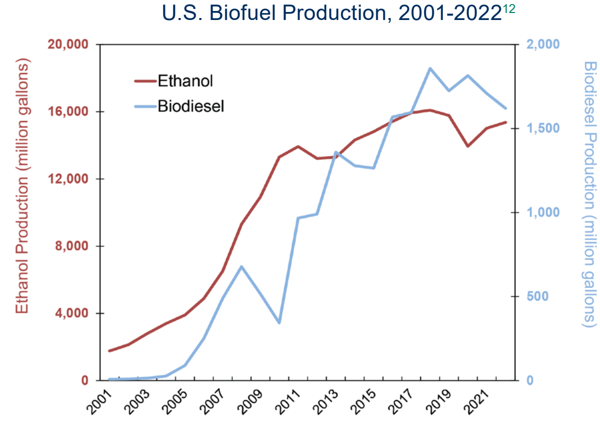


Life Cycle Impacts

Energy

- The Fossil Energy Ratio (FER) is the ratio of energy output to nonrenewable energy inputs.[18] Gasoline has a value of 0.8 (1.2 BTU of fossil fuel needed to supply 1 BTU of gas at the pump).[20] Recent estimates of ethanol's FER is around 1.5, though areas with highly efficient corn agriculture, such as Iowa and Minnesota, have FERs close to 4, and scientists believe with increased efficiency in biomass handling, the FER could eventually rise to 60.[21]
- From 1990-2006, the FER for soybean biodiesel improved from around 3.2 to 5.5.[22] During the same period, ethanol transitioned from an energy sink to a net energy gain. Much of the improvement came from the reduction of fertilizer inputs to grow corn.[21]
- In comparison, petroleum-based diesel has a FER of 0.83.[23]

U.S. Biofuel Production, 2001-2022[12]

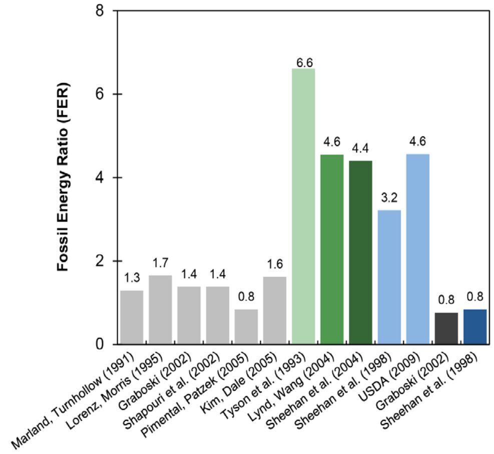


Greenhouse Gases (GHGs)

- Globally, biofuels replaced the consumption of 2 million barrels of oil equivalent per day in 2022, or 4% of the global transport sector oil demand.[16]
- On average, GHG emissions from corn ethanol are 34% lower than gasoline when including Land Use Change (LUC) emissions and 44% lower when excluding them.[24]
- GHG emissions for cellulosic ethanol average around 97% lower than gasoline when including LUC emissions and 93% lower when excluding LUC emissions.[24]

- The use of B20 (20% biodiesel, 80% petroleum diesel), a common biodiesel blend in the U.S., can reduce CO_2 emissions by 15% compared to petroleum diesel. The use of B100 (100% biodiesel) can reduce CO_2 emissions by 74%.[25,26]
- Biodiesel CO_2 emissions are assumed to be taken up again by growth of new feedstock, thus, tailpipe CO_2 emissions from biofuels are excluded from emissions calculations.[27,28]
- Studies have suggested that increased biofuel production in the U.S. will increase global GHG emissions, due to higher crop prices motivating farmers in other countries to convert non-cropland to cropland. Clearing new cropland releases carbon stored in vegetation, preventing the future storage of carbon in those plants.[29]

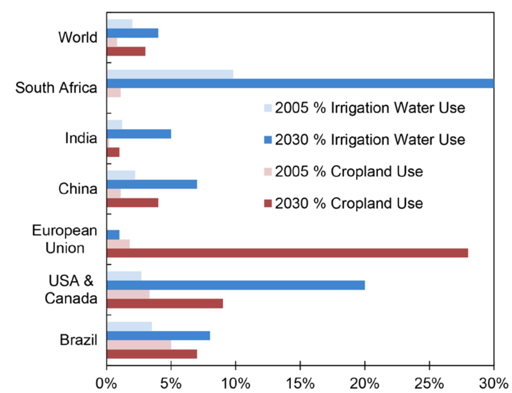
Fuel Return on Fossil Energy Investment[18,19]



Other Impacts

- A large hypoxic zone occurs in the Gulf of Mexico each summer, with a five-year average area of 4,280 square miles.[30] Excess nitrogen, primarily from fertilizer runoff from Midwestern farms, causes algae blooms that decompose and deplete dissolved oxygen, injuring or killing aquatic life. Increasing corn ethanol acreage without changing cultivation techniques will make reducing the hypoxic zone more difficult.[31]
- Globally, average arable land used for biofuels is predicted to rise from 2.5% today to 6% in 2050. However, the impacts of growing biofuel crops vary widely due to regional differences in climate and farmland availability.[32]
- The irrigation of feedstocks requires considerably more water than the manufacturing of biofuels. Although a typical biorefinery consumes 1 to 4 gallons of water per gallon of biofuel, corn grown in 2003 in Nebraska's dry climate required 780 gallons of irrigation water per gallon of ethanol.[34] The majority of corn production for ethanol relies on substantial irrigation from groundwater.[35]
- A review of studies focused on the food price crisis of 2006-2008 found that the growth of biofuel feedstock contributes 20-50% to the price increase of maize. Land use change resulting from the expected increase in biofuel demand is expected to increase global maize and wheat prices 1-2% and vegetable oil prices by around 10%.[36]

Percentage of Cropland and Irrigation Water Required for Biofuels, 2005 vs 2030[33]



Solutions and Sustainable Actions

- Under the Energy Independence and Security Act of 2007, the Renewable Fuel Standard (RFS2) required 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.[37]
- U.S. ethanol producers, blenders, and resellers have been supported by tax incentives, some of which were extended in 2022 by the IRA.[15]
- Fuel content standards are one policy option to encourage biofuel use. Regular gasoline sold in Brazil is required to contain 27% ethanol.[38]
- In 2012, new auto manufacturing standards for model years 2017-2025 were set, raising corporate average fuel economy (CAFE) standards to 54.5 miles per gallon for new light-duty vehicles in 2025. In 2020, the Safer Affordable Fuel-Efficient (SAFE) Vehicle Rule weakened the CAFE standards.[39,40] In 2022, the Biden administration directed the NHTSA to revise the SAFE Rule, which set fuel economy standards for passenger cars and light trucks to approximately 49 mpg by 2026.[41]
- Public transportation, carpooling, biking, and telecommuting are excellent ways to reduce transportation energy use and related impacts. See the CSS Personal Transportation Factsheet for more information.

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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Biofuels Factsheet." Pub. No. CSS08-09. **August 2023**

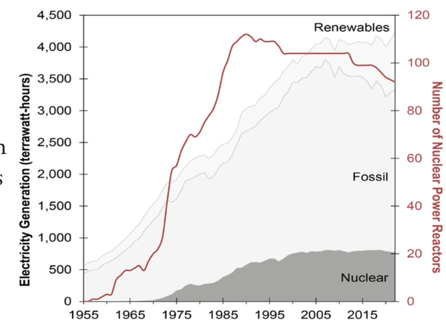
Nuclear Energy

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 spent nuclear fuel and radioactive waste.

Nuclear Energy Use and Potential

- Nuclear energy provides about 19% of U.S. electricity, and this share has remained stable since around 1990. Nuclear power plants had a capacity factor of 92.6% in 2022.[1]
- The first U.S. nuclear power plant began commercial operations in 1958.[2] During the 1970s, more than 50 nuclear reactors went online.[1] Presently, 28 states have at least one nuclear plant and 32 plants have two or more reactors.[2]
- 667 reactors have been built worldwide since the first was built in 1954 in Obninsk, Russia, though currently, there are only 436 in operation, 93 of which are in the U.S.[3,4] As of May 2023, 59 reactors were under construction, including 1 in the U.S. and 23 in China.[4]
- In 2021, the U.S. generated nearly a third of the world’s nuclear electricity. Countries generating the next largest amounts of electricity using nuclear were China, France, and Russia.[5]
- Levelized cost of energy (LCOE) includes the lifetime costs of building, operating, maintaining, and fueling a power plant. Estimated LCOE for plants built in the near future are: combined cycle natural gas: 4.27 ¢/kWh; advanced nuclear: 7.10 ¢/kWh; and biomass: 7.72 ¢/kWh.[6]
- Estimated LCOE for new nuclear plants built in the near future are about two times higher than estimates for wind and about three times higher than solar.[6]
- Final construction costs for U.S. nuclear plants have typically been 2 to 3 times higher than original estimates.[7]

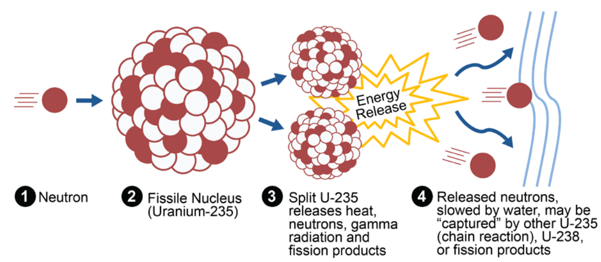
U.S. Electricity Generation by Source[1]



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.[8]
- The highest grade ore in the U.S. average less than 1% uranium, some Canadian ore is more than 15% uranium.[9,10]
- 1% of uranium available at reasonable cost is found in the U.S. The largest deposits are in Australia (28%), Kazakhstan (13%), Canada (10%), Russia (8%), and Namibia (8%).[10] U.S. nuclear plants purchased 18,370 metric tons (t) of uranium in 2022. Fuel was imported mostly from Canada (27%), Kazakhstan (25%), Russia (12%) and Uzbekistan (11%).[11]
- Globally, nuclear power reactors required 62,496 t of uranium in 2021.[4]

Fission of Uranium-235 in a Nuclear Reactor

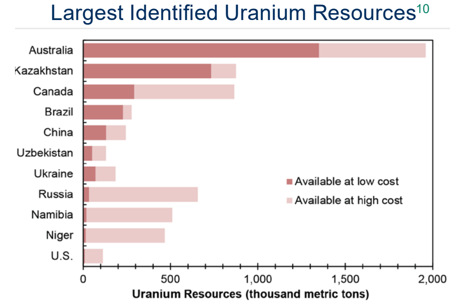


Energy and Environmental Impacts

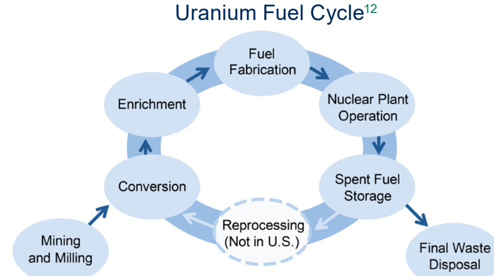
The nuclear fuel cycle is the entire process of producing, using, and disposing of uranium fuel. Powering a one-gigawatt nuclear plant for a year can require mining 20,000-400,000 t of ore, processing it into 27.6 mt of uranium fuel, and disposing of 27.6 t of highly radioactive spent fuel, of which 90% (by volume) is low-level waste, 7% is intermediate-level waste, and 3% is high-level waste.[12,13] U.S. plants currently use “once-through” fuel cycles with no reprocessing.[14,15]

- Uranium is mostly extracted by in-situ leaching (ISL) (58.3%), open pit mining (18.7%), and underground mining (16.1%).[10]
- A uranium fuel pellet (~1/2 in. height and diameter) contains the energy equivalent of one ton of coal or 149 gallons of oil.[16] Typical reactors hold 18 million pellets.[17]
- Each kWh of nuclear electricity requires 0.1-0.3 kWh of life cycle energy inputs.[18]
- Although nuclear electricity generation itself produces no GHG emissions, other fuel cycle activities do release emissions.[19] The life cycle GHG intensity of nuclear power is estimated to be 34-60 gCO_2e/kWh—far below baseload sources such as coal (1,001 gCO_2e/kWh).[19,20]
- Nuclear power plants consume 270-670 gallons of water/MWh, depending on operating efficiency and site conditions.[21]
- For pressurized water reactors and boiling water reactors most environmental impacts are caused by the extraction and production of fuel elements.[23]

Largest Identified Uranium Resources[10]



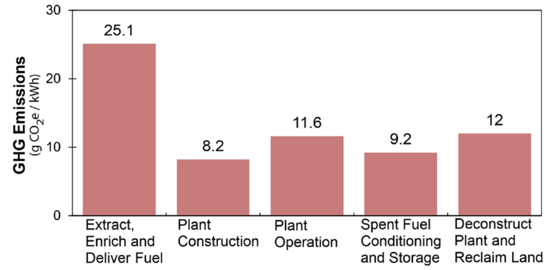
Uranium Fuel Cycle[12]



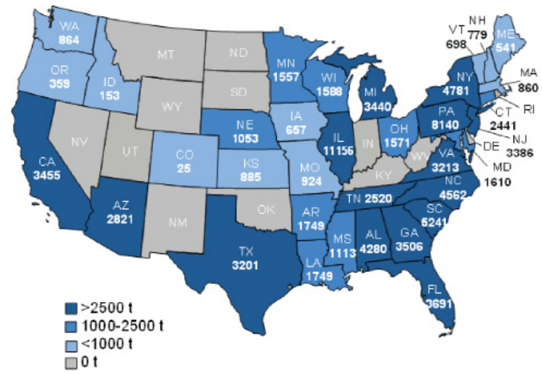
Nuclear Waste

- The U.S. annually accumulates about 2,000 mt of spent fuel.[24]
- 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.[12]
- Spent fuel is placed in a storage pool of circulating cooled water to absorb heat and block the high radioactivity of fission products.[25]
- Many countries, though not the U.S., reprocess used nuclear fuel. The process reduces waste and extracts 25-30% more energy.[15]
- 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.[26]
- 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).[14] 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.[27]
- The U.S. has no permanent storage site. Nevada's Yucca Mountain was to hold 70,000 t waste, but is no longer under consideration, mostly due to political pressure and opposition by Nevadans.[28,29]
- 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 storage at reactor sites.[30]

Life Cycle GHG Emissions of Nuclear Power[22]



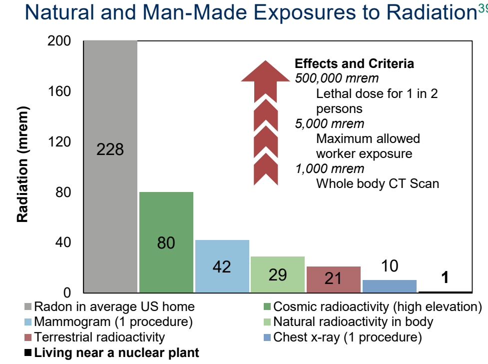
Spent Commercial Nuclear Fuel, Metric Tons[38]



Safety and Public Policy

- In 1986, a series of explosions occurred at the Chernobyl power plant in Ukraine. The loss of water in the reactor allowed the fuel to heat to the point of core meltdown. 134 workers and emergency responders were diagnosed with acute radiation syndrome and 28 died within weeks. Radiation releases were highest in Belarus, Ukraine, and Russia, lower in other parts of Europe. About 350,000 people were evacuated and/or permanently resettled, and a 1,000 square mile Chernobyl Exclusion Zone has been established to restrict public access. The number of long-term cancers and deaths are unknown, with most fatality estimates in the low thousands.[31]
- On March 11, 2011, a magnitude 9.0 earthquake occurred near Fukushima, Japan. The resulting tsunami damaged the reactor cooling system, leading to 3 meltdowns and hydrogen explosions. No deaths or radiation sickness have been directly linked to the accident. Radiation releases were lower than from Chernobyl, and mostly deposited in the Pacific Ocean. About 150,000 people were evacuated. The long-term cancers and deaths are unknown, with most fatality estimates in the hundreds to very low thousands.[32]
- The U.S. Price-Anderson Act limits the liability of nuclear plant owners if a radioactive release occurs to $450 million for individual plants and $13.5 billion across all plants.[33]
- Incentives for new nuclear plants include insurance against regulatory delays, a production tax credit of 1.8¢/kWh of electricity generated and $10.9 billion for federal loan guarantees.[34,35]
- In 2022, The Inflation Reduction Act (IRA) provided updated production tax credits for existing reactors and new nuclear deployment. Other incentives are also available to promote nuclear advancement and electricity generation including an investment tax credit.[36]
- The Bipartisan Infrastructure Deal allocated $6 billion for the Civilian Nuclear Credit program to prevent premature retirement of existing nuclear plants.[37]

Natural and Man-Made Exposures to Radiation[39]



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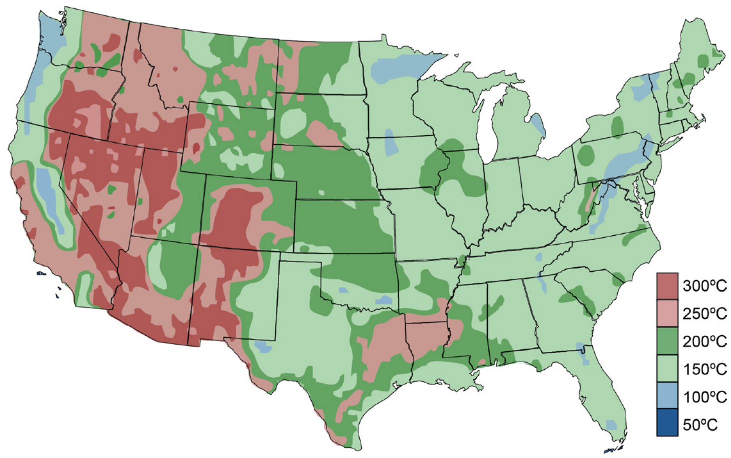
Geothermal Energy

Geothermal Resource and Potential

U.S. Geothermal Resources[3]
at 10 km depth

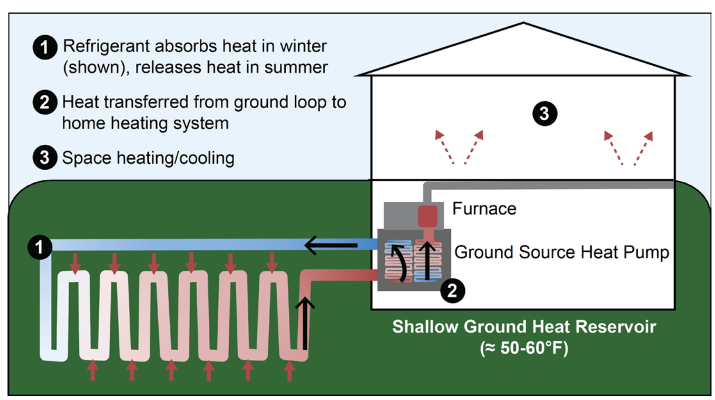


- Geothermal energy is derived from the natural heat of the earth.[1] It exists in both high enthalpy (volcanoes, geysers) and low enthalpy forms (heat stored in rocks in the Earth's crust). Nearly all heating and cooling applications utilize low enthalpy heat.[2]
- Geothermal energy has two primary applications: heating/cooling and electricity generation.[1]
- Ground source heat pumps for heating and cooling use 75% less energy than traditional heating and cooling systems.[4]
- The U.S. has tapped less than 0.7% of geothermal electricity resources; the majority can become available with Enhanced Geothermal System technology.[5,6]
- In 2021, there were 3,692 MW of geothermal electricity plants in operation in the U.S.—the most of any country—and development has been growing at a rate of 3% per year.[6]
- Electricity generated from geothermal plants is projected to increase from 17 billion kWh in 2022 to 37.2 billion kWh in 2050.[7,8] In 2021, California and Nevada were the states with the most installed geothermal energy capacity, with 95% of U.S capacity.[6]
- The U.S., Indonesia, Philippines, Turkey, New Zealand, and Mexico had 74% of global installed geothermal power capacity in 2022.[9]

Geothermal Technology and Impacts

Direct Use and Heating/Cooling

Ground Source Heat Pump in a Residential Heating Application[10]



- Geothermal (or ground source) heat pumps (GSHPs) are the primary method for direct use of geothermal energy. GSHPs use the shallow ground as an energy reservoir because it maintains a nearly constant temperature between 50-60°F (10–16°C).[11]
- GSHPs transfer heat from a building to the ground during the cooling season, and from the ground into a building during the heating season.[11]
- Direct-use applications include space and district heating, greenhouses, aquaculture, and commercial and industrial processes.[12]

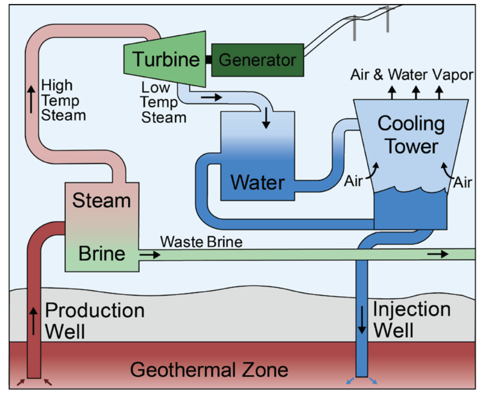
Electricity Generation

- Geothermal energy currently accounts for 0.4% of electricity generation in the United States.[7]
- In 2020, the U.S. generated the most geothermal electricity in the world: 18,831 GWh.[9]
- Hydrothermal energy, typically supplied by underground water reservoirs, is a main source of thermal energy used in electricity generation. The water is often pumped as steam to the earth's surface to spin turbines that generate electricity.[13]
- Dry steam power plants use steam from a geothermal reservoir and route it directly through turbines, which drive generators to produce electricity.[13]
- 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.[13]
- 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.[13]
- Enhanced Geothermal System (EGS) is a technology under development that could expand the use of geothermal resources to new geographic areas. EGS creates 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.[14]
- 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.[14]

Installation, Manufacturing, and Cost

- The main stages of geothermal power development are resource exploration, drilling, reservoir/plant development, and power generation.[16]
- Capital costs for conventional geothermal power plants in the U.S. are approximately $2,500 per installed kilowatt of capacity.[17]
- Although the development of geothermal power requires a large capital investment, geothermal has low operating costs and a capacity factor of >90% (ratio of actual power production to production potential).[16,18]
- In 2016, geothermal electricity cost between 7.8-22.5¢ per kWh. As of May 2020, geothermal plants qualified for the federal Production Tax Credit (PTC).[18]
- In 2022, the Inflation Reduction Act renewed and expanded the PTC, which provides up to 2.6¢ per kWh for electricity generated from geothermal resources.[19]

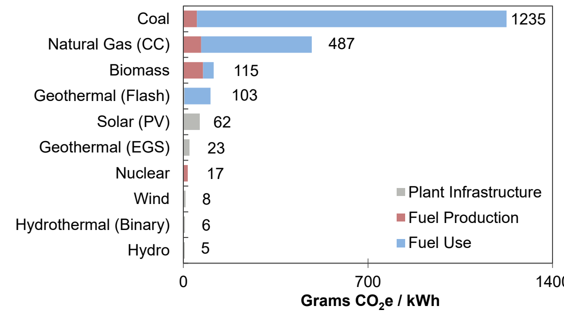
Flash Steam Geothermal Power Plant[15]



Energy Performance and Environmental Impacts

- An average U.S. coal power plant emits roughly 35 times more carbon dioxide (CO_2) per kWh of electricity generated than a geothermal power plant.[20]
- 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).[21,22]
- Each year, U.S. geothermal electricity offsets the emission of 22 million metric tons (Mt) of CO2, 200 thousand metric tons (t) of nitrogen oxides, and 110 thousand t of particulate matter from coal-powered plants.[18]
- The U.S. DOE is actively funding research into combining carbon capture and storage with geothermal energy production, although the risks of long-term and high-volume geologic carbon sequestration are uncertain.[23, 24]
- Some geothermal facilities produce solid waste that must be disposed of in approved sites, though some by-products can be recovered and recycled.[25]

GHG Emissions from Power Generation[32]
by Life Cycle Stage



Solutions and Sustainable Actions

Funding Opportunities

- In 2019, there were 16 national laboratories and research institutions in the U.S. conducting research into geothermal energy technologies.[26]
- 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.[17]
- Renewable Portfolio Standards (RPS) require electricity providers to obtain a minimum fraction of energy from renewable resources.[27]
- 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.[28]
- A federal tax credit for homeowners can cover up to 30% of qualifying ground source heat pump system costs depending on construction date from 2006 through 2034.[29]
- Around 850 utilities in the U.S. offer consumers the option to purchase renewable energy, or "green power."[30]
- Many companies purchase renewable energy as part of their environmental programs. Google, Microsoft, T-Mobile, Walmart, and The Proctor & Gamble Company were the top five users of renewable energy as of April 2023.[31]

Steamboat Hills Geothermal Power Plant[33]
Steamboat Springs, Nevada

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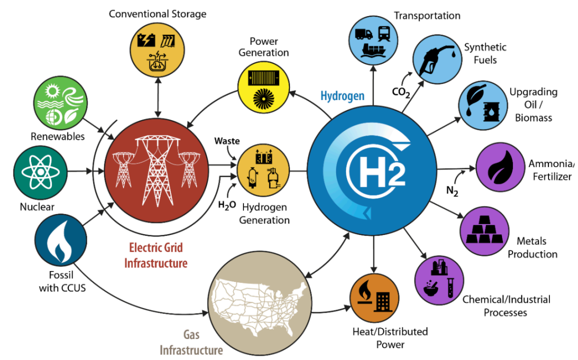
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Geothermal Energy Factsheet." Pub. No. CSS10-10. **July 2023**

Hydrogen

Hydrogen Economy

Hydrogen is a feedstock and energy carrier used in multiple sectors of our economy. Globally 90 million metric tons (Mt) of hydrogen were produced and used in 2020, with U.S. production being approximately 10 Mt. Hydrogen is the most abundant element in the universe, but is present in limited amounts in elemental form on Earth. The primary method of producing hydrogen globally and in the U.S. is steam methane reforming (SMR) of natural gas. SMR results in CO_2 emissions, which is problematic from a climate change perspective. Electrolysis is a hydrogen production process that uses electricity to split water into hydrogen and oxygen. This production process can provide a pathway for decarbonizing some sectors of the economy if the electricity is generated from zero- or low-carbon sources such as renewables and nuclear power. Hydrogen can play a key role in decarbonizing end-use applications where other alternatives such as electrification are problematic.[1]

H2@Scale Diagram[2]



- Global demand for hydrogen could reach 150 Mt by 2030.[3]
- Hydrogen has a very low volumetric energy density and is stored as either a high-pressure gas, or low-temperature liquid.[4]

Hydrogen Technologies and Impacts

Production

- Hydrogen can be produced via several pathways including SMR, electrolysis of water, and gasification of coal or biomass.[5]
- Color codes have been used to describe hydrogen production pathways. Commonly used colors include grey for SMR, blue for SMR with carbon capture and sequestration (CCS), and green for electrolysis using renewable electricity.[6]
- In SMR, natural gas is reacted with high temperature steam to produce hydrogen. The resulting synthesis gas also contains CO and CO_2. Using the "water-gas shift reaction" the CO and steam are reacted together over a catalyst producing more hydrogen and CO_2.[7]
- SMR is the least expensive ($1-2/kg$H_2$) and widely used method of producing hydrogen.[5,8] Currently about 95% of hydrogen in the U.S. is produced using SMR at large central plants.[7] Hydrogen produced with SMR emits about 7-10 kgCO_2/kgH_2.[9]
- The 2020 production cost for green hydrogen is about $7.5/kg$H_2$. The U.S. Department of Energy (DOE) targets are to lower this to $2/kg$H_2$ by 2026 and $1/kg$H_2$ by 2031.[2]
- Alkaline and proton exchange membrane (PEM) electrolyzers are commercially available, while solid oxide electrolyzer cell (SOEC) and anion exchange membrane (AEM) electrolyzers are maturing.[10] In 2019, electrolyzers had a baseline higher heating value conversion efficiency of 71%.[11]
- The current grid mix is not ideal for electrolysis as around 60% of U.S. electricity is still produced using fossil fuels.[12] The CO_2 intensity of hydrogen produced by electrolysis is approximately 20-25 kgCO_2/kgH_2 in the U.S.[2]

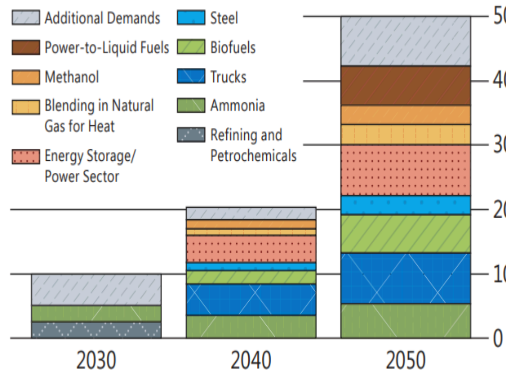
Distribution and Storage

- Hydrogen in the U.S. is produced at, or near, where it will be used, reflecting difficulties with transportation.[5]
- Hydrogen can be transported to point of use via pipeline, or over the road using liquid tanker, or tube trailer trucks.[13]
- Pipelines are the least expensive way to deliver hydrogen at a cost $0.2-0.5/kg$H_2$. There are approximately 1600 miles of pipeline in the U.S.[5,14]
- Tube trailers can transport compressed hydrogen, typically used over distances of 200 miles or less, but are expensive at $0.9-1.9/kg$H_2$.[5,14]
- Liquid tankers are better suited than tube trailers for transporting larger amounts of hydrogen over longer distances, but are more expensive at $2.7-3.2/kg$H_2$ due to the energy and equipment requirements for the liquefaction process.[5,14]
- Hydrogen has the highest energy per mass of any fuel at 120 MJ/kgH_2 on a lower heating value basis, but a low volumetric energy density of 8 MJ/l for liquid hydrogen, compared to a volumetric energy density of 32 MJ/l for gasoline.[4]
- At 1 bar and 25°C, the volumetric energy density of hydrogen is lower than those of gasoline, diesel, jet fuel, and marine bunker fuel by factors of approximately 3200, 3700, 3600, and 4000, respectively.[1]
- Even as a compressed gas at 700 bar or as a liquid at -253°C the volumetric energy density of hydrogen is 7-8 and 4-5 times lower, respectively, than conventional liquid hydrocarbon fuels at ambient conditions.[1]
- Using compression or liquefaction, hydrogen can be stored in its pure form as a compressed gas or cryogenic liquid. Liquefaction can achieve greater densities than compressed gas, but is more energy intensive and requires specialized equipment.[15]
- Hydrogen gas is typically stored at 350 or 700 bar while liquid storage requires cryogenic temperatures since its boiling point is −253°C.
- Underground hydrogen storage may be possible, conventional options include using salt caverns, while proposed methods include abandoned coal mines and refrigerated mined caverns.[16]

End-Uses

- Petroleum refineries are the largest consumers of hydrogen in the U.S. using about 5.5 Mt annually in 2021. Second to refineries, U.S. ammonia synthesis consumed around 3.5 Mt of hydrogen in 2021.[2] Other uses of hydrogen include the production of methanol used in industrial applications and chemical manufacturing, and the reduction of iron ore through direct reduction.
- A variety of hydrocarbon synfuels can be produced by reacting hydrogen with CO_2, making production of synfuels a potential demand for hydrogen. When CO_2 is captured from the atmosphere and used for hydrocarbon synfuel production the carbon in the fuel can be considered net zero in terms of emissions, though there are potentially emissions associated with the CO_2 capture process.[18]
- Blending hydrogen with natural gas could result in rapid demand increase.[18] Preliminary estimates say hydrogen can be injected into natural gas pipelines up to concentrations of 20% by volume, but co-firing with natural gas reduces greenhouse gas emissions only 6-7%.[18,19]
- Direct reduction of iron (DRI) using hydrogen has potential to replace blast furnace steel production - 47-68 $kgH_2/tDRI$ is estimated to be required in this process.[8]

Projected Growth in Hydrogen End-Uses in U.S.[17]
(million metric tons H_2 per year)



- Hydrogen burners are currently under development to replace natural gas and other fossil fuels in high-temperature heat applications. These applications include cement clinker kilns, glass furnaces, aluminum remelting furnaces, metal rolling and heat treatment furnaces.
- Hydrogen can be used in residential buildings to power fuel cell combined heat and power (CHP) systems, direct flame combustion boilers, catalytic boilers, and gas powered heat pumps. Larger district heat and CHP devices using NG could be redesigned for hydrogen.[20]
- Hydrogen can be used directly or indirectly in conventional and synfuels, in all forms of transportation (road, rail, water, air). Global petroleum refining used 40 Mt H_2 in 2021, which was more than 1000 times the direct use of hydrogen as a transportation fuel. Clean hydrogen is expected to play an important role in decarbonizing heavy-duty transport (road, marine fuels, aviation fuels) by 2050.
- Direct use of electricity in light-duty vehicles is about 3 times more energy efficient than conversion into hydrogen and use in fuel cell vehicles.
- Hydrogen is not well suited for use in light-duty cars and trucks, but may find use in medium- and heavy-duty vehicles that need to store large amounts of energy and refuel rapidly, both of which are challenging for electric vehicles.

Environmental Impacts

- Global hydrogen production currently accounts for approximately 1 Gt of CO_2 emissions.
- Electrolysis represents less than 5% of worldwide hydrogen production now, but is a pathway to zero-carbon emissions.[20]
- On a stoichiometric basis the water consumption required for electrolysis is 9 kgH_2O/kgH_2.[22] When accounting for electricity generation, water consumption increases to 15-20 kgH_2O/kgH_2.[23]
- The water required to produce 800 Mt of hydrogen for a net zero economy in 2050 is much less than what is needed for the extraction and processing of fossil fuels today.[23]
- Hydrogen production on this scale would account for 0.7% of global freshwater use. Desalination would add approximately $0.02/kg to the price of hydrogen.[23]

U.S. Hydrogen Strategy and Policy

To bolster development of the hydrogen economy the U.S. the Infrastructure, Investment, and Jobs Act (IIJA) contains $9.5 billion of funding for hydrogen. The Inflation Reduction Act (IRA) contains two provisions that will subsidize clean hydrogen production.[24] The U.S. National Clean Hydrogen Strategy and Roadmap from the DOE explores pathways for clean hydrogen to aid in decarbonization goals across the economy.[2] The U.S. Department of Transportation Federal Highway Administration designated a national network of electric vehicle charging and hydrogen, propane, and natural gas fueling infrastructure along national highway system corridors.[25]

Hydrogen Hubs

- The U.S. DOE aims to establish 6-10 regional clean hydrogen hubs across the U.S. through a Regional Clean Hydrogen Hubs Program (H2Hubs). H2Hubs has a $7 billion budget and is part of the larger hydrogen hub program funded by the IIJA with the goal of creating networks of hydrogen producers, consumers, and local connective infrastructure.[26]

Tax Credits Promoting Hydrogen

- The value of the IRA tax credits (IRC Sec 45V) are determined based on life cycle CO_2e emissions per kg of hydrogen produced. The IRA also increases the rate of an existing tax credit for carbon sequestration (IRC Sec 45Q) that cannot be combined with 45V.[24]

IRA Hydrogen Investment Tax Credit and Production Tax Credit[24]

Life Cycle Emissions ($kgCO_2e/kgH_2$)	Investment Tax Credit (%)	Production Tax Credit (2022$/$kgH_2$)
2.5-4	6%	0.60
1.5-2.5	7.5%	0.75
0.45-1.5	10%	1.00
0-0.45	30%	3.00

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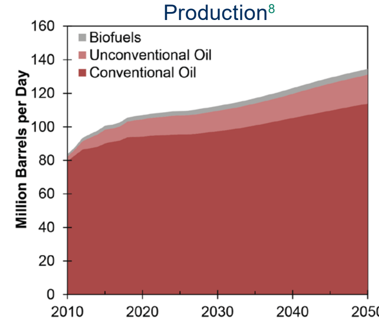
Unconventional Fossil Fuels

Patterns of Use

Globally, fossil fuels supply 81% of primary energy.[1] In 2022, 79% of U.S. primary energy consumption came from fossil fuels.[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 are found in pore spaces throughout a wide geologic formation, requiring advanced extraction techniques.[3] If unconventional oil resources (oil shale, tar sands, extra heavy oil, and natural bitumen) are accounted for, global oil reserves are quadruple current conventional reserves.[4] The price of crude oil peaked in 2008 at $145.31 per barrel, making unconventional fossil fuels more cost-competitive.[5] The price of crude oil temporarily fell below zero in 2020.[5] Partially as a result of sustained low oil prices, over 270 oil and gas producers have filed for bankruptcy since 2015.[6] The Energy Policy Act of 2005 includes provisions to promote U.S. oil sands, oil shale, and unconventional natural gas development.[7]

Global Projected Liquid Fuel Production[8]

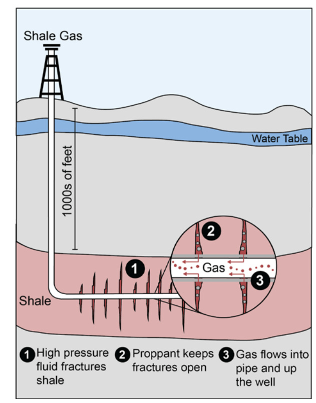


Major Unconventional Sources

Unconventional Natural Gas

- Unconventional natural gas (UG) comes primarily from three sources: shale gas in low-permeability shale formations; tight gas in low-permeability sandstone and carbonate reservoirs; and coalbed methane (CBM) in coal seams.[9]
- 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 cubic feet (Tcf), followed by Argentina (802 Tcf) and Algeria (707 Tcf).[10] Global tight gas resources are estimated at 2,684 Tcf, with the largest in Asia/Pacific and Latin America.[9] Resources of CBM are estimated at 1,660 Tcf, with more than 75% in Eastern Europe/Eurasia and Asia/Pacific.[9]
- Recoverable U.S. resources are estimated at 1,778 Tcf from shale and tight gas and 76 Tcf from CBM.[11]
- 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.[9]
- UG accounted for 89% of total U.S. natural gas production in 2022 and is expected to account for 93% of production by 2050.[12]

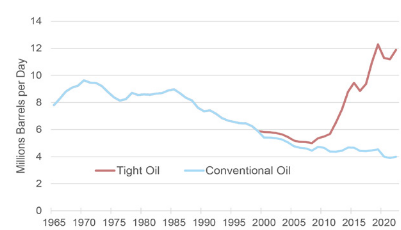
Hydraulic Fracturing Horizontal Well[9]



Tight Oil

- Tight oil, or shale oil, is found in impermeable rocks such as shale or limestone and is extracted through fracking, often concurrently with natural gas.[13]
- Over the past decade, tight oil production has expanded significantly. In 2022, 66% (7.8 million barrels per day) of crude oil production in the U.S. came from tight oil.[14] In 2021 the top tight oil producing states were Texas, New Mexico, North Dakota, Alaska, and Colorado.[15]
- It is estimated that the U.S. has 191 billion barrels of technically recoverable tight oil.[11]
- Negative health effects in newborns from *in utero* exposure to fracking sites have been found.[18]

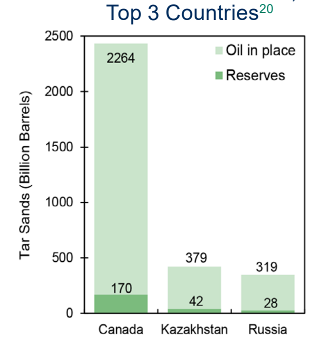
Annual U.S. Crude Oil Production[16,17]



Tar Sands

- Tar sands, i.e., "oil sands" or "natural bitumen," are a combination of sand (83%), bitumen (10%), water (4%), and clay (3%). Bitumen is a semisolid, tar-like mixture of hydrocarbons.[19]
- Known tar sands deposits exist in 23 countries. Canada has 73% of global estimated tar sands, approximately 2.4 trillion barrels (bbls) of oil.[20] The U.S. has 1.6% of global tar sands resources; however, 60% of U.S. crude oil imports came from Canada in 2022, and 66% of Canadian production comes from tar sands.[20,20,22]
- Deposits less than 250 feet below the surface are mined and processed to separate the bitumen.[23] Deeper deposits employ *in situ* (underground) methods, including steam or solvent injection to liquify the bitumen so that it can be extracted from the ground. Bitumen must be upgraded to synthetic crude oil (SCO) before it is refined into petroleum products.[19]
- Around two U.S. short tons (tons) of tar sands produce one barrel of SCO.[19]

Tar Sands Resources, Top 3 Countries[20]

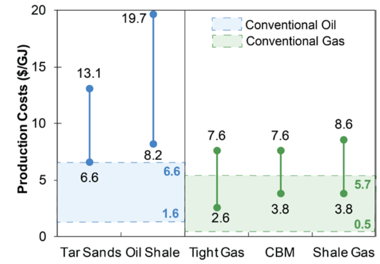


Oil Shale

- Oil shale is a sedimentary rock with deposits of organic compounds called kerogen, which has not undergone enough geologic pressure, heat, and time to become conventional oil. Oil shale can be heated to generate petroleum-like liquids.[24]
- Oil shale deposits exist in 33 countries.[4] The U.S. has the largest oil shale resource in the world, approximately 6 trillion bbls of oil in place, though oil shale is far from commercial development.[4,25]

Life Cycle Impacts

Production Cost Ranges, Conventional and Unconventional Fossil Fuels[19]



Greenhouse Gases

- Fossil fuel combustion accounted for 73% of U.S. greenhouse gas (GHG) emissions in 2021.[26]
- Equivalent amounts of GHGs are released by conventional and unconventional fuels at the point of use. Life cycle emissions for unconventional oil are higher than conventional oil on average, though some studies suggest they are similar.[27] Studies have found life cycle emissions for tar sands are 17% higher than average refined U.S. crude, and oil shale emissions are 21% to 47% higher than conventional oil.[28,29] Studies of life cycle emissions for UG have resulted in estimates from 6% lower to 43% higher than conventional natural gas sources.[30,31]
- Natural gas generates fewer GHG emissions when combusted than other fossil fuels.[32] Natural gas is primarily methane (CH_4) and CH_4 leakage can significantly decrease any emissions benefit of natural gas over other fossil fuels.[30] CH_4 leakage from the U.S. oil and natural gas supply chain is estimated to be 13 million metric tons (MMT) per year, equivalent to 2.3% of U.S. annual gross natural gas production and nearly 42% of U.S. anthropogenic CH_4 emissions. With a global warming potential of almost 30, this leakage is equivalent to 387 MMT of CO2, or 6.1% of total U.S. GHG emissions in 2021.[26,33,34]

Water

- Producing one barrel of oil from oil shale uses 1 to 12 barrels of water for *in situ* production and 2 to 4 barrels of water for mining production; one barrel of oil from tar sands uses 0.4 to 3.1 barrels of water.[35,36] Producing one barrel of oil in Saudi Arabia requires 1.4 barrels of water.[37]
- A horizontal gas well can require 2 to 4 million gallons of water to drill and fracture.[38] One study found shale gas production uses up to four times more water than producing conventional natural gas.[32]
- CBM production requires groundwater extraction; U.S. CBM basins withdraw 32 million to 15 billion gallons of water from aquifers per year.[39]
- Wastewater, produced water, and flowback water from oil and gas extraction can contain excess salts, high levels of trace elements, and naturally-occurring radioactive materials.[40] Groundwater can be polluted through above- and below-ground activities, including construction, drilling, chemical spills, leaks, and discharge of wastewater.[41]

Land Impacts and Waste

- More than 75% of U.S. oil shale is on federal land, of which 678,700 acres has been designated for development.[42,43] A 20,000 bbl/day tar sands facility requires 2,950 acres of land and creates 52,000 tons/day of waste sand; 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. An oil shale facility often remains active for several years.[44]
- One gas well requires one to two hectares of land, in addition to road networks.[45] Drilling fluid, or "mud," is used to cool the drill bit, regulate pressure, and remove rock fragments. One well may require hundreds of tons of mud and produce 110 to 550 tons of rock cuttings.[9]
- Small to moderate magnitude (<M6) seismic activity has been linked to underground injection of wastewater produced in oil and gas operations.[46] Fracking has been associated with microearthquakes (<M2), but no association has been found with larger magnitude events.[47]
- 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.[48]

Solutions and Sustainable Alternatives

- Chemicals used in hydraulic fracturing fluid are often considered proprietary.[45] Requiring companies to disclose these chemicals will lead to better understanding of the risk to public health from their use.[38] Twenty eight U.S. states required disclosure as of 2016.[49]
- Careful siting and monitoring of injection wells can reduce the potential for seismic events.[9]
- Water consumption in oil and gas extraction can be significantly reduced through efficiency improvements and the recycling of wastewater.
- 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 fuel and a source of GHG emissions.

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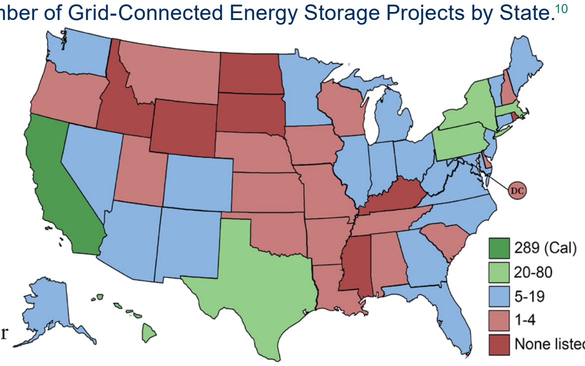
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Unconventional Fossil Fuels Factsheet." Pub. No. CSS13-19. **August 2023**

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.[1] Batteries are one of the most common forms of electrical energy storage, ubiquitous in most peoples' lives. The first battery—called Volta's cell—was developed in 1800. The first U.S. large-scale energy storage facility was the Rocky River Pumped Storage plant in 1929, on the Housatonic River in Connecticut.[2,3] Research in energy storage has increased dramatically, especially after the first U.S. oil crisis in the 1970s, and resulted in advancements in the cost and performance of rechargeable batteries.[2,4,5] The impact energy storage can have on the current and future sustainable energy grid is substantial.[6]

- EES systems are characterized by rated power in kilowatts (kW) and energy storage capacity in kilowatt-hours (kWh).[7]
- In 2022, the rated power of U.S. EES was 31.6 GW compared to 1,167 GW of total installed generation.[8,9] Globally, the rated power of installed EES was 174 GW.[10]
- In 2021, 1,595 energy storage projects were operational globally, with 125 projects under construction. 51% of operational projects are located in the U.S.[10]
- California leads the U.S. in energy storage with 289 operational projects (5.6 GW), followed by Massachusetts, Texas, and New York.[10]

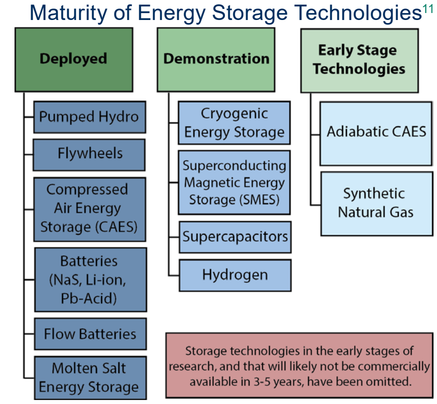
Number of Grid-Connected Energy Storage Projects by State.[10]



Deployed Technologies

Key EES technologies include: Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES), Advanced Battery Energy Storage (ABES), Flywheel Energy Storage (FES), Thermal Energy Storage (TES), and Hydrogen Energy Storage (HES).[13] PHS and CAES are large-scale technologies capable of discharge times of tens of hours and power capacities up to 1 GW, 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.[14]

Maturity of Energy Storage Technologies[11]



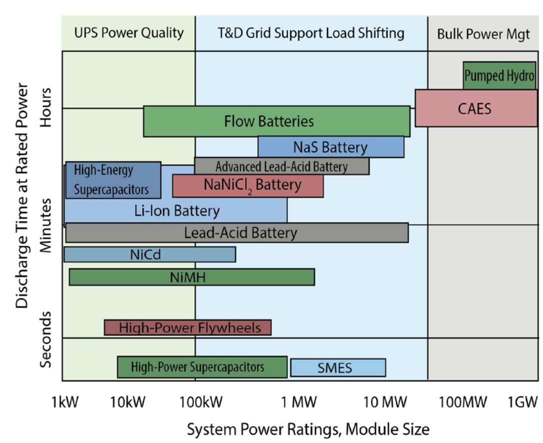
Pumped Hydroelectric Storage (PHS)

- PHS systems pump water from a low to high reservoir and, when electricity is needed, water is released through a hydroelectric turbine, generating electricity from kinetic energy.[14,15]
- Globally, 96% of energy storage is from PHS.[15]
- PHS plants have long lifetimes (50-60 years) and operational efficiencies between 70 and 85%.[14,15]

Compressed Air Energy Storage (CAES)

- CAES systems store compressed air in an underground cavern. The pressurized air is heated and expanded in a natural gas combustion turbine, driving a generator.[16,17]
- Existing CAES plants are diabatic, 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, reduces CO_2 emissions by 40-60%, and enables plant efficiencies of 42-55%.[17]
- As of August 2019, there were 2 CAES plants operating in the U.S. and Germany. The U.S. facility is a 110 MW plant in Alabama.[18]

Characteristics of Energy Storage Technologies[12]



Advanced Battery Energy Storage (ABES)

- ABES stores electrical energy in the form of chemical energy.[19]
- Batteries contain two electrodes (anode and cathode) composed of different materials and an electrolyte that separates the electrodes. The electrolyte enables the flow of ions between the two electrodes and external wires allow for electrical charge to flow.[19]
- The U.S. has over 580 operational battery-related energy storage projects using lead-acid, lithium-ion, nickel-based, sodium-based, and flow batteries.[10] These projects account for 4.8 GW of rated power in 2021 and have round-trip efficiencies (the ratio of net energy discharged to the grid to the net energy used to charge the battery) between 60-95%.[10,20]

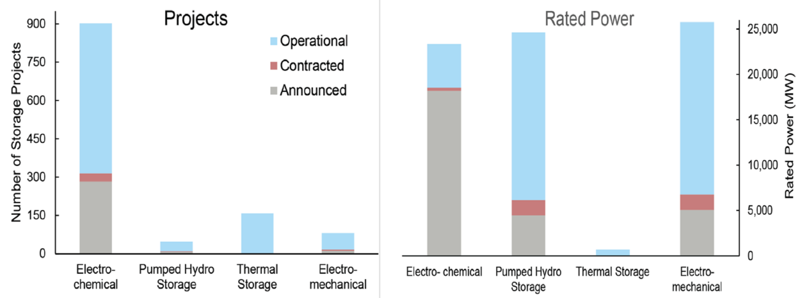
Flywheel Energy Storage (FES)

- FES systems store kinetic energy by spinning a rotor in a low-friction enclosure, and are used mainly for grid management rather than long-term energy storage.[17] The rotor changes speed to shift energy to or from the grid, as needed for grid stability.[14]
- In 2021, flywheels account for 0.10 GW of rated power in the U.S. with efficiencies between 85-87%.[10,20]
- There are two categories of FES: low-speed and high-speed. These systems rotate at rates up to 10,000 and 100,000 RPM (revolutions per minute), respectively, and are best used for high power/low energy applications.[17]

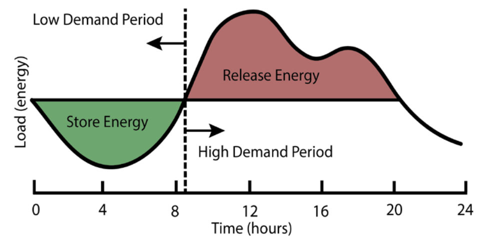
Applications

- EES systems have 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).[22]
- EES can operate at partial output levels with low losses and can respond quickly to changes in electricity demand.[23] Much of the current energy infrastructure is approaching—or beyond—its intended lifetime.[24] Storing energy in off-peak hours and using that energy during peak hours saves money and prolongs the lifetime of energy infrastructure.[21]
- Round-trip efficiency, annual degradation, and generator heat rate have a moderate to strong influence on the environmental performance of grid connected energy storage.[25]
- Energy storage will help with the adoption of renewable energy by storing excess energy for times when renewable energy sources are unavailable.[26]

U.S. Energy Storage Projects by Technology Type in 2021[10]



Daily Energy Storage and Load Leveling[21]



Five Categories of Energy Storage Applications[23]

1) Electric Supply	i) Transmission & Distribution Upgrade Deferral
a) Electric Energy Time-shift	j) Substation On-site Power
b) Electric Supply Capacity	**4) End User/Utility Customer**
2) Ancillary Services	k) Time-of-use Energy Cost Management
c) Load Following	l) Demand Charge Management
d) Area Regulation	m) Electric Service Reliability
e) Electric Supply Reserve Capacity	n) Electric Service Power Quality
f) Voltage Support	**5) Renewables Integration**
3) Grid System	o) Renewable Energy Time-shift
g) Transmission Support	p) Renewables Capacity Firming
h) Transmission Congestion Relief	q) Wind Generation Grid Integration

Solutions

Research & Development

- The U.S. Department of Energy (DOE) administered $185 million of the American Recovery and Reinvestment Act (ARRA) funding to support 16 large-scale energy storage projects with a combined power capacity of over 0.53 GW.[27]
- Storage technologies are becoming more efficient and economically viable. One study found that the economic value of energy storage in the U.S. is $228.4 billion over a 10 year period.[23]
- Lithium-ion batteries are one of the fastest-growing energy storage technologies due to their high energy densities, high power, near 100% efficiency, and low self-discharge.[28,29] The U.S. has 1 million metric tons (Mt) of lithium reserves; globally, there are 26 Mt of reserves.[30]
- Long-term (10-100 hours) and seasonal (100+ hours) energy storage are also important areas of research. Hydrogen, compressed air, and hydropower are the most viable technologies for these types of storage.[31]
- When designing EES, ensure system deployment results in a net reduction in environmental impacts.[32]

Policy & Standardization

- The Energy Independence and Security Act of 2007 enabled an Energy Storage Technologies Subcommittee through the Electricity Advisory Committee (EAC), whose members assess and advise the U.S. DOE every two years on progress towards domestic energy storage goals.[27]
- 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.[33] Massachusetts, Nevada, New Jersey, New York, Oregon and Virginia all have similar mandates.[34]
- In 2018, the U.S. Federal Energy Regulatory Commission (FERC) issued Order No. 841, which requires wholesale electricity markets to establish participation models that recognize energy storage's physical and operational characteristics. The order builds on past FERC Orders No. 755 and No. 784.[35]
- The 2022 Inflation Reduction Act was passed to accelerate the clean energy transition. Its provisions include incentives, like the Investment Tax Credit, for energy storage systems.[36]

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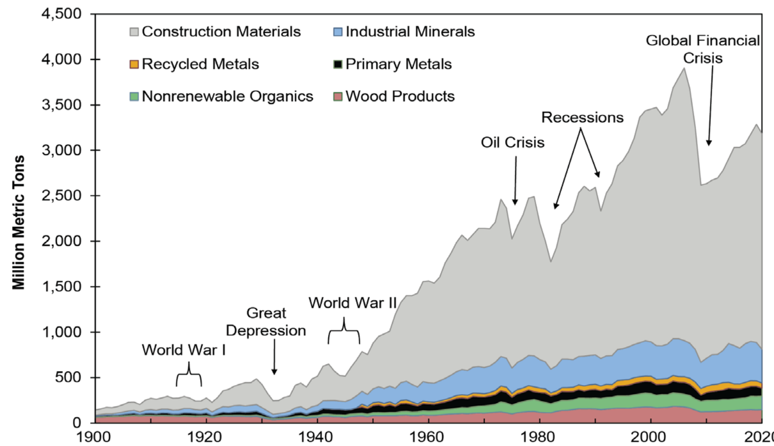
Cite as: Center for Sustainable Systems, University of Michigan. 2023. “U.S. Grid Energy Storage Factsheet.” Pub. No. CSS15-17. **August 2023**

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 material 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.

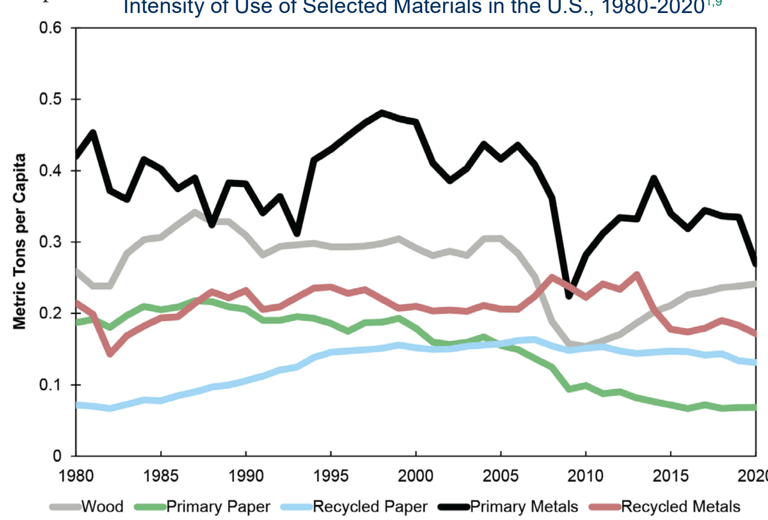
U.S. Nonfuel Material Consumption, 1900-2020[1]



- U.S. raw material (non-fossil fuel or food) use rose 3.23 times more than the population from 1910 to 2020.[1,2,3]
- After rising 54% from 1970 to 2005, total material consumption in the U.S. (including fuels and other materials) reached 7.8 billion metric tons (Gt) in 2019, which is still 34% higher than 1970 levels of material consumption.[4]
- In 2019, U.S. per capita total material consumption (including fuels) was 23.75 metric tons (t), 88% higher than Europe.[5]
- U.S. raw material use increased by 30% from 1996 to 2006, but decreased 32% from 2006 to 2010 following the global financial crisis. By 2020, U.S. raw material use had increased by 20% to over 3 Gt.[1]
- Construction materials, including stone, gravel, and sand, account for 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.[6]
- 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, iron, lithium, platinum, phosphate rock), to several decades (copper and gold).[7]
- Rare earth elements (REEs) are a group of 17 elements used in metal alloys, batteries, and as catalysts, with 74% used as catalysts.[7,8] Substitutes for REEs are available but are less effective.[7] China controlled more than 60% of REE production in 2021.[7]

Intensity of Raw Material Use

Intensity of Use of Selected Materials in the U.S., 1980-2020[1,9]

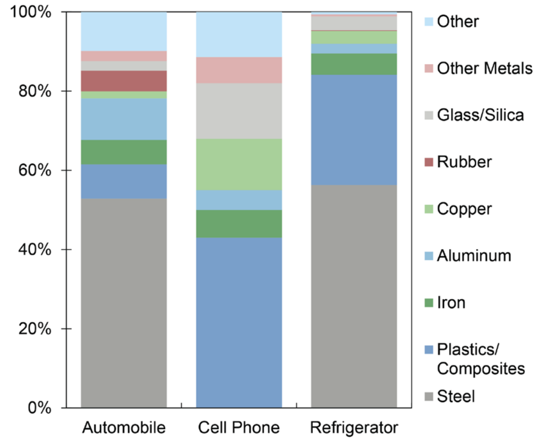


- Material intensity of use refers to the amount of material consumed per unit of economic output, generally measured by the total gross domestic product (GDP) of a country.[10] The domestic processed output, or total weight of materials and emissions produced by the domestic economy, declined per unit of GDP by about 44% in the U.S. over the last few decades, similar to other industrialized nations.[11]
- 44% of materials used in the U.S. economy are added to long-term (+30 years) domestic stock, 2% remain in stock between 2-30 years, 39% remain in stock less than 2 years, and the remaining 15% are recycled back into the economy.[11]
- Of the materials remaining in 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.[11]
- There has been an appreciable decline in the use intensity of primary metals (except aluminum), while plastics use continues to grow.[12]
- The composition of materials used in the U.S. economy has become less dense, i.e., less iron and steel and more lighter metals, plastics, and composites.[13]

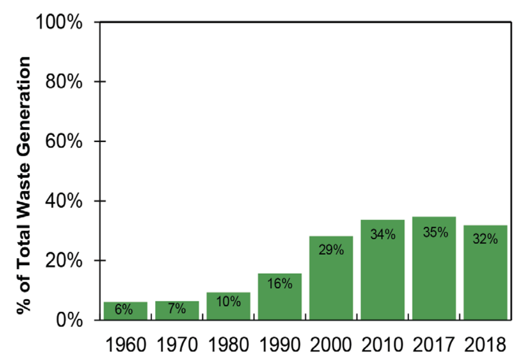
Environmental Impacts

- In 2017, it was estimated that only 8% of plastics disposed of in the U.S. were recycled. A further 2% "leaked" into the environment, often in the form of microplastics from tire abrasion and synthetic textiles, which is of growing concern globally due to impacts on organisms and unknown health consequences in humans.[17]
- 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.[18]
- 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.[19]
- The primary metals and metal mining sectors accounted for 52% of the total 3 billion pounds of toxic releases in 2021.[20]
- In 2021, almost 36 million metric tons (Mt) of Resource Conservation and Recovery Act (RCRA) regulated hazardous waste were generated in the U.S. The largest sources were chemical manufacturing (61%) and petroleum and coal products manufacturing (14%).[21]
- In 2018, nonmetallic mineral (stone, clay, glass, cement) manufacturing used 0.8 quads (1 quad = 10^{15} Btu) of energy; primary metal industries used 1.5 quads; petroleum/coal products used 4.2 quads; chemical manufacturing used 7.1 quads (total U.S. consumption was 101.2 quads).[22,23]
- Energy-related CO2 emissions from the industrial sector have fallen 23% since 2000, mainly due to a shift away from energy-intensive manufacturing in the U.S. economy.[23]
- 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 gasoline combustion.[24] However, in 2021, more than 228,000 U.S. short tons (tons) of lead and lead compounds were released; 86% came from metal mining, while metal production and electric utilities accounted for 4.5% and 0.6%, respectively.[20] New chemicals have been introduced that persist in the environment, bioaccumulate (move up the food chain), and/or are toxic, e.g., per-and polyfluoroalkyl substances (PFAS) which are used in products to make them heat, water, and oil resistant.[25,26]

Material Composition of Selected Products[14,15,16]



U.S. Recovery of Municipal Solid Waste, 1960-2018[27]



Solutions and Sustainable Actions

- *Conserve materials:* "Reduce, Reuse, Remanufacture, and Recycle." U.S. recycling and remanufacturing industries accounted for over 681,000 jobs and more than $5.4 billion in tax revenue in 2012.[28] In 2018, 32.1% of municipal solid waste in the U.S. was recovered for recycling and composting, diverting more than 93 million tons of material from landfills and incinerators.[27]
- *Change material composition of products:* Create products using materials that are less toxic, recyclable, and less energy intensive to make.
- *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.[29] Beverage cans are also made with an average of 73% recycled aluminum, representing a huge decrease in energy requirements and greenhouse gas emissions compared to using virgin materials.[30]
- *Promote product stewardship:* Appropriate policy and regulatory frameworks can help ensure product manufacturers' responsibility for the environmentally conscious management of retired products. The European Union's regulations on waste electrical and electronic equipment (WEEE) included a target of an 85% increase in proper WEEE collection and disposal.[31] It also has an Extended Producer Responsibility (EPR) policy that seeks to shift responsibility for life cycle environmental impacts from governments to producers.[32]
- *Encourage renewable material use:* Biobased materials such as polylactic acid (PLA), a biodegradable polymer, can provide performance similar to petroleum-based plastics. Manufacturing these materials may require less energy and emits fewer greenhouse gases, but the use of land and chemicals required to grow the feedstock may have adverse environmental consequences.[33]

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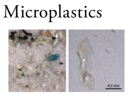
Plastic Waste

Due to the design potential, diversity, flexibility, low cost, and durability of plastics, their global use now exceeds most other man-made materials in nearly all industrial sectors. Plastics have made possible many technological advances and a tremendous array of products, creating numerous societal benefits. The high performance-to-weight ratio of plastics relative to alternative materials has reduced environmental footprints across the life cycle of several key sectors including transportation and food delivery. Despite the material value plastics hold, plastics often end up landfilled at end of life (EOL) and are a major source of marine litter. Plastics leakage out of the economy is due to the low cost of virgin plastic feedstocks and the challenges that come with recycling combinations of different plastic resins, plastics with additives, and contaminated plastics. Thus, design and reuse strategies along with policy instruments such as recycled content standards, virgin resin taxes, and tradable permits are needed to increase the service life of plastic products and plastic circularity. Impact investing is also needed for plastic waste reduction innovation and commercialization; sustainability criteria and life cycle assessment should be used to guide such investment to avoid greenwashing.[1, 2]

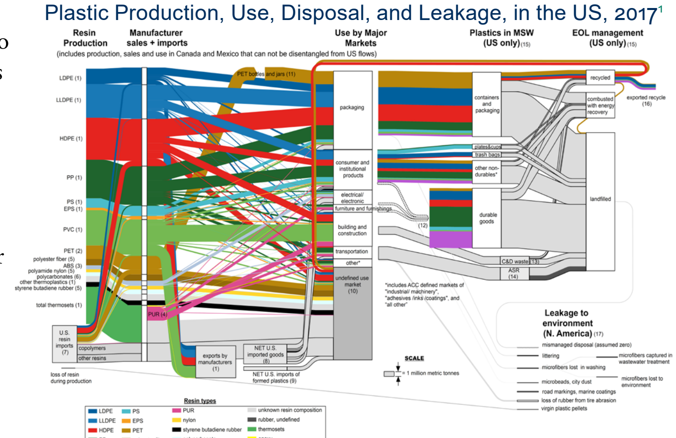
Table of Plastic Definitions

Term	Definition
Thermoplastics  E.g. PVC Piping	Thermoplastics are polymers that melt or soften when heated and can be melted down, molded, and recycled into something new. Common thermoplastics include polyvinyl chloride (PVC), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and polystyrene. Thermoplastics have wide-ranging applications from plastic bags to piping.
Thermosets  E.g. Epoxy resins	Thermosets are plastic polymers that form strong, cross-linked, three-dimensional chemical networks when they react with one another and, once formed, harden irreversibly. They are commonly used in construction, as well as in transportation, adhesives, and electrical equipment. Unlike thermoplastics, thermosets are resistant to high heat so recycling them is challenging. Examples of thermosets include silicones, polyesters, polyurethanes, and epoxies.
Bioplastics  E.g. PLA cups	Bioplastics are partially or entirely composed of plant-based renewable sources such as sugarcane, vegetable oils, starches, and even microbes. By 2025, bioplastics could decrease the amount of petroleum used in plastic production by 15–20%.[3] Given the right conditions, many bioplastics can biodegrade or become compost. Applications of bioplastics include food packaging, agriculture, and hygiene.
Composites  E.g. Fiberglass in wind turbine blades Note: Epoxy thermoset resins are also used.	Plastic composites are plastic polymers that are reinforced with non-plastic fillers, giving the resulting composite different properties than the materials that comprise it. Examples of plastic composites include fiberglass reinforced polyesters and biofiber-reinforced plastic composites used for building and construction. Plastic composites are difficult to recycle due to the combination of materials used to create them.
Macroplastics  E.g. Fishing nets Credit: NOAA	Macroplastics are plastics that are equal to or over 5mm in diameter.Examples of macroplastics include fishing nets, food wrappers, plastic bottles, and plastic bags.[4]
Microplastics  E.g. Microplastics found in table salt[5]	Microplastics are plastic particles that are under 5 mm in diameter. Microplastics fall into two categories: primary, which are designed and produced to be small (e.g. virgin plastic pellets used to manufacture plastic products and microbeads used in cosmetic products) and secondary microplastics, which are smaller pieces of plastic released from larger plastics when they break down (e.g. microfibers from clothing and microplastics released from tire abrasion).[6]

Patterns of Use

- Global plastic use is estimated to increase from 460 million metric tons (Mt) in 2019 to 1,231 Mt in 2060.[7]
- At 139 kg per capita per year (not including fiber and rubber polymers) North America has the highest per capita plastic consumption in the world and represents 19% of global plastics production and 21% of consumption.[1]
- Packaging was the largest defined use market for plastics that entered the U.S. economy in 2017. However, two-thirds of the plastic put into use went into other markets. The plastic products in these different applications have varying lifetimes: short (disposable serviceware, trash bags, diapers), medium (clothing, tools, electronics, furniture, small appliances), or long (large appliances, automobiles, buildings).[1]
- By 2060, the use of plastic in packaging will more than double compared to 2019. Of the seven commodity plastics, the amount of LDPE (including LLDPE) used in packaging is expected to triple, and PP, HDPE, and PET used in packaging will more than double.[7]
- About 30% of all the plastics ever made globally are still in use, and 60% have been discarded in landfills or elsewhere in the environment.[1,2]
- 12% of plastics put into use in the U.S. in 2017 went into building and construction. Plastic use in buildings is increasing, primarily in the form of PVC and HDPE used for piping, house wraps and siding, trim and window framing, and plastic-wood composites, as well as PUR used primarily as insulation. EOL recovery of these plastic materials is challenging because building demolition often produces mixed waste with low fractions of plastics, and materials such as PVC and PUR thermosets cannot be recycled easily.[1]
- The transportation sector used over 4% of plastics that entered the U.S. economy in 2017, primarily in the production of new automobiles. Due to lightweighting efforts and new applications of engineering resins, plastics in automobiles have increased over the past several decades, representing 8.6% of the material weight of N. American light vehicles in 2017. Over 95% of EOL vehicles in the US are recycled for their metals content. However, due to the large variety of plastics used in automobiles and the cost of collection, separation, and cleaning often exceeding that of virgin plastic materials, most automotive plastics end up in automotive shredder residue (ASR) and then go to landfill.[1, 8]
- Electronic waste (e-waste) is becoming an increasing concern, with a global annual growth rate of 3%–4%. An estimated 2.6 Mt of selected consumer electronics appeared in MSW in the U.S. in 2017 with plastic contents of 20% to 33%. If efficient and cost-effective recovery methods become available, up to 2.5 Mt of polycarbonates can potentially be recovered from e-waste globally each year.[1]

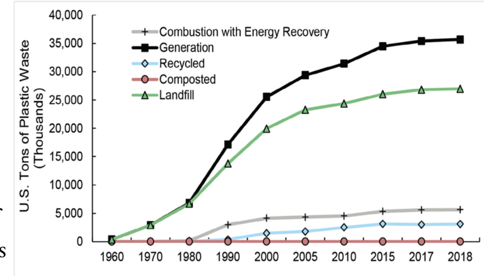
Plastic Production, Use, Disposal, and Leakage, in the US, 2017[1]



Link to Flow Diagram

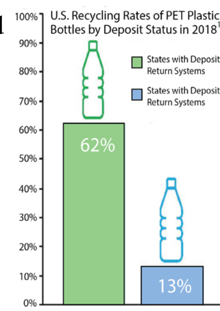
Environmental Impacts

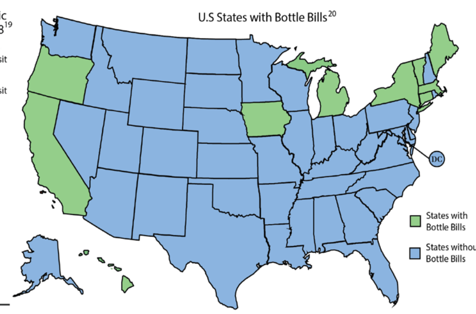
Plastic Materials Management of U.S. Municipal Solid Waste (MSW)[10]



- Globally, 99% of plastic resin is derived from fossil-based feedstocks. Global production (including both feedstock and manufacturing energy requirements) currently represents around 8% of global annual oil and gas consumption.[1, 9]
- According to projections based on current growth rates, life-cycle greenhouse gas emissions from plastics could reach 15% of the global carbon budget by 2050.[11]
- Despite representing only 4.3% of the global population, the U.S. produced more plastic waste than any other nation in 2016, generating 42 Mt of plastic waste total and 130 kg of plastic waste per capita per year.[9]
- In 2017, 2% of plastics disposed of in the U.S. "leaked" into the environment, often in the form of microplastics from tire abrasion and synthetic textiles, which is of growing concern due to impacts on organisms and unknown health consequences in humans.[1, 9]
- In 2019, 86% of plastic waste managed as MSW in the U.S. went to landfill. This landfilled plastic had an average market value of 7.2 billion USD. Only 5% of plastic waste was recycled and 9% was combusted.[12]
- In 2019, 9% of global plastic waste was recycled, 19% was incinerated, about 50% was sent to sanitary landfills, and 22% was openly burned, sent to unsanitary dumpsites, or leaked into the environment.[7]
- Rapidly developing middle-income countries in Asia, which often have inadequate collection systems, are responsible for an estimated 80% of global leakage. The U.S. and Europe, which have advanced collection systems, leak 170,000 metric tons (t) of plastics into the ocean annually.[13]
- Ocean plastic pollution impacts over 800 species of marine organisms, affecting all sea turtle species, 40% of cetacean species, and 44% of marine bird species.[14]
- If current practices continue, by 2050, there could be more plastic than fish in the ocean by weight.[15]

Solutions





- A circular economy for plastics is one in which plastic remains in service and maintains its material value.[16]
- By 2040, a circular economy could result in an 80% reduction in the volume of plastics entering oceans each year, a 25% reduction in greenhouse gas emissions, savings of 200 billion USD per year, and the creation of 700,000 additional jobs.[17]
- Redesigning products to increase recyclability can help increase plastic circularity. For example, using thermoplastic resin as opposed to thermoset resin in wind turbine blades can make them recyclable.[13, 18]
- Reuse is a key circular economy strategy to encourage; for food containers sustainability performance depends on reuse rates and washing practices.[1]
- Policy instruments that can reduce plastic packaging pollution and increase plastic recycling rates include command-and-control policies (e.g. product take-back mandates, landfill/disposal bans, product/material bans, and recycled content standards) as well as market-based policies (e.g. advanced disposal fees, deposit-refund systems, pay-as-you-throw programs, product taxes, virgin resin taxes, and tradable permits).[1]
- In 2018, states with bottle deposit systems had a PET plastic bottle recycling rate of 62% whereas states without deposit systems had a rate of 13%. In the U.S., 10 of the 50 states (CA, CT, HI, IA, ME, MA, MI, NY, OR, VT) plus Guam have bottle bills as of 2022.[19, 20]
- Taxes on specific plastic polymers and specific uses of plastics can lead to reductions in plastic consumption. For example, in 2002, Ireland introduced a €0.15 plastic bag tax (raised to €0.22 in 2006), leading to an immediate 90% reduction in the use of plastic bags.[21]
- Canada started banning the manufacturing and import of single-use plastics such as plastic bags and utensils in 2022 and ring carriers in 2023. By the end of 2025, the regulations will extend to prohibit the manufacture, import, sale, and sale for export of these product.[22] This ban is expected to eliminate about 1.3 Mt of plastic waste and over 22,000 t of plastic litter over the next ten years. While bans are one tool that can be used to reduce plastic waste, providing alternatives before imposing bans is important to avoid perverse outcomes.[23]
- Combustion and pyrolysis solutions for energy recovery and fuels can address plastic waste but are problematic with regard to carbon emissions.[1]
- Some restaurants and food manufacturers have begun to transition to reusable containers as an alternative to plastic packaging such as Burger King®, which launched reusable container programs in its New York City, Portland, and Tokyo restaurants in 2021.[24]
- Finding new creative uses for plastic waste can help establish a circular plastics economy. For example, the company Rebricks processes low-value plastic waste such as bubble wrap and combines it with cement to create building materials. Additionally, larger brands such as Patagonia®, which makes its Baggies™ (shorts) out of recycled nylon from fishing nets, are incorporating recycled plastic waste into their products.[25, 26]

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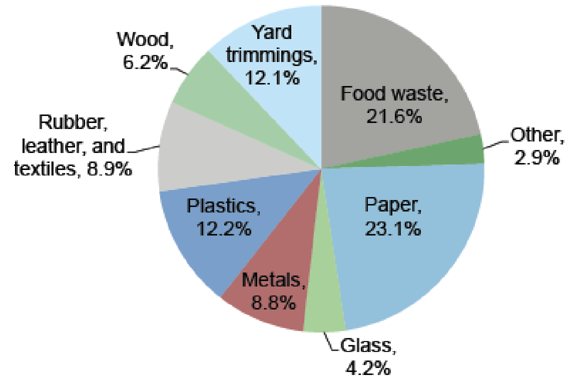
U.S. Municipal Solid Waste

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]

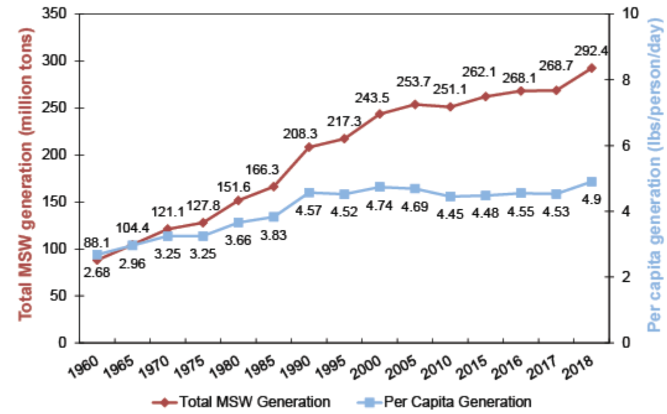
U.S. MSW Composition, 2018[1]



Generation Statistics

- Total annual MSW generation in the U.S. has increased by 93% since 1980, to 292 million U.S. short tons (tons) per year in 2018.[1]
- Per capita MSW generation increased by 34% over the same time period, from 3.7 to 4.9 pounds per person per day.[1] For comparison, MSW generation rates (in lbs/person/day) are 2.5 in Sweden, 3.9 in Germany, and 2.8 in the United Kingdom.[2] At the 2018 per capita rate, an American weighing 180 pounds generates their own weight in MSW every 37 days.
- In 2021, per capita generation of MSW was 29 pounds per $1,000 of GDP in the U.S., 18 in Sweden, 23 in the UK, and 29 in Germany.[3,4]
- Packaging, containers, and durable goods made up 48% of MSW generation in 2018. Most of the remainder was split between nondurable goods, food waste, and yard waste.[1]

U.S. Annual MSW Generation[1]

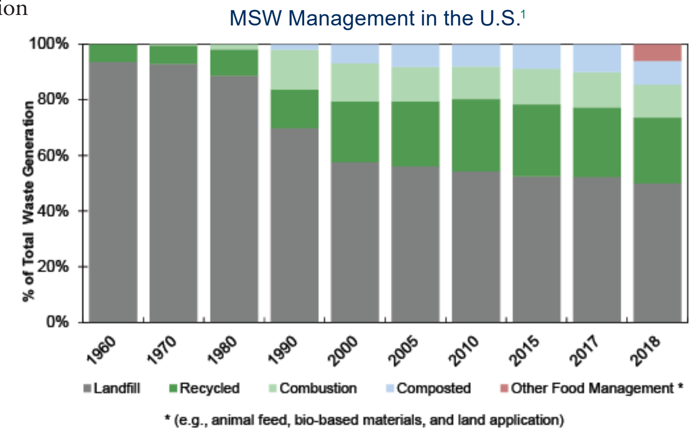


Management Methods

Landfill

- In 2018, 50% of MSW generated in the U.S. was disposed of in 1,278 landfills.[1,5]
- The 2022 combined capacity of the two largest landfill corporations in the U.S. was 10.3 billion cubic yards.[6]
- Landfill disposal ("tipping") fees in 2020 in the U.S. averaged $53.72 per ton, a 3% decrease from 2019.[7] These fees are used as funding for operation and maintenance of landfills, but there is still a lack of funding for research and technologies for waste diversion.[8]
- Environmental impacts of landfill disposal include loss of land area, emissions of methane (CH_4, a greenhouse gas) to the atmosphere, and potential leaching of hazardous materials to groundwater, though proper design reduces this possibility.[9,10]
- Landfills were the third largest source of U.S. anthropogenic CH4 emissions in 2021, accounting for 122.6 million metric tons (Mt) CO2e emissions, about 1.9% of total GHG emissions.[9]

MSW Management in the U.S.[1]



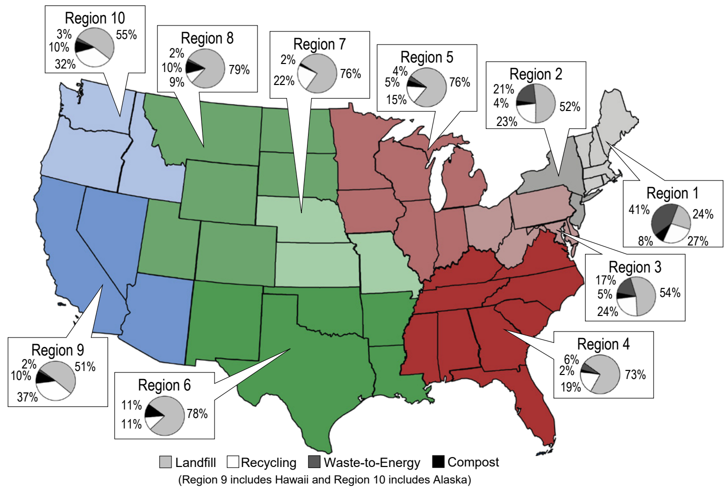
Combustion

- In 2018, 11.8% of MSW generated in the U.S. was disposed of through waste incineration with energy recovery.[1]
- Combustion reduces waste 75-85% by weight and 85-95% 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.[12] In 2021, 64 power plants burned 28 million tons of MSW and generated about 13.6 billion kWh of electricity.[13]
- Biogenic MSW (paper, food, and yard waste) accounted for 45% (6.12 billion kWh) of the electricity produced, or about 0.15% of total U.S. electricity generation.[13,14]
- Incineration of MSW generates a variety of pollutants (CO_2, heavy metals, dioxins, particulates) that contribute to impacts such as climate change, smog, acidification, and human health impacts (asthma and heart and nervous system damage).[15]

Recycling and Composting

- In 2018, 32.1% of MSW (by weight) generated in the U.S. was recovered for recycling or composting, diverting 93.9 million tons of material from landfills and incinerators—about 2.8 times the amount diverted in 1990.[1]
- In 2018, 27% of recovered MSW was composted.[1]
- Only 53% of people in the U.S. live in communities that automatically provide curbside recycling services; 82% of cities with curbside recycling collect material single-stream, meaning materials such as glass and paper are separated at the recycling plant.[16,17] The number of curbside programs in the U.S. has increased more than ninefold since 1988.[18,19]
- In 2018, 97% of corrugated boxes were recovered for recycling in 2018; other highly recycled products include lead-acid batteries (99%), newspapers (65%), major appliances (60%), and aluminum beverage cans (50%).[1]
- Common products with poor recycling rates include: carpet (9%), small appliances (6%), and furniture (0.3%).[20]

Regional MSW Management, 2010[11]

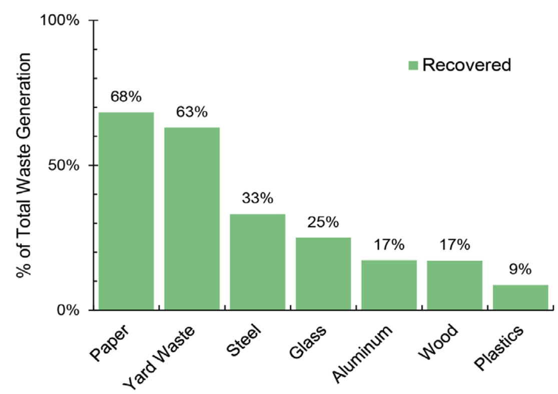


Solutions and Sustainable Alternatives

Source Reduction

- Source reduction activities help prevent materials from entering the MSW stream and are the most effective way to reduce waste generation.[21]
- Identify opportunities to reuse materials at home or in your community. Purchase items like furniture and appliances from reuse centers and consignment shops.
- Packaging and containers made up 28% of the MSW generated in 2018. Minimize the volume of packaging material required by selecting efficiently packaged products or buying in bulk.[1]
- Purchase products with post-consumer recycled content and encourage companies to implement source reduction programs.
- In 2018, 2.5 million tons of paper and plastic plates and cups were disposed.[20] Choose reusable plates, cups, and silverware over disposable goods and reuse them to make up for for their greater production burdens compared to disposables.[22]
- Food waste makes up 24% of MSW in the U.S., more than any other material. Yet only 5% is recovered or composted. Reduce food waste through meal planning and composting of scraps.[23]

Recovery of Materials in MSW, 2018[1]



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 weight they throw away.[24]
- In 2020, the U.S. Department of Agriculture, Environmental Protection Agency and Food and Drug Administration renewed the Winning on Reducing Food Waste initiative, to continue to promote the reduction of food loss and waste.[25]
- In 2021, 25 states introduced food waste-related legislation to reduce the amount of food waste going to landfills.[23]
- Implementation of curbside recycling and composting programs 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, tires, and electronics).[26]
- Ten states (CA, CT, HI, IA, ME, MA, MI, NY, OR, and VT) have deposit laws to encourage the return of empty beverage containers.[27]
- In June 2021, the U.S. House of Representatives held a hearing to discuss plastic waste reduction and recycling research. The Plastic Waste Reduction and Recycling Research Act was also considered for the role it could play in support of increasing federal investments in plastic waste reduction, recycling R&D, and recycling standards development.[28]

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Critical Materials

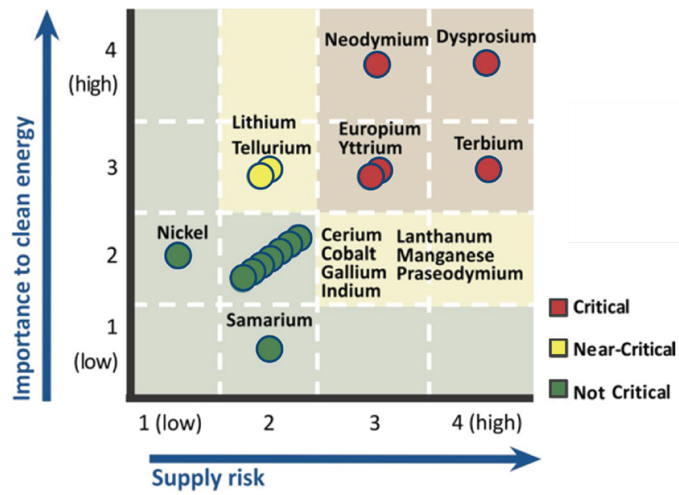
Minerals are integral to the functioning of modern society. They are found in alloys, magnets, batteries, catalysts, phosphors, and polishing compounds, which in turn are integrated into countless products such as aircraft, communication systems, electric vehicles (EV), lasers, naval vessels, and various types of consumer electronics and lighting.[1] 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 can be assessed in terms of supply risk, vulnerability to supply restriction, and environmental implications.[2] Rare earth elements (REEs) are a group of 17 elements used in various products, many of which are vital for renewable energy and energy storage.[1] Global demand for critical materials is expected to rise over the next several decades as the world shifts to clean energy. Demand for lithium and graphite, used in EV batteries, is forecasted to increase as much as 4,000% and 2,500% respectively.[3] Unless action is taken, the U.S. could face an annual shortfall of up to $3.2 billion worth of critical materials.[4] The average amount of critical materials needed to generate a new unit of power has increased by 50% since 2010.[3]

Critical Materials Categories

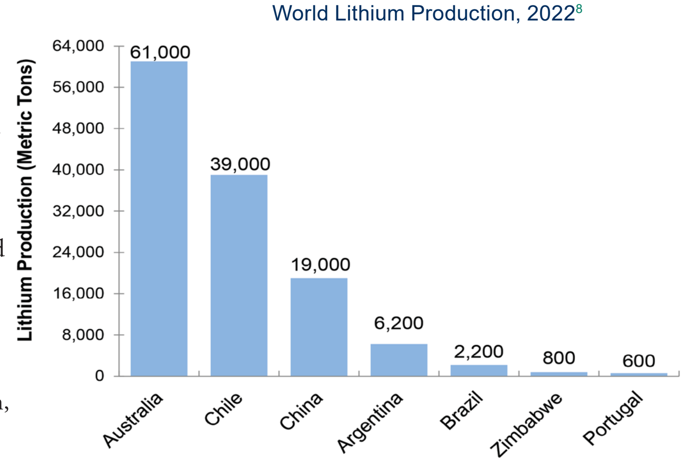
Energy Critical Elements

- Energy critical elements (ECEs) are elements integral to advanced energy production, transmission, and storage. This category includes lithium, cobalt, selenium, silicon, tellurium, indium, and REEs.[6]
- 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.[6]
- Some ECEs form deposits on their own, others are obtained solely as byproducts or coproducts from the mining of other ores.[6]
- Silicon, tellurium, and indium are necessary parts of solar photovoltaic (PV) panels.[7]
- Platinum group elements (PGEs) are necessary components of fuel cells and have potential for other advanced vehicle uses.[6] Platinum and palladium production are concentrated in South Africa (74% and 38%, respectively) and Russia (11% and 42%, respectively).[8]
- Lithium is an element of growing importance due to its use in batteries for cell phones, laptops, and electric vehicles. Chile, Bolivia, and Argentina account for 53% of worldwide lithium resources. Australia, Chile, China, and Argentina accounted for 96% of world lithium production in 2022.[8]
- 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.[9]
- 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.[5]
- DOE's Critical Materials Institute has more recently focused on key materials including graphite, manganese, cobalt, lithium, gallium, indium, and tellurium.[10]
- Current DOE strategies for addressing material criticality include diversifying supply, developing substitutes, and improving reuse and recycling of critical materials.[11]
- Copper is a key element in electrical wiring and appliances and may also be a limiting factor in future renewable energy deployment. At current production levels, existing copper resources may only last another 60 years and its extraction will become more energy intensive as ore quality decreases.[12] Top copper producing countries include Chile (23.6%), Peru (10.0%), Congo (10.0%) China (8.6%), and the U.S. (5.9%).[8] Copper is unique in that it does not degrade or lose its physical and chemical properties when it is recycled.[13] In 2022, only 32% of copper came from recycled sources. Old (post-consumer) scrap accounted for almost 20% of this total recovered scrap, while more than 80% was recovered new (manufacturing) scrap.[8]

Materials Criticality Matrix, Medium Term (2015-2025)[5]

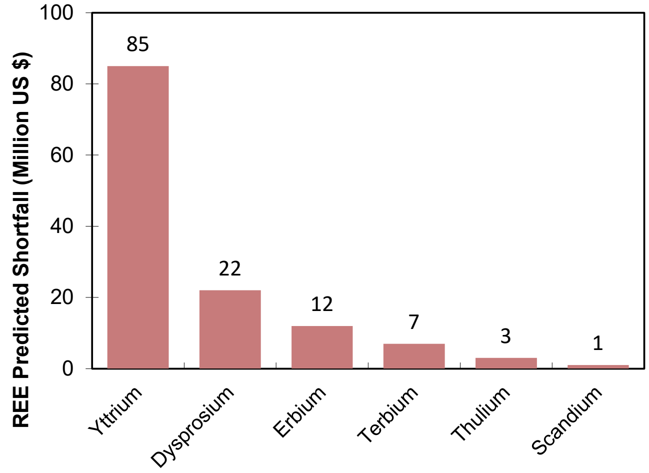


World Lithium Production, 2022[8]



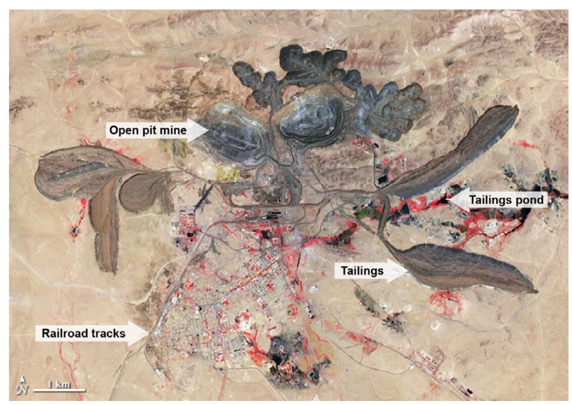
Rare Earth Elements

Rare Earth Element Predicted Shortfall[14]



- 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.[15]
- 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 yttrium and elements 65 through 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.[15] The REEs terbium, neodymium, praseodymium, and dysprosium are key components of the permanent magnets used in wind turbines.[7] Substitutes for REEs are available but are less effective.[8]
- In 2022, China controlled an estimated 70% of REE production, a 12% increase from its control of 58% in 2021.[8] The U.S. is 100% reliant on imports for 14 critical minerals and more than 75% reliant on imports for another 10. These materials are key to industrial and commercial processes as well as national defense.[7]
- The U.S. has increased REE production to 43,000 metric tons (t) in 2022. U.S. REE reserves are estimated 2.3 million metric tons (Mt). In comparison, China produced 210,000 t of REEs in 2022 and possesses reserves of 44 Mt. Vietnam had a 975% increase in REE production between 2021 and 2022, making it the 6th largest REE producing country in the world.[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, developing nations naturally contain greater quantities of ECE ore deposits.[6]
- The U.S. used $613 million of REEs which in turn generated $496 billion in economic activity in other sectors, including petroleum refining, and electromedical device and automotive manufacturing in 2016.[3]

Rare Earth Mining Damage in China[18]



Life Cycle Impacts

- Mining is a destructive process that disrupts the environment and widely disperses waste. Chemical compounds used in extraction processes can enter the air, surface water, and groundwater near mines.[16]
- The grinding and crushing of ore containing critical elements often releases dust, which can have carcinogenic and negative respiratory effects on exposed workers and nearby residents.[16]
- Beyond health impacts, mining can also negatively impact human rights. For example, the Democratic Republic of Congo is the world's leading producer of cobalt, widely used in advanced battery technology, but child labor is routine there as a result of lax regulation and oversight.[17]
- Some REE deposits contain thorium and uranium, which pose significant radiation hazards. While thorium and uranium can be used to generate nuclear energy, they are rarely economically 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, which often occur in developing nations where regulations to limit worker exposure are lax or nonexistent, can lead to exposure to carcinogenic and toxic materials.[16]

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.[5]
- Buy refurbished rather than new products. Rent products from companies with take-back programs that require material recycling.[6]
- Support government programs like the DOE's Advanced Manufacturing Office, which funds projects related to reducing environmental impacts, lowering costs, and improving the process of manufacturing clean energy technologies in the U.S.[19]

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U.S. Food System

Americans enjoy a diverse abundance of low-cost food, spending a mere 11.3% of disposable income on food.[1] 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.

The Food System Life Cycle

Patterns of Use

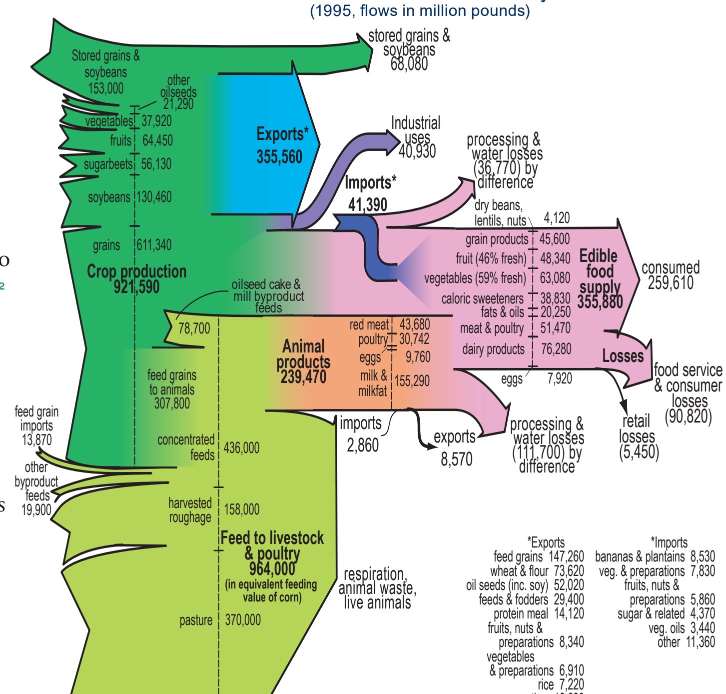
Agricultural Production

- Farmers account for 1% of the population. Over 60% of these farmers are above the age of 55.[2,3]
- Large-scale family farms and industrial nonfamily farms account for only 5% of farms, but 63.8% of production (in $). Small-scale family farms represent 89% of U.S. farms, but only 17.8% of production.[4]
- Just 14.5¢ of every dollar spent on food in 2021 went back to the farm; in 1975, it was 40¢.[5,6]
- In 2018-2020, 41% of the hired agricultural labor force lacked authorization to work in the United States.[7]
- From 1992 to 2012, total cropland decreased from 460 million acres to 392 million acres.[8]
- Many parts of the U.S., including agricultural regions, are experiencing increasing groundwater depletion (withdrawal exceeds recharge rate).[9] In 2015, 118,000 million gallons per day of water were used for irrigation - 52% of this water came from surface-water sources.[10]
- In 2017, the amount of irrigated farmland in the U.S. was over 58 million acres, 2 million more acres than in 2012.[2]
- Nutrient runoff from the upper agricultural regions of the Mississippi River watershed creates a hypoxic "dead zone" in the Gulf of Mexico. The 2017 hypoxic dead zone was the largest measured since 1985, at 8,776 sq mi.[11]
- From 2007 to 2012, pesticide use increased by 10% while herbicide use increased by 20% from 2010 to 2014. In 2012, the U.S. agriculture sector used 899 million pounds of pesticides.[12]
- In 2000, 25% of corn, 61% of cotton, and 54% of soybeans planted were genetically engineered; by 2022, these percentages increased to 93%, 95%, and 95%, respectively.[13]
- The UN's Food and Agriculture Organization estimates 75 billion metric tons (Gt) of soil are lost annually to erosion from fertile lands.[14]
- Agriculture was responsible for 10% of total U.S. greenhouse gas (GHGs) emissions in 2021. Methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) are the main GHGs emitted by agricultural activities. Livestock and soil management are major contributors.[15]

Consumption Patterns

- In 2010, the U.S. food supply provided 4,000 calories per person per day.[17] Accounting for waste, the average American consumed 2,501 calories per day in 2010, an increase of 22% from 1970.[18]
- In 2021, 185 lbs of meat per person were available for consumption, up 11.6 lbs from 1969. Although red meat consumption declined 24% since the 1970s, chicken consumption has increased.[19]
- 34% of grains grown are used to feed animals.[20]
- 22.2 teaspoons of sweeteners are available per capita in the U.S. daily; the American Heart Association recommends limiting added sugars to 6 and 9 teaspoons daily for average females and males, respectively.[21,22]
- Approximately 41% of U.S. adults and over 20% of 12-19 year olds are obese (BMI > 30).[23]
- Diet plays a significant role in health. Diets lacking fruits and vegetables can increase risk of heart disease, certain cancers, and stroke—leading causes of U.S. deaths.[23,24]
- The EPA estimates that 30%-40% of the current food supply was lost as waste, 50% more than in 1970.[25,26] More food waste reaches landfills than any other material. This waste accounted for roughly 22% of the municipal solid waste stream in 2018 and represents a loss of $450 and around 350 pounds of food waste per person each year.[25,26,27]
- One estimate suggests that 2% of total annual energy use in the U.S. is used to produce food that is later wasted.[28]

Material Flow in the U.S. Food System[16]
(1995, flows in million pounds)

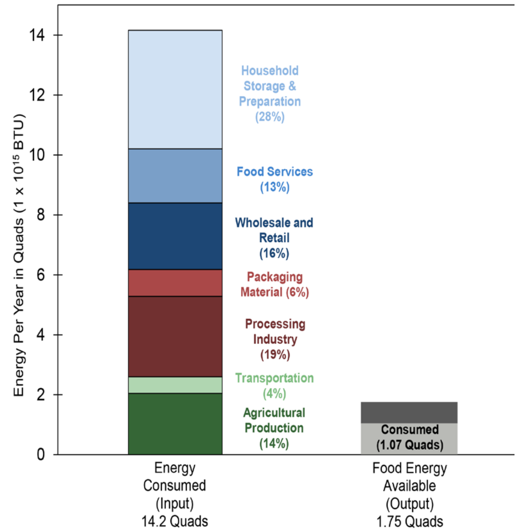


Life Cycle Impacts

The energy used by a system is often a useful indicator of its sustainability. Food-related energy use accounts for over 12% of the national energy budget.[31] Agriculture and the food system as a whole have developed a dependence on fossil energy; 13 units of (primarily) fossil energy are used for every unit of food energy produced.[18,29]

- Food production of U.S. self-selected diets results in 4.7 kg CO_2e and 25.2 MJ fossil fuel energy demand per capita per day.[32]
- Reliance on fossil fuel inputs makes the food system vulnerable to oil price fluctuations.[16]
- Consolidation of farms, food processing operations, and distribution warehouses often increases distance between food sources and consumers.[16]
- 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 four firms.[33]
  - The top four food retailers sold almost 35% of America's food in 2019, compared to only 15% in 1990.[34]

Energy Flow in the U.S. Food System[16,17,18,29,30]



Solutions and Sustainable Alternatives

Eat Less Meat

Meat-based diets use more energy to produce than vegetarian diets, one study suggests twice as much.[16] One serving of beef has more associated GHG emissions than 20 servings of vegetables.[35] Current meat production also has significant environmental impacts on land use, water use, and water pollution.[36] In an average diet, meat consumption accounts for 31% of the water scarcity footprint— the water use that accounts for regional scarcity.[37] 20% of Americans cause half of the food-related GHG emissions; a diet shift away from meat could reduce this up to 73%.[32,38]

Reduce Waste

Much of household food waste is due to spoilage. Prevent this by buying smaller amounts; planning meals and sticking to shopping lists; and freezing, canning, or preserving extra produce.[39] Direct-to-consumer meals streamline the supply chain, reduce food waste and last-mile transportation, and have 25% lower GHG emissions than a store bought meal.[40] Many safe foods are thrown out due to confusion about "sell-by" and "use-by" dates; for guidance, see the USDA.[41] Whether washing dishes manually or in a dishwasher, save water and energy by practices such as not letting water run constantly, rinsing in cold water, only running dishwashers with full loads, and avoiding pre-rinsing dishes.[42]

Use Less Refrigeration

Home refrigeration accounts for 13% of all energy consumed by our food system.[16] Refrigerator efficiency more than doubled from 1972 to 1990, when the first set of efficiency standards took effect. Yet increases in size have largely offset this improvement.[16,43] Today's convenience foods rely heavily on refrigeration for preservation. Switching out old refrigerators with more efficient models (e.g., ENERGY STAR) can save energy and money. Also consider buying smaller quantities of fresh produce more frequently.[16,44]

Eat Organic

Organic farms do not use chemicals that require large amounts of energy to produce, pollute soil and water, and cause human health impacts. U.S. sales of organic food in 2022 were $61.7 billion, 19.6% higher than in 2019; organic food now accounts for approximately 6% of all food sold in the U.S.[45]

Eat Local

Transportation accounts for approximately 14% of the total energy used in the U.S. food system.[46] There is significant room for improvement in how people acquire their food. Community Supported Agriculture and Farmers Markets are great ways to support your local food system.

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U.S. Water Supply and Distribution

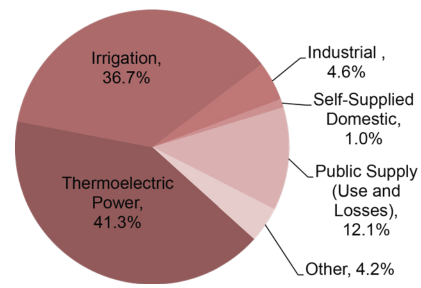
Patterns of Use

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. The problems and solutions to maintaining water supply vary significantly by region. Failure by the government to enforce drinking water regulations and promptly protect public health resulted in lead contamination and cases of Legionnaires' disease in Flint, MI.[1] The arid southwest faces droughts, and decreasing water levels at the U.S.'s largest reservoirs Lake Powell and Lake Mead are impacting hydropower production.[2] In marine systems such as south Florida, increased fresh water demand has led to the use of desalination plants.[3]

Water Uses

- In 2015, total U.S. water use was approximately 322 billion gallons per day (Bgal/d), 87% of which was freshwater. Thermoelectric power (133 Bgal/d) and irrigation (118 Bgal/d) accounted for the largest withdrawals.[4] Thermoelectric power plants use water for cooling. Though 41% of daily water use is for power generation, only 3% of these withdrawals are consumptive.[4] Irrigation includes water applied to agricultural crops along with the water used for landscaping, golf courses, parks, etc.[4]
- In 2015, California and Texas accounted for 16% of U.S. water withdrawals.[4] These states along with Idaho, Florida, Arkansas, New York, Illinois, Colorado, North Carolina, Michigan, Montana, and Nebraska account for more than 50% of U.S. withdrawals.[4] Florida, New York, and Maryland accounted for 50% of saline water withdrawals.[4]

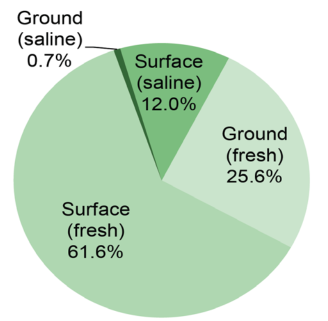
Estimated Uses of Water, 2015[4]



Sources of Water

- Approximately 87% of the U.S. population relied on public water supply in 2015; the remainder rely on water from domestic wells.[4]
- Surface sources account for 74% of all water withdrawals.[4]
- In 2010, annual U.S. water withdrawal measured 1,543 m^3 per person.[5]
- Approximately 152,548 publicly owned water systems provide piped water for human consumption in 2022, of which roughly 50,000 (33%) are community water systems (CWSs). Of all CWSs, 9% provide water to 83% of the population.[6]
- 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.[7]

Sources of Water Withdrawals, 2015[4]



Energy Consumption

- Two percent of total U.S. electricity use goes towards pumping and treating water and wastewater, a 52% increase in electricity use since 1996.[8] Cities, on average, use 3,300-3,600 kWh/million gallons of water delivered and treated. Electricity use accounts for around 80% of municipal water processing and distribution costs.[9]
- Groundwater supply from public sources requires 2,100 kWh/million gallons, about 31% more electricity than surface water supply, mainly due to higher water pumping requirements for groundwater systems.[8]
- The California State Water Project is the largest single user of energy in California, consuming between 6-9.5 billion kWh per year, partially offset by its own hydroelectric generation. In the process of delivering water from the San Francisco Bay-Delta to Southern California, the project uses 3%-4% of all electricity consumed in the state.[10,11]

Size Categories of Community Water Systems[6]

System Size (population served)	Number of CWSs	Population Served (millions)	% of CWSs	% of U.S. Population Served by CWSs
Very Small (25-500)	26,897	4.6	54.1%	1.4%
Small (501-3,300)	13,321	19.2	26.8%	6.1%
Medium (3,301-10,000)	5,010	29.5	10.1%	9.3%
Large (10,001-100,000)	4,005	115.6	8.1%	36.5%
Very Large (>100,000)	447	147.6	0.9%	46.7%
Total	**49,680**	**316.4**	**100%**	**100%**

Water Treatment

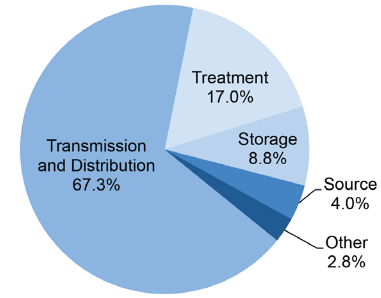
- The Safe Drinking Water Act (SDWA), enacted in 1974 and amended in 1986, 1996, and 2018, regulates contaminants in public water supplies, provides funding for infrastructure projects, protects sources of drinking water, and promotes the capacity of water systems to comply with SDWA regulations.[12]
- Typical parameters that the U.S. EPA uses to monitor the quality of drinking water include: microorganisms, disinfectants, radionuclides, organic and inorganic compounds.[13]
- Ninety-one percent of CWSs 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.[7]
- Use the Municipal Drinking Water Database to learn more about the drinking water systems of over 2,000 U.S. cities and the communities that they serve.[14]

Life Cycle Impacts

Infrastructure Requirements

- The 2023 Drinking Water Infrastructure Needs Survey and Assessment found that U.S. water systems need $625 billion of investment by 2041 to continue providing clean safe drinking water.[15]
- The total national investment need for transmission and distribution is $420.8 billion. The other needs include treatment ($106.4 billion), storage ($55.3 billion), source development ($24.9 billion), and other systems ($17.6 billion).[15]
- Water systems maintain more than 2.2 million miles of transmission and distribution mains.[16] In 2020, the average age of water pipes in the U.S. was 45 years old -- an increase in average age from 25 years old in 1970.[17] Each year, 250,000 to 300,000 main breaks occur in the U.S., disrupting supply and risking contamination of drinking water.[18]

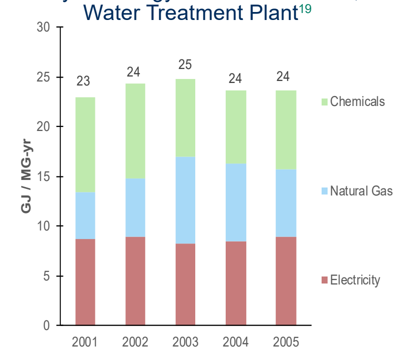
Drinking Water Need by 2041, by Project Type[5]



Electricity Requirements

- Supplying fresh water to public agencies required about 39 billion kWh of electricity in 2011, which increased by 39% beyond the 1996 values, mostly due to population growth and expansion of treatment facilities. This trend will likely continue in the coming years.[8]
- 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.[20]

Life Cycle Energy Use for Ann Arbor, MI Water Treatment Plant[19]



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.[4]
- Agriculture accounts for the largest loss of water (80-90% of total U.S. consumptive water use).[21] Of the 118 Bgal/d freshwater withdrawn for irrigation, over half is lost to consumptive use.[4]
- Over the past 50 years, the consumption of water has tripled. With at least 40 states anticipating water shortages by 2024, the need to conserve water is critical.[22]

Solutions and Sustainable Alternatives

Supply Side

- Periodic rehabilitation, repair, and replacement of water distribution infrastructure would help improve water quality and avoid leaks.[16]
- Right-sizing, upgrading to energy efficient equipment, and monitoring and control systems can optimize systems for the communities they serve, and save energy and water in the process.[9]
- Significant energy efficiency improvement opportunities include pumps and motors.[23]
- Achieve on-site energy and chemical use efficiency to minimize the life cycle environmental impacts related to the production of energy and chemicals used in the treatment and distribution process.
- Reduce chemical use for treatment and sludge disposal by efficient process design, recycling of sludge, and recovery and reuse of chemicals.
- Generate energy on-site with renewable sources such as solar and wind.[24]
- 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.[25]
- 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.[8]

Demand Side

- Better engineering practices:
  - Plumbing fixtures to reduce water consumption, e.g., high-efficiency toilets, low-flow showerheads, and faucet aerators.[26]
  - Water reuse and recycling, e.g., graywater systems and rain barrels.[27]
  - Efficient landscape irrigation practices.[27]
- Better planning and management practices:
  - Pricing and retrofit programs, proper leak detection and metering, residential water audit programs and public education programs.[26,27]
- Communities experiencing environmental injustice can use environmental justice toolkits, such as the Water Justice Toolkit.[28]

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U.S. Wastewater Treatment

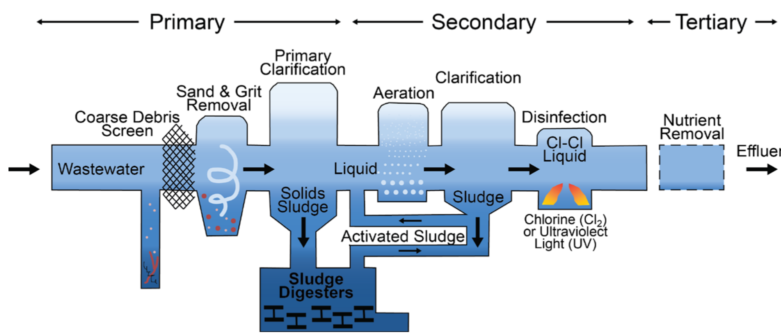
Patterns of Use

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.

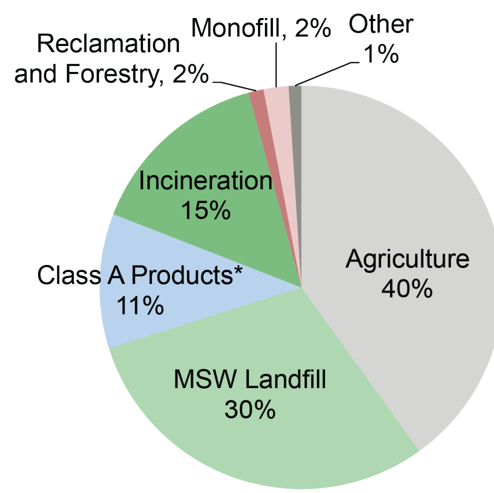
Contamination and Impacts

- 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).
- In the U.S., 58% of river and stream miles, 40% of lake acres, 17% of estuarine square miles, and 23% of Great Lakes shoreline miles that have been assessed by the U.S. EPA have excess nutrients.[2]
- Excess nutrients can come from agriculture, urban runoff, and wastewater treatment and cause water quality problems, such as algal blooms and fish kills.[2]
- Around 16% of households are not served by public sewers and usually depend on septic systems to treat wastewater.[3]
- Failing septic systems may contaminate surface and groundwater.[4]

Wastewater Treatment Process[1]



Biosolids Use and Disposal[5]



*(e.g., treated for horticulture use)

Treatment of Municipal Wastewater

- An estimated 14,748 POTWs provide wastewater collection, treatment, and disposal service to more than 238 million people.[6] Use of reclaimed water for consumption is becoming more common, particularly in regions prone to drought or with growing water demand (such as the U.S. southwest).[7]
- In 2015, California recycled roughly 714,000 acre-feet of water per year (ac-ft/yr). It has set ambitious goals to increase water recycling, with at least 1.5 million ac-ft/yr recycled by 2020, and 2.5 million ac-ft/yr by 2030.[8]
- POTWs generate over 13.8 million U.S. short 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 mean of disinfection. Chlorination may be followed by dechlorination to avoid deteriorating ecological health of the receiving stream and the production of carcinogenic by-products.[11]
- Ultraviolet (UV) disinfection is an alternative to chlorination that does not add chemicals to the water. However, this method can have higher maintenance, energy and capital costs.[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 and personal care products.[14] Polybrominated diphenyl ethers (PBDEs) and per- and polyfluoroalkyl substances (PFASs) have become CECs due to their wide distribution and persistence in the environment.[15] Some of these chemicals are endocrine disruptors, a class of compounds that alter the normal functioning of endocrine systems, including those that affect growth and reproduction.[16] Many of these chemicals are not removed by POTWs.[17] Currently, researchers are studying the effectiveness of technologies for removing PFAS from drinking water.[18]

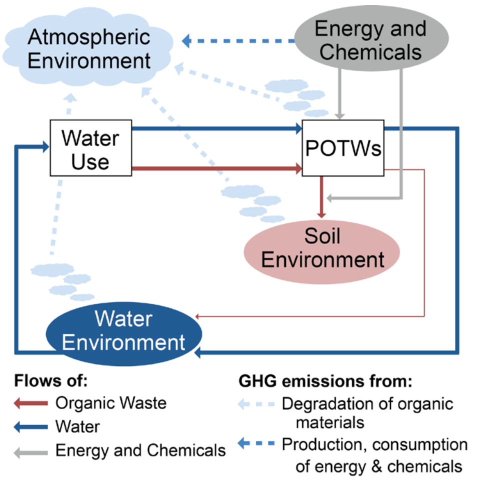
Biosolids (Sludge) End-of-Life

- Qualified biosolids can be beneficially used after “stabilization,” which kills pathogens and decomposes vector-attractive substances.[19]
- U.S. management practices amount to 54% of biosolids being beneficially used. Most is applied to agricultural sites, with minor amounts applied to forestry and reclamation sites (e.g., Superfund and brownfield lands) and urban areas (e.g., maintaining park land).[20]

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.

Life Cycle Impact of Wastewater Treatment Systems[1]



Electricity Consumption and Emissions

- About 2% of U.S. electricity use goes towards pumping and treating water and wastewater.[10]
- In 2013, energy-related emissions resulting from POTW operations, excluding organic sludge degradation, were 15.5 teragrams (Tg) CO_2-equivalents (CO_2e), 22.3 gigagrams (Gg) SO_2, and 12.7 Gg NO_X. SO_2 and NO_X contribute to acidification and eutrophication.[10,21]
- CH_4 and N_2O are emitted during organic sludge degradation by aerobic and anaerobic bacteria in the POTW and receiving water body. In 2021, an estimated 21.1 and 20.9 MMT CO2e of CH4 and N2O, respectively, resulted from wastewater treatment processes, about 0.7% of total U.S. GHG emissions.[22]

Social and Economic Impacts

- In the U.S., an average single family household pays around $500 annually for wastewater collection and treatment.[23]
- Population growth and urban sprawl increase the collection (sewer) infrastructure needed.
- Although the lifetime of a sewer system (50 years) is longer than that of treatment equipment (15 to 20 years), renovation needs of a sewer system can be more costly. An EPA analysis estimated that if 600,000 miles of existing sewer systems were not renovated, the amount of deteriorated pipe would increase to 44% of the total network by 2020.[24] U.S. costs for building new and updating existing wastewater treatment plants ($102.0 billion), pipe repair and new pipes ($95.7 billion), and combined sewer overflow corrections ($48.0 billion) totalled around $250 billion in 2012.[6]

City Hall Green Roof, Chicago, Illinois[25]

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 programs for combined sewer overflow, sanitary sewer overflow, and stormwater management need to be permanent.[26]
- To meet ambient water quality standards, total maximum daily loads (TMDLs) considering both point and non-point source pollutant loadings can be developed. Watershed or waterbody-based management of clean water is expected to facilitate establishment of these TMDLs.[27]

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 64% of all indoor water use. Install high-efficiency toilets, composting toilets, low-flow shower heads, faucet aerators, and rain barrels. A 2016 survey found that water-efficient appliances contributed to a 22% decline in household water use since 1999.[28]
- Graywater—wash water from kitchen sinks, tubs and showers, clothes washers, and laundry tubs—can be used for gardening, lawn maintenance, landscaping, and other uses.[29]

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.[30]
- 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.[10]
- A number of treatment plants are considering using methane generated from anaerobic digestion of biosolids as an energy resource.[10]
- Water reuse can significantly decrease system energy usage and reduce nutrient loads to waterbodies.[31]
- Large-scale urine diversion could decrease nutrient loading in wastewater treatment plants and lead to reductions of up to 47% in GHG emission and 41% in energy consumption.[32]

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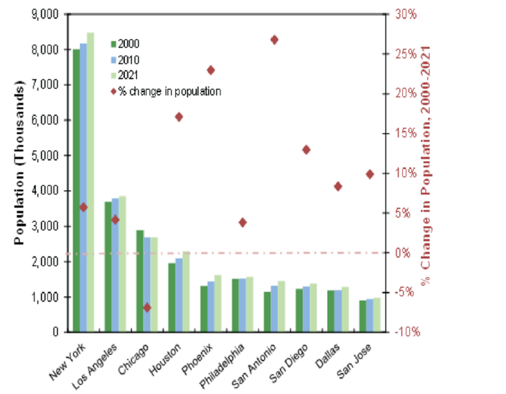
U.S. Cities

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

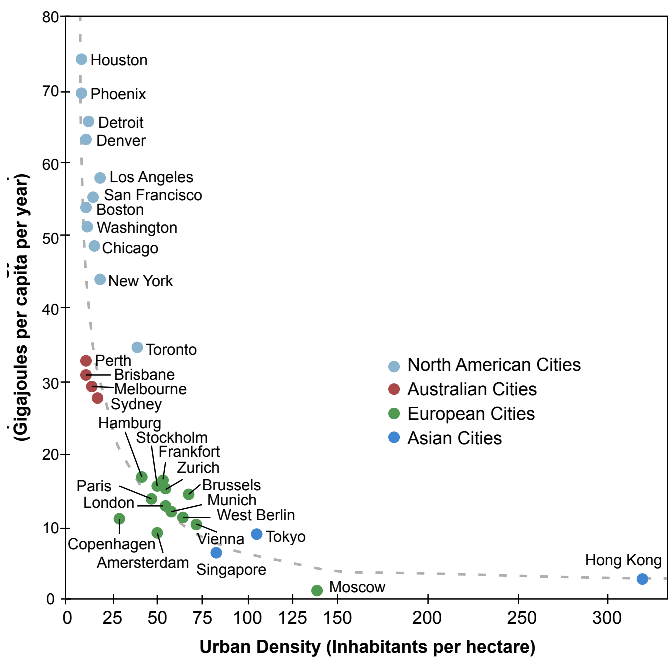
Population Trends of the Largest U.S. Cities, 2000-2021[2,3]



- It is estimated that 83% of the U.S. population lives in urban areas, up from 64% in 1950. By 2050, 89% of the U.S. population and 68% of the world population is projected to live in urban areas.[1]
- More than 325 urban areas in the U.S. have populations above 100,000; New York City, with 8.47 million inhabitants, is the largest.[3,4]
- While the rate of urbanization, i.e., the changing of land from forest or agricultural uses to suburban and urban uses, is decreasing, an increasing percentage of the world's population is living in urban centers.[5,6] 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 more than double by 2060.[7,8,9]
- The average population density of the U.S. is 94 people per square mile.[10]
- The average population density of metropolitan statistical areas (MSA) is 283 people per square mile; in New York City, the population density is 29,303 people per square mile.[4,7] The county of New York, New York has the greatest density of housing units (40,339) per square mile of land area.[8]
- One study found that doubling population-weighted urban density reduces CO_2 emissions from household travel and residential energy use by 48% and 35%, respectively.[11]
- Sprawl, the spreading of a city and suburbs into surrounding rural land, increases traffic and energy use, and results in air and water pollution and flooding.[12]
- According to Smart Growth America's Sprawl Index (based on development density, land use mix, activity centering and street accessibility), the most sprawling MSAs 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.[13]

Built and Natural Environment

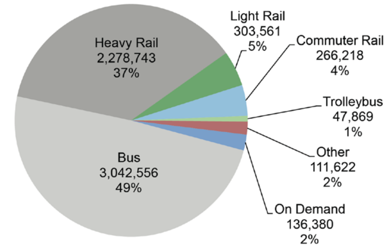
Urban Density and Transportation-Related Energy Consumption[14]



- Residential (21.8 quadrillion Btu; "quads") and commercial (18.2 quads) sectors accounted for 40% of total energy consumption and 35% (1,741 million metric tons, Mt, of CO_2) of energy-related emissions in 2022.[15]
- Approximately 70% of global emissions can be attributed to urban areas, driven by population size, income, and state and form of urbanisation.[16]
- The "urban heat island effect," in which average annual temperatures are 1-7°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.[17]
- Urban tree canopies decrease the urban heat island effect.[18] Urban tree cover in the U.S. is 39.4% and has been declining, while impervious surfaces have expanded to 26.6% of urban areas.[9]
- Air Quality Index is an important environmental metric monitored in cities. Since 2000, emissions from key pollutants have decreased and, with them, the number of unhealthy air days for urban residents.[19]
- The concentration and toxicity of contaminants in streams increases with the degree of urban development. Pollutants are introduced from runoff, treated sewage, and industrial processes.[20]
- Vegetation and topsoil loss and the constructed drainage networks associated with urbanization alter natural hydrology.[21]
- Stormwater runoff from the built environment is a principal contributor to water quality impairment of water bodies nationwide.[21]
- Hot extremes have intensified in cities, which worsens air pollution events and has compromised key infrastructure such as transportation, water, and sanitation.[16]

Transportation and Mobility

Public Transportation Ridership, 2022[27]
(number of passenger trips)



- In 2020, 32.9 billion passenger-miles (PM) were traveled on U.S. public transit, a 41% decrease from the 56.1 billion PM traveled in 2019 as a result of COVID-19 pandemic.[22] Similarly, vehicle-miles traveled (VMT) decreased by 11% to 2.9 trillion VMT in 2020. 3.1 trillion VMT occurred on public roads in 2021.[23]
- There are 23 light rail, 15 heavy rail, and 30 commuter rail systems in the U.S. If pre-pandemic trends had continued, fixed-guideway modes of public transit (light and commuter rail) would soon have had a greater share of passenger trips than roadway modes (buses).[22] Without public transportation, the annual impacts in the U.S. would include an additional 102.2 billion VMT, 5.3 billion gallons of gasoline, and 37 Mt of CO_2 emissions.[24]
- Congestion is a serious problem in urban areas, causing an additional 8.7 billion hours of travel time and an extra 3.5 billion gallons of fuel use by urban Americans in 2019.[25]
- In 2019, transit buses used 89.5 trillion Btu and traveled 19.3 billion PM, while rail used 47.1 trillion Btu and traveled 39.3 billion PM. In comparison, passenger cars and trucks used 15,108 trillion Btu and traveled 4,470 billion PM.[26]
- By number of riders, New York City has the most utilized heavy rail, commuter rail, and bus systems in the U.S., San Diego has the most utilized light rail system, and San Francisco has the most utilized trolley bus system.[27]
- Between 2020 and 2022, there was an overall 33% increase in total public ridership on all modes of public transportation.[27,28]

Socioeconomic Patterns

- In 2018, U.S. metro economies account for 91.1% of GDP, 91.8% of wage income, and 88.1% of jobs. Only 9 countries (including the U.S.) had a higher GDP than the New York City area.[29]
- The median household income inside MSAs is $73,823; outside MSAs it is $53,750.[30] The average unemployment rate of metropolitan areas in February 2023 was 3.9%, ranging from a low of 1.9% in Ames, IA and Madison, WI to a high of 15.6% in El Centro, CA.[31]
- Poverty rates are lower within metropolitan areas than outside: 11% compared to 14.1% in 2020.[32]

Solutions and Sustainable Alternatives

SDG Index Ranking, 2019[35]

The Top 10 U.S. City Regions
San Francisco-Oakland-Hayward, CA
San Jose-Sunnyvale-Santa Clara, CA
Washington Metro, DC-VA-MD-WV
Seattle-Tacoma-Bellevue, WA
Madison, WI
Portland-Vancouver-Hillsboro, OR-WA
San Diego-Carlsbad, CA
Boston-Cambridge-Newton, MA-NH
Austin-Round Rock, TX
Raleigh, NC

A sustainable urban area is characterized by the preservation of a quality environment, efficient use of renewable energy resources, the maintenance of a healthy population with access to health services, and the presence of economic vitality, social equity, and engaged citizenry.[33] 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.[33,34]

- Well-being in urban areas can be improved by prioritizing means to reduce climate risk for low-income and marginalized communities.[16]
- The San Francisco-Oakland-Hayward metro region in California placed first on a United Nations' Sustainability Development Goal (SDG) Index ranking based on 57 indicators across 15 of the 17 SDGs.[35]
- As of November 2019, 1,066 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.[36]
- A National Oceanic and Atmospheric Administration report found that as of 2017, 455 U.S. cities surveyed had plans for reducing GHG emissions.[37] Many cities, including New York, Los Angeles, and Chicago, have created Climate Action Plans, demonstrating environmental leadership and commitment to reducing climate change.[38]
- The EPA offers many clean energy programs, information, training opportunities, grants, resources, and tools to assist local governments.
- ICLEI (International Council for Local Environmental Initiatives), an international association of local governments and national, regional, and local government organizations, develops locally designed initiatives to achieve sustainability objectives.[39]
- Smart Growth America is a coalition working to improve the planning and building of towns, cities, and metro areas.[40]
- The U.S. DOE's Clean Cities Coalition Network works locally in advancing affordable and efficient transportation.[41]
- The U.S. EPA's Local Government Solar Project Portal provides guidance to local governments for community-wide solar power deployment.[42]

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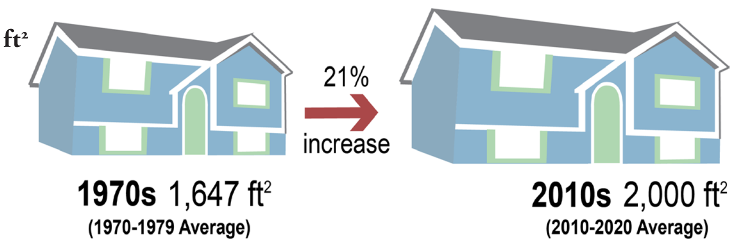
Residential Buildings

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 2000–2020, the U.S. population increased by 17.8%, while the number of housing units increased by 21.5%.[1,2,3] Between 2000 and 2020, urban land area in the U.S. increased by 14%. Urban land area is 3% of total land area in the U.S.[1,4] The following trends illustrate use patterns in the residential building sector.

Size and Occupancy

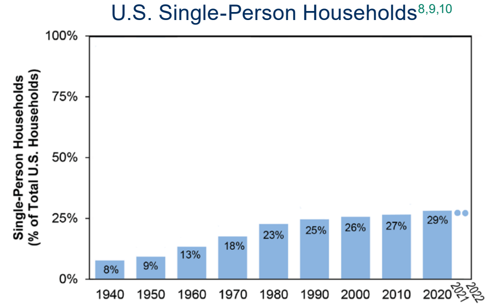
Average Size of a New U.S. Single-Family House, 1970s and 2010s[5,6]



- Increased average area of U.S. houses:[5]
  1970s **1,647 ft^2**; 1990s **2,000 ft^2**; 2000s **2,131 ft^2**; 2010s **2,000 ft^2**
  21% increase from 1970s
- Decreased average number of occupants in U.S. households:[6]
  1970s **2.96**; 1990s **2.64;** 2000s **2.58;** 2010s **2.55**
  14% decrease from the 1970s
- Increased average area per person in U.S. houses:[5,6]
  1970s **556 ft^2**; 1990s **758 ft^2**; 2000s **826 ft^2**; 2010s **784 ft^2**
  41% increase from the 1970s
- A majority of Americans live in single-family houses. In 2021, 70% of the 128.5 million U.S. households were single family.[7]
- In 1950, 9% of housing units were occupied by only one person.[8] By 2022, this value had increased to 29%.[9]

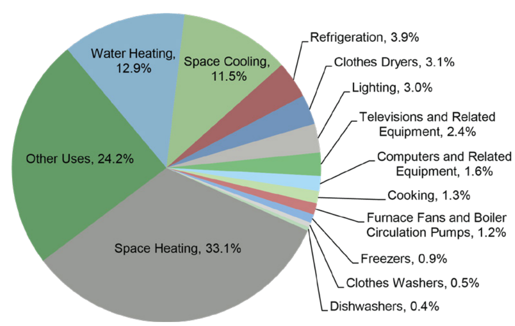
Energy Use

U.S. Single-Person Households[8,9,10]



- A University of Michigan study showed the average house in the U.S. consumed 147 kWh/m^2 annually in 2015.[12]
- Electricity consumption increased 14-fold from 1950 to 2022. In 2022, the residential sector used 1.42 trillion kWh of electricity, 35% of U.S. total electricity use.[13]
- In 2022, the U.S. residential sector consumed 21.8 quadrillion Btu of primary energy, 22% of U.S. primary energy consumption.[14]
- Miscellaneous plug loads per household doubled from 1976 to 2006.[15] These are appliances and devices outside of a building's core functions (HVAC, lighting, etc.) such as computers, fitness equipment, TVs, and security systems.[16] In 2022, miscellaneous loads consumed more electricity than any other residential end use (lighting, HVAC, water heating, and refrigeration), accounting for 36% of primary energy and 50% of electricity consumption.[11]
- Wasteful energy uses include heating and cooling of unoccupied buildings and rooms, inefficient appliances, thermostat oversetting, and standby power loss.[17] Heating and cooling account for 45% of the total energy use in the residential sector.[11]
- 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%.[18]

U.S. Residential Energy Consumption by End Use, 2022[11]



Material Use

- The average U.S. single-family house built in 2000 required 19 U.S. short tons (tons) of concrete, 13,837 board-feet of lumber, and 3,061 ft^2 of insulation.[19]
- From 1975 to 2000, the use of clay for housing and construction more than quadrupled, due to use in tiles and bathroom fixtures.[20]
- In 2012, around 24% of all wood products consumed in the U.S. were used for residential construction.[21]
- Approximately 10 million tons of waste were generated in the construction of new residential buildings in 2003—4.4 lbs per ft^2.[22]
- U.S. average recycling rate of waste from construction and demolition (C&D) is 20-30%.[23] Seattle recycled 68.1% of its C&D waste in 2021.[24]

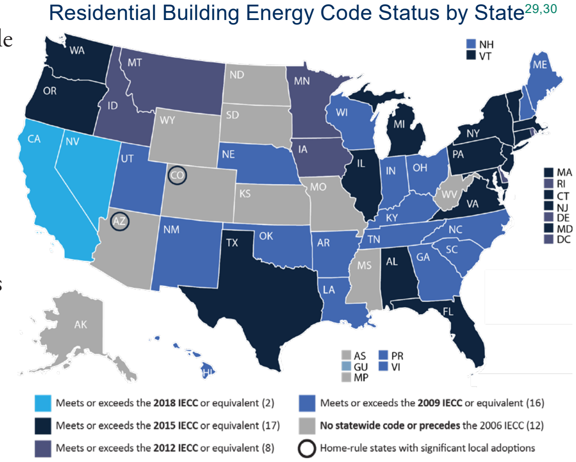
Codes and Standards

- DOE Pacific Northwest National Laboratory estimated cumulative savings from the International Energy Conservation Code (IECC) for 42 states. From 2010–2030, the IECC would save 3.44 quads of primary energy, 16% of residential primary energy consumption in 2022.[14,25] Cumulative energy savings would generate \$40.6 billion (2020 dollars) in cost savings and avoid 224.7 million metric tons (Mt) of CO_2.[25]
- Houses built to Energy Star program requirements are 20% more energy efficient than houses built to 2009 IECC or better.[26]
- Florida's 2007 energy code saved 13% relative to pre-2007 energy consumption through reduction in heating, cooling, and hot water demand. Efficiency gains were offset by increasing house sizes and plug loads.[27]
- 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.[28]

Life Cycle Impacts

- Between 1990 and 2021, residential GHG emissions decreased less than 1%, reaching 954 Mt CO_2e.[31]
- In 1998, CSS conducted a life cycle energy consumption inventory of a 2,450 square foot, single-family house built in Ann Arbor, Michigan.[32]
  - Only 10% of the house's life cycle energy consumption was attributed to construction and maintenance; 90% occurred during operation.[32]
  - Energy efficiency measures reduced life-cycle energy consumption by 63%. Careful selection of materials reduced embodied energy by 4%.[32]
  - Life cycle GHG emissions were reduced from 1,013 to 374 metric tons (t) CO_2e over the 50-year life of the house.[32]
  - Top contributors to primary energy consumption were polyamide for carpet, concrete, asphalt roofing shingles, and PVC for siding, window frames, and pipes. Improved HVAC system and cellulose insulation were the most effective strategies to reduce energy costs.[32]
  - Substituting recycled plastic/wood fiber shingles for asphalt shingle roofing reduced embodied energy by 98% over 50 years.[32]
- A 900-ft² house in Davis, CA, demonstrated design and technologies to reduce energy consumption, such as LED lighting, efficient appliances, graywater heat recovery, and a radiant heating and cooling system. Annual energy consumption fell 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.[33]
- Operating energy accounts for 80-90% of a building's life cycle energy consumption and embodied energy accounts for 10-20%. As energy efficiency improves and operating energy decreases, embodied energy accounts for a larger fraction of life cycle energy. Design and materials selection are key ways to reduce embodied energy.[34]
- Energy retrofits, reduced in-home fuel use, and encouraging denser settlement could decrease residential greenhouse gas (GHG) emissions.[12]

Residential Building Energy Code Status by State[29,30]



Solutions and Sustainable Alternatives

Reduce Operational Energy Demand

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

- Downsizing: build smaller to reduce embodied and operating energy.[35]
- Operating energy can be reduced through passive space heating and cooling.[32]
- By adding ceiling fans, air conditioning can be comfortably set about 4°F higher.[36]
- Install low-flow water fixtures to save both water and energy.[37]
- Adequate insulation can reduce heating and cooling costs. R-value needs differ based on location, building design, and heating methods.[38]
- Water heating accounts for 13% of residential energy consumption.[11] Save energy with a graywater heat recovery system.[39]
- Maximize natural lighting with south-facing windows. Properly shade windows to minimize summer heat gain.[40]
- Purchase energy efficient appliances and lighting. Appliances and lighting typically account for 24% of household energy costs.[41]
- Replace incandescent lamps and halogen lamps with LEDs to reduce energy costs and GHG emissions.[42]
- Pursue net-zero carbon/energy certifications including LEED, Living Building Challenge, GreenGlobes, BREEAM, Passive House.[43]
- Federal rebates, tax credits, and financing strategies are available to homeowners and renters when purchasing new efficient appliances and electrification technologies. These technologies can lower household energy use and incentives make cleaner technology more affordable.[44,45]

Select Durable and Renewable Materials

As operational energy is reduced, the embodied energy of building materials becomes more significant to long-term energy conservation and GHG emission reduction.[46] Durable building materials last longer and require fewer replacements. Renewable materials generally have lower environmental burdens and many sequester carbon.

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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Residential Buildings Factsheet." Pub. No. CSS01-08. **August 2023**

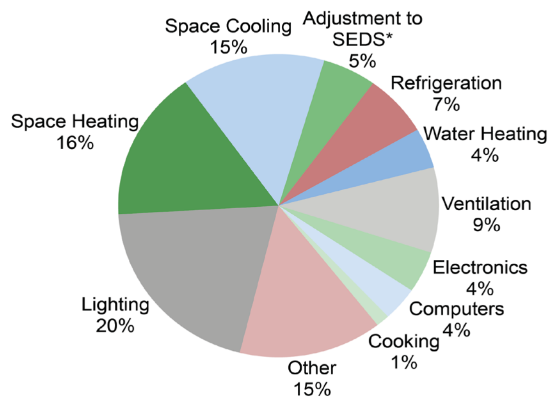
Commercial Buildings

Commercial buildings include, but are not limited to, stores, offices, schools, places of worship, 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., 5.9 million commercial buildings contained 96 billion square feet of floor space in 2018—an increase of 56% in number of buildings and 89% in floor space since 1979.[1,2]
- By 2050, commercial building floor space is expected to reach 124.6 billion square feet, a 29% increase from 2022.[3]
- Education, mercantile, office, and warehouse/storage buildings make up 61% of total commercial floor space and 49% of buildings.[1]

U.S. Commercial Sector Primary Energy End Use, 2010[5]



*State Energy Database System (SEDS) is an energy adjustment that EIA uses to relieve discrepancies between data sources. Energy in this case is attributable to the commercial sector, but not to specific end uses.

Resource Consumption

Energy Use

- Commercial buildings consumed 18% of all energy in the U.S. in 2022.[4]
- In 2022, the commercial sector consumed 18.15 quads (1 quad = 10^{15} Btu) of primary energy, a 72% increase from 1980.[4,5]
- Operational 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

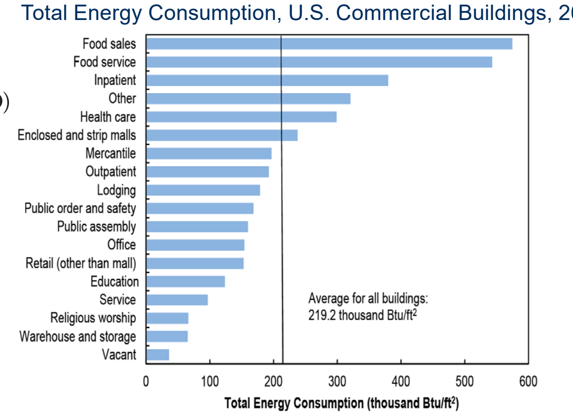
- Typical buildings contain materials including concrete, metals, drywall, asphalt, and wood products.[8] To make concrete, cement (a combination of ground minerals) is mixed with sand, water, gravel, and other materials.[9] Structural steel made up 46% of material market share for structural building, followed by concrete in 2017.[10] While strong and durable, both concrete and steel require significant energy to create and have higher embodied emissions than other materials.
- In 2011, the construction of new low-rise nonresidential buildings in the U.S. used about 1.2 billion board feet equivalents of lumber, accounting for approximately 1% of all lumber consumed in the U.S.[11]

Water Consumption

- In 2005, commercial buildings used an estimated 10.2 billion gallons of water per day, an increase of 23% from 1990 levels.[5]
- Domestic and restroom water is the largest use in commercial buildings, except in restaurants where 52% of water is used for dishwashing or kitchen use.[12]

Life Cycle Impacts

Total Energy Consumption, U.S. Commercial Buildings, 2018[13]



Construction and Demolition Waste

- In 2018, 600 million U.S. short tons (tons) of construction and demolition (C&D) waste was generated.[8] This amounted to approximately 10.0 lbs per capita daily compared to the U.S. average of 4.9 lbs per capita per day of municipal solid waste.[8,14]
- Approximately 38% of C&D waste was recovered for processing and recycling in 2014. 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 in nature. Exposure to high concentrations of VOCs can result in eye, nose, and throat irritation; headaches and nausea; and extreme effects, such as cancer or nervous system damage. VOCs are emitted from adhesives, paints, solvents, aerosol sprays, and disinfectants.[16]

Greenhouse Gas Emissions

- The combustion of fossil fuels to provide energy to commercial buildings emitted 765 million metric tons (Mt) of carbon dioxide (CO_2) in 2022, approximately 16% of all U.S. CO_2 emissions that year.[3]
- As operational emissions drop with the adoption of energy efficiency and renewable energy, embodied emissions, which are attributed to the building materials and energy required for construction, will likely dominate new building life cycle emissions by 2050.[17]

Solutions and Sustainable Alternatives

Opportunities

- Before 2000, little attention was paid to energy use and environmental impact of buildings during design and construction. In 2013, an estimated 72% of buildings were more than 20 years old.[18] For typical commercial buildings, energy efficiency measures can reduce energy consumption by 20-30% with no significant design alterations.[19]
- 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 PV, average energy use intensity can be reduced from 1020 to 139 MJ/m^2-yr, an 86% reduction in energy use intensity.[20]
- Energy Star's Portfolio Manager tracks energy and water consumption.[21] The tool includes nearly 25% of total U.S. commercial building space, making it the industry-leading database to benchmark building performance and provide transparency to building managers and tenants.[21]
- 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 the runoff than a woodland area of equal size.[22]

Design Guidelines and Rating Systems

- The U.S. Green Building Council developed the Leadership in Energy and Environmental Design (LEED) rating system. LEED is a tool for measuring building performance, assigning points for design attributes that reduce environmental burdens and promote healthy, sustainable buildings.[23] As of June 2023, the U.S. has 82,121 buildings that are LEED certified.[24]
- Passive House Institute US provides a climate-specific building standard to minimize energy use and emissions.[25] There are 4 principles of PHIUS buildings, mainly focused on insulation and airtightness.[26] As of June 2023, there are 384 certified PHIUS buildings.[27]
- The Living Building Challenge, an initiative by the International Living Future Institute, comprises seven performance areas, or 'petals': place, water, health and happiness, energy, materials, equity, and beauty.[28] As of 2022, there are 333 certified Living Buildings.[29]
- The U.S. EPA Energy Star buildings program recognizes and assists organizations that have committed to energy efficiency improvement.[30]
- SITES certification for landscapes promotes nature-based solutions to protect ecosystems, while enhancing benefits to communities (e.g., climate mitigation and improving public health). As of 2023, 86 projects have SITES certification.[31]
- BREEAM certification measures sustainability across multiple categories that range from ecology to energy. As of June 2023, there are 170 projects that have achieved BREEAM Outstanding In-Use.[32]

Case Studies

Harvard University Science and Engineering Complex, AIA COTE Top Ten Award, 2023[36]

- The Center for Sustainable Landscapes (CSL) was recognized by the American Institute of Architects (AIA) in its 2016 Commitment to the Environment Top Ten Projects, and was the first building to meet seven of the highest green certifications — the Living Building Challenge, LEED Platinum, SITES Platinum, WELL Building Platinum, BREEAM Outstanding In-Use, Zero Energy Certification, and Fitwel 3 Star green certifications.[33,34] CSL is a net-zero energy building, which significantly reduces its environmental impact during use, but a study revealed its materials had near equal embodied energy and 10% higher global warming potential than a conventional building. As operational efficiencies continue to decrease the impact of a building's use phase, greater attention will be needed to address embodied energy requirements in the resource extraction and construction phases.[35]
- Harvard's Science and Engineering Complex, an AIA COTE 2023 Top Ten Award Winner, achieved Living Building certification (materials, beauty, and equity petal requirements) and LEED Platinum certification. Solar shading, adaptable ventilation, water conservation and stormwater reuse, a heat recovery system, and an energy-saving air cascade system are all employed within the facility.[36]
- There is a movement to make the energy and water use of buildings more transparent to both building owners and tenants. For example, New York City passed Local Laws 84 (2009) and 113 (2016) requiring large building owners to report energy and water through the EPA's Energy Star Portfolio Manager. The information is analyzed by the New York City government and is also available to the public.[37]

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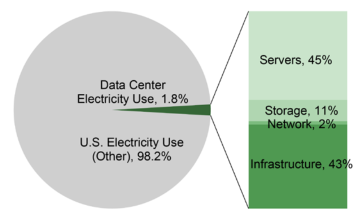
Green IT

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]

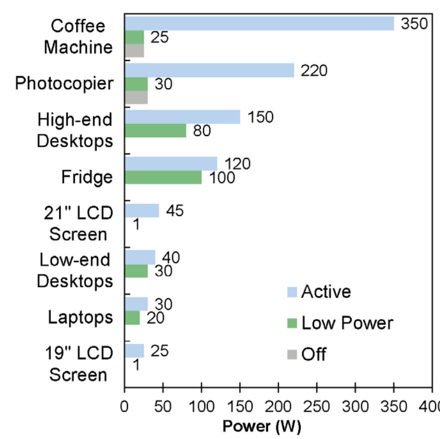
Patterns of Use

- In 2019, 2.16 billion mobile phones, tablets, and PCs were sold worldwide.[3]
- In 2010, 297 million smartphones were sold globally. Over 1.4 billion were sold in 2021.[4]
- Globally, more people have mobile phones than access to safe sanitation.[5,6]
- In 2018, 92% of households in the U.S. had a computer at home, compared to 8% in 1984. Of all households in 2018, 63% had a tablet, 78% had a desktop or laptop, 84% had a smartphone, and 85% had a broadband internet connection.[7]
- More than 14% of households used their primary computer for 10+ hours per day in 2009.[8]
- Computers and office equipment accounted for 13% of the total electricity consumption (227 billion kWh) of office buildings in 2018.[9]
- In 2014, U.S. data centers used 70 billion kWh of electricity—1.8% of total electricity consumption.[2]
- 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%.[10]
- Many countries have seen an increase in telecommuting in response to COVID.[11]
- Telecommuting during COVID in 2020 resulted in a 13% reduction in work-related energy consumption and a 14% reduction in GHG emissions.[12]
- The IT sector accounts for 4% of global GHG emissions and this could double by 2025.[11]

End Use Electricity Consumption of U.S. Data Centers[2]



Office Equipment Power Demand[13]



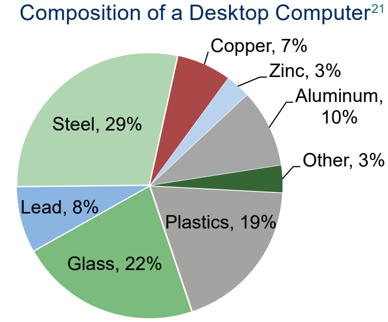
Energy and Environmental Impact

- Electricity used for U.S. servers and data centers emits 28.4 million metric tons (Mt) CO2e annually.[2,14]
- Computer electricity consumption varies greatly with age, hardware, and user habits. An average desktop computer requires 66 W when idle and 1.9 W in sleep mode. Laptops require less power on average - 33 W when idle and 1.0 W in sleep mode.[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 for 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 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.[19]
- 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 CO_2 emissions by 131-526 Mt by 2025.[20]

Electronic Waste

- In 2019, approximately 54 Mt of e-waste were generated worldwide—only 17% was recycled properly.[22]
- U.S. federal regulations currently 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.[25] In 2016, Basel Action Network found that 34% of the e-waste tracked by GPS trackers in the U.S. moved offshore, almost all to developing countries.[26]
- In 2018, the U.S. disposed of 2.7 million U.S. short tons of consumer electronics such as TVs, computer equipment, and telephones, 38.5% of which were 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 Pd, and toxic metals As, Be, Cr, and Pb.[28]
- One metric ton of printed circuit boards has a higher concentration of precious metals than one metric ton of mined ore.[29]

Composition of a Desktop Computer[21]



Paper Industry

- After slow growth from 2014 to 2017, paper production decreased by 2% globally in 2018, and decreased by 3% in North America.[30] Annual consumption of printing and writing paper is expected to rise from 109 to 274 Mt 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 2021, greenhouse gas emissions of the U.S. pulp and paper manufacturing industry were 35 Mt CO2e, approximately equivalent to the annual carbon sequestered by 42 million acres of U.S. forests.[33,34]

Sustainable Alternatives

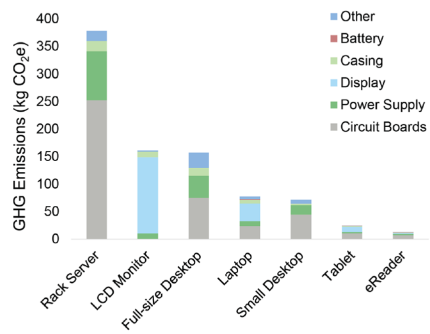
Technology

- Virtualization enables one physical server to run many independent programs and/or operating systems.[35] 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%.[36] Virtualization reduces cost, material waste, electricity use, server sprawl, and cooling loads, saving money while reducing the environmental burdens of running a data center.[35]
- 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.[37]
- Telecommuting or working from home, in which employees work remotely, is becoming more common. Studies suggest energy savings as a result of decreased commuting transportation. When examining the broader energy system impacts, however, increased energy use at home for IT, lighting, and heating/cooling partially offsets the transportation energy savings.[38]

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%.[39]
- Energy Star certified computer servers are, on average, 30% more energy efficient than standard servers. If all servers in the U.S. met Energy Star standards, $1 billion in energy would be saved and 8.2 Mt of GHG emissions would be avoided per year.[41]
- Energy consumed by devices in standby mode accounts for 5-10% of residential energy use. Unplug electronic devices when not in use, or plug them into a power strip and turn that off.[42] Turning off a computer when it is not in use can save $50, 505 kWh, and 433 lbs of CO2 per computer annually.[14, 43]
- When leaving computers on, EPA recommends setting computer monitors to go to sleep after 5-20 minutes of inactivity, and for desktop computers to enter standby after 30-60 minutes.[44]

Embodied Greenhouse Gas Emissions: Computing and Electronics Products[40]



Take Action

- Make informed purchases. Energy Star's Excel-based calculators estimate energy and cost savings for office equipment, appliances, electronics, and lighting.[45] The Green Electronics Council's Electronic Product Environmental Assessment Tool (EPEAT) rates and verifies the environmental impacts of computer products across multiple criteria, including energy efficiency, GHG emissions reduction, and recyclability.[46]
- Purchase Energy Star certified products, consolidate multiple devices into all-in-one equipment, and turn off devices when not in use.[47]
- The average American generates 410 pounds of paper waste each year, and 45% of printed paper in offices is discarded by the end of the day. Save resources by not printing or, when a paper version is necessary, by printing double-sided on recycled paper.[48,49,50]
- Extend the life of personal computers to delay the energy and materials burdens associated with making new equipment.[18]
- Maximize the life of batteries with these practices: minimize exposure to extreme hot and cold temperatures and time spent at both 0% and 100% charge; avoid fast charging, discharging faster than required, use in high moisture environments, and mechanical damage; and follow manufacturer calibration instructions.[51]
- Recycle your unused electronics. Responsible Recycling (R2) and e-Stewards offer third-party certification for electronics recyclers to ensure the proper disposal of used electronics.[52]

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Personal Transportation

In the U.S., the predominant mode of travel is by automobile and light truck, accounting for 87% of passenger miles traveled in 2020.[1] The U.S. has just over 4% of the world's population, but has 12% of the world's cars, compared to 19.6% in China, 5.7% in Japan, 4.4% in Germany, and 4.9% in Russia.[2,3] The countries with the most growth in registered cars since 1990 are China (18%), India (9.8%), and Indonesia (9.6%).[3] The transportation use patterns that follow indicate that the current system is unsustainable.

Patterns of Use

Miles Traveled

- Total U.S. person-miles traveled in 2020 were 4.95 trillion.[1]
- U.S. population increased 36% from 1990 to 2022. Vehicle miles traveled (VMT) increased 35% over the same time period.[1,2,4]
- 69% of the total annual vehicle miles traveled in the U.S. occur in urban areas.[1]

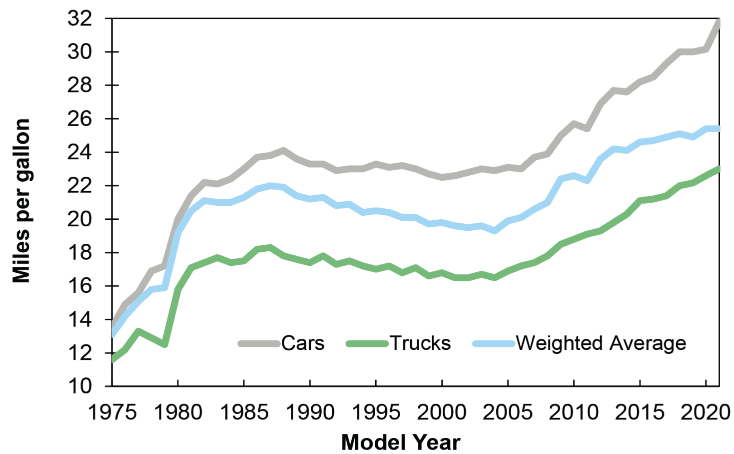
Vehicles and Occupancy

- In 1977, the U.S. average vehicle occupancy was 1.87 persons per vehicle.[5]
- In 2019, average car occupancy was 1.5 persons per vehicle.[3]
- In 2020, the U.S. had 276 million registered vehicles and 228 million licensed drivers.[1]
- In 2017, 24% of U.S. households had three or more vehicles.[6]

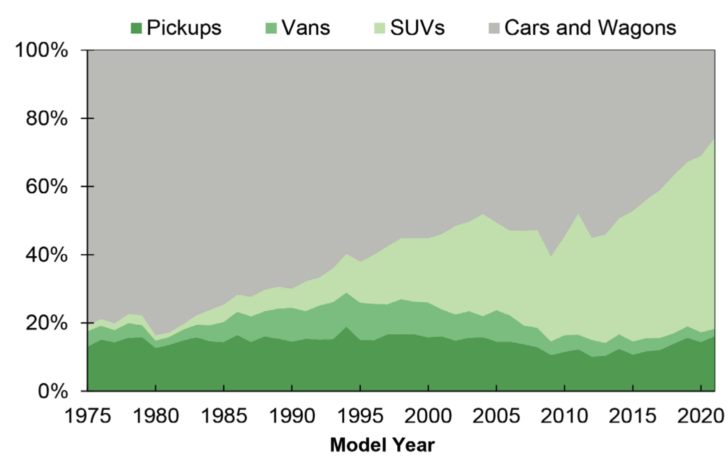
Average Fuel Economy

- The average vehicle fleet 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.[7]
- The average fuel economy for a 2021 model year vehicle was 25.4 mpg: 31.8 mpg for a new passenger car (sedan/wagon and car SUV) and 23.0 mpg for a new truck (truck SUV, minivan/van, and pickup).[7]
- Given the legislation in place, the U.S. has some of the lowest fuel economy standards of any industrialized nation, well below the European Union, China, and Japan.[8]

MPG by Model Year, 1975-2021[7]



Market Share by Vehicle Type, 1975-2021[7]



Vehicle Size

- From 1990 to 2021, average new vehicle weight increased 25% (due to SUV market share growth), horsepower increased by 87%, and acceleration increased (i.e., 0-60 mph times dropped) by 33%.[7]
- During the same period, the average weight of a new passenger car increased 12%, while the average weight of a new pickup truck increased by 32%.[7]
- SUVs, vans, and pickups accounted for 63% of new vehicles sold in the U. S. in 2021.[7]
- A study from the University of Michigan recommends following green lightweighting principles to reduce vehicle mass and improve energy efficiency.[9]

Energy Use

- The transportation sector makes up 28% of total U.S. energy use. Since 1990, the energy use in the transportation sector grew by 20%, though the share of U.S. energy used for transportation increased by 1 percent.[3]
- In 2019, American cars and light trucks used 15.1 quadrillion Btus of energy, representing 15% of total U.S. energy consumption.[3]
- In 2022, 94% of total primary energy used for transportation came from fossil fuels; 90% of total primary energy was from petroleum.[10]
- The transportation sector accounted for 28.5% of U.S. greenhouse gas emissions in 2021—1,804 million metric tons (Mt) CO_2e.[11]
- In 2021, passenger cars and light-duty trucks were responsible for 374 Mt CO_2e and 672 Mt CO_2e, respectively, together making up 58% of U.S. transportation emissions and 16% of total U.S. emissions.[11]

Life Cycle Impacts

A typical passenger car is responsible for various burdens during its lifetime (raw material extraction through end-of-life). Most of these impacts are due to fuel production and vehicle operations. Vehicle lifetime energy use for fuel production and vehicle operations is 1.22 and 4.54 MJ/mi, respectively, while energy use for material production, manufacturing, maintenance, and end-of-life combined is only 0.56 MJ/mi.[12]

Total Life Cycle Burdens, 2016 Mid-Size Sedan[12]

Environmental Flow	Per Mile (g)
CO_2	426
CO	2.92
SO_X	0.13
NO_X	0.24
VOC	0.55
Methane	0.61
GHG	449
Energy (MJ)	6.37 MJ

Solutions and Sustainable Alternatives

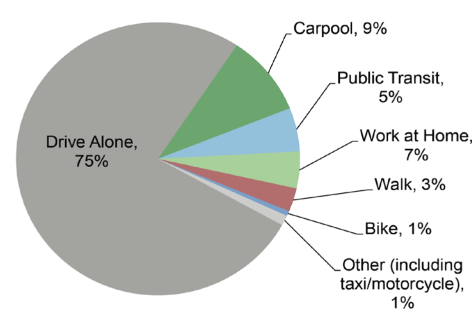
Reduce Vehicle Miles Traveled

- Live closer to work. Driving to/from work represents 30% of vehicle miles driven, and the average commute is 12 miles.[3] Consider telecommuting or working from home if possible.
- In 2020, 74.9% of workers in the U.S. commuted by driving alone, and only 9% of workers carpooled (a drop from 19.7% in 1980).[3] Joining a carpool can help lower household fuel costs, prevent GHG emissions, and reduce traffic congestion.
- Roughly one-fifth of vehicle trips are shopping-related. Combine errands (trip chaining) to avoid unnecessary driving.[3]
- In 2019, traffic congestion caused Americans to spend an extra 8.7 billion hours on roads and burn an additional 3.5 billion gallons of gas. Using alternative modes of transportation, such as bikes, buses, or trains can reduce GHG emissions and decrease wasted time and money.[13]
- Micromobility (e.g., bikes, scooters, etc.) and shared transportation services (e.g., bike shares) have grown rapidly in recent years. In 2019, 136 million trips were taken by shared micromobility users, more than 6 times the number of trips taken in 2015.[3]

Promote Energy 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.[14]
- 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.[16]
- Improvements in information technology related to vehicles such as automation and platooning will likely reduce energy wasted from drivers stuck in traffic.[17]
- When driving electric vehicles, use battery charging best practices to maximize battery life and minimize GHG emissions.[18]

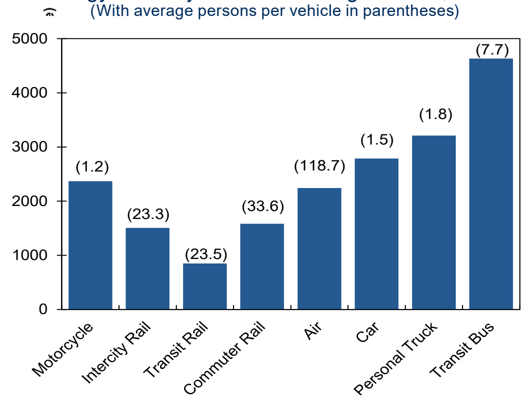
U.S. Modes of Transportation to Work, 2020[3]



Encourage Supportive Public Policy

- Dense, mixed-use communities encourage foot and bike travel while reducing time between residences, businesses, and office spaces.
- In 2012, the Obama National Highway Traffic Safety Administration (NHTSA) set stringent fuel economy and GHG emissions standards.[19] In 2020, the Trump NHTSA and EPA significantly weakened these standards.[20] In 2022, the Biden administration directed the NHTSA to revise the current standards. The final rule set the fuel economy standards to approximately 49 mpg for passenger cars and light trucks by 2026.[21] The next set of fuel economy and GHG standards, for new sales in Model Year 2027 and later, will determine whether U.S. light vehicles can do their fair share toward meeting long-term climate goals.[22]
- Some believe that fuel economy standards tied to vehicle size could incentivize a market shift toward larger vehicles (current trend). A University of Michigan study predicted vehicle size increases of 2-32%, which could undermine the progress made in fuel economy by 1-4 mpg.[23]

Energy Intensity of U.S. Passenger Travel, 2019[3]
(With average persons per vehicle in parentheses)



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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Personal Transportation Factsheet." Pub. No. CSS01-07. **July 2023**

Electric Vehicles

Types of Electric Vehicles

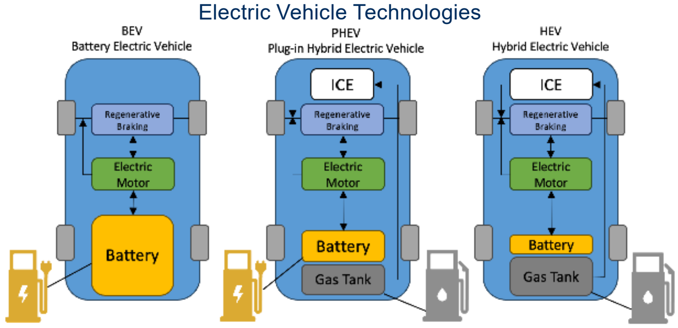
- Not all vehicles that use electricity are called EVs—some vehicles use liquid fuels in conjunction with electricity.[1]
- Hybrid electric vehicles (HEVs) use an internal combustion engine (ICE) and one or more electric motors and energy stored in a battery. Unlike in pure EVs and plug-in hybrid electric vehicles (PHEV) this battery is charged by the ICE and regenerative braking rather than by plugging in.[1]
- Plug-in hybrid electric vehicles are powered by an ICE but PHEV batteries can also be charged from the grid, enabling the vehicle to run on liquid fuels and in all-electric mode. PHEVs can typically travel between 20 and 40 miles solely on electricity before switching to gasoline.[1]
- Battery electric vehicles (BEVs) are powered exclusively by an electric motor and onboard battery that is usually recharged from the grid.[1]
- BEVs achieve their best travel range in moderate temperatures and offer better range in cities due to regenerative braking.[2]
- BEVs have no tailpipe emissions, although the grid from which they draw electricity is likely to be responsible for emissions.[3]
- Fuel cell electric vehicles (FCEVs) convert energy stored as hydrogen into electricity using a fuel cell. Similar to BEVs, FCEVs produce no harmful tailpipe emissions, emitting only water vapor, oxygen, and heat; their impact is dependent on the process used for hydrogen production.[4]
- Vehicles that produce no emissions from the onboard source of power—including BEVs and FCEVs—are called zero emission vehicles (ZEV).

Battery Electric Vehicle Technologies

Since BEVs run only on electricity, they do not include liquid fuel components or exhaust systems.[5]

- *Electric Traction Motor* drives the vehicle wheels using energy from the traction battery pack. All EVs use electric motors that have both drive and regeneration functions.[5]
- *Traction Battery Pack* stores electricity for use by the electric traction motor.[5]
- Battery size, chemistry, and vehicle efficiency determine the range of the vehicle with current BEVs having a range between 110-520 miles.[1]
- BEVs typically use three types of lithium-ion batteries: lithium manganese cobalt oxide (NMC), lithium iron phosphate (LFP), and lithium nickel-cobalt-aluminum oxide (NCA).[1] LFP is gaining in market share due to lower cost.[6]
- *Charge Port* allows the vehicle to connect to an external power supply to charge the traction battery pack.[5]
- BEVs can be charged using electric vehicle service equipment (EVSE) at different charging speeds. Level 1 (approx. 5 miles of range per 1 hour 120 V charging) equipment can take 40-50+ hours to charge a BEV from empty to 80%. Level 2 (approx. 25 miles range per 1 hour 240 V residential or 208 V commercial charging) equipment can charge a BEV from empty to 80% in 4-10 hours. Direct current fast charging (DCFC) equipment (approx. 100 to 200+ miles of range per 30 minutes of charging, typically a three-phase AC input) can charge a BEV from empty to 80% in 20 minutes to 1 hour. Level 2 and DCFC equipment are deployed at many public locations.[7,8]

Electric Vehicle Technologies



Current Market

Market Leaders

- In December 2010 BEVs accounted for 0.002% of light-duty vehicles sold in the U.S., while in May 2023 they accounted for 6.6%.[9]
- In the first half of 2023, Tesla led the market with 336,892 BEV sales in the U.S. Following Tesla were Hyundai-Kia, General Motors, the Volkswagen Group, and Ford with 38,457, 36,322, 26,538, and 25,709 in BEV sales in the U.S. respectively.[10] Globally, Tesla led the market with BYD second.[11]
- Global spending on EVs exceeded $425 billion in 2022, 10% of spending was attributed to government support through direct purchasing incentives with the rest coming from consumers.[6]
- Electric light commercial vehicle (LCV) sales increased over 90% in 2022 to more than 310,000 vehicles even as total LCV sales declined 15%.[6]
- China accounted for 60% of global EV sales with Europe and the U.S. making up 10% and 8% of the global sales share respectively. Over half of the world's EVs are in China.[6] In 2022, Norway was the global leader with a 79% share of the country's new light duty vehicle (LDV) sales as EVs.[12]

Policies and Incentives

- In 2021 President Biden set a target to make 50% of all new LDVs ZEVs by 2030.[13]
- Under the Inflation Reduction Act, the Clean Vehicle Credit qualifies taxpayers who purchase eligible new electric vehicles in 2023 for a federal income tax credit up to $7,500.[14]
- Taxpayers who purchase eligible used EVs from a licensed dealer for $25,000 or less may be eligible to receive a tax credit of up to $4,000.[15]
- Businesses and tax-exempt organizations that purchase a qualified commercial vehicle may be able to take a clean vehicle tax credit of up to $7,500 for vehicles under 14,000 lbs and $40,000 for all other vehicles.[16]

- The Alternative Fuel Vehicle Refueling Property Credit was extended until December 31, 2032. It allows taxpayers to claim up to $1,000 for EV charger and hardware installation.[17]
- California, Oregon, and Pennsylvania have incorporated equity aspects into EV incentives to address needs of low-income individuals, those living in air pollution districts, and disadvantaged communities.[18]
- The California Air Resources Board (CARB) has implemented income caps and MSRP caps to target incentives at those who need them most. Oregon offers up to $2,500 for the purchase of new EVs, with an additional Charge Ahead rebate of $2,500 for qualifying low or moderate income households. Low-income buyers in Pennsylvania receive an additional $1,000 rebate in addition to the $750 state rebate for BEVs.[18]

Current Limitations and Barriers

- As range anxiety concerns have hindered consumer buy-in, the U.S. Department of Energy (DOE) has committed to expanding charging infrastructure and improving battery capacity.[19]
- Most of the critical minerals used in BEVs are concentrated in electric motors (neodymium, praseodymium, and dysprosium) and batteries (lithium, cobalt, manganese, nickel, and graphite).[20]
- Permanent-magnet motors are the most commonly used type in electric vehicles. They can contain 0.06-0.35 kg rare earth elements along with 0.25-0.50 kg neodymium, 3-6 kg copper, 0.9-2 kg iron, and 0.01-0.03 kg boron per vehicle.[20]
- Lithium-ion batteries contain minerals such as lithium, nickel, cobalt, manganese, graphite, and copper.[20] As a result of these mineral-intensive components BEVs use approximately six times more minerals by mass than ICE vehicles.[20]
- Lithium recycling infrastructure could ease the strain on the supply chain, but the non-standardization and lack of regulation for lithium-ion batteries paired with the cost of keeping recycling plants operational in the developing supply chain make recovering lithium a difficult task.[21,22]
- Lower income households experience the highest BEV energy burdens, or portion of income spent on energy services, as 96% of households with incomes less than 30% of area median income would experience moderate or high BEV burdens.[23]

Impacts, Solutions, and Sustainability

Lifetime GHG Emissions for Each Vehicle Class and Powertrain Combination Averaged Across the U.S.[24,25] (g CO_2e/mi and average emissions as % of ICEV pickup emissions)

	ICEV	HEV	BEV
Pickup	543-573 100%	388-410 72%	182-207 35%
SUV	435-485 82%	317-345 59%	162-170 31%
Sedan	373-420 71%	262-287 49%	129-136 24%

- While BEVs have roughly double the greenhouse gas (GHG) emissions of ICE vehicles in the production phase of their lifecycle due to emissions during battery production, they have lower use phase emissions across vehicle types. Consequently, total life cycle GHG emissions for new BEVs are 57% lower compared to the same ICEVs (pickup truck, SUV, sedan) on average across the U.S.[24,25]
- Use phase GHG emissions are dependent on charging location (grid fuel mix, temperature, etc.)[See 25 for U.S. map]
- To maximize battery life, BEV owners should minimize exposure to high and low temperatures, time spent at 100% or 0% state of charge, and fast charging (level 2 charging creates less battery degradation).[26]
- In addition to GHG benefits, BEVs do not directly emit PM, NO_X, and other pollutants that contribute to local air pollution that disproportionately impacts lower income communities.
- BEVs typically have higher purchase prices than ICEVs, but lower maintenance and fuel costs (cost of electricity needed to charge vs. gasoline). The total cost of ownership is favorable towards BEVs for smaller vehicle classes, and when owners have high annual mileage and have access to home charging. Home charging is significantly less expensive than public charging.[27]
- There are 59,758 electric charging stations in the U.S. with a total of 161,118 EVSE ports as of 2023, compared to about 145,000 gas stations.[28,29]
- Most charging stations are located near the coasts and urban centers, which has led to charger availability concerns.[28,30] To ease these concerns, Ford and GM made an agreement with Tesla allowing owners of their EVs to use 12,000 of Tesla's DC fast chargers across the U.S. and Canada starting in spring 2024.[31,32]
- Despite range anxiety, 25-37% of the vehicle population can meet trip needs using a smaller EV battery combined with community charging.[33]
- The households that are best suited for early EV adoption are those with multiple vehicles, access to an outlet for home recharging, and who do mostly urban, low-speed trips.[34]
- By 2050 zero-emission vehicles such as BEVs in conjunction with clean power grids could lead to $978 billion in public health benefits, 89,300 fewer premature deaths, 2.2 million fewer asthma attacks, and 10.7 million fewer lost work days.[35]
- It has been estimated that global automakers expect to spend $1.2 trillion through 2030 on EVs, batteries, and minerals.[36]

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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Electric Vehicles Factsheet." Pub. No. CSS23-08. **September 2023**

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.[1] The Society of Automotive Engineers (SAE) has developed a widely-adopted classification system with six levels based on the level of human intervention. The U.S. National Highway Traffic Safety Administration (NHTSA) uses this classification system.[2]

Levels of Automation

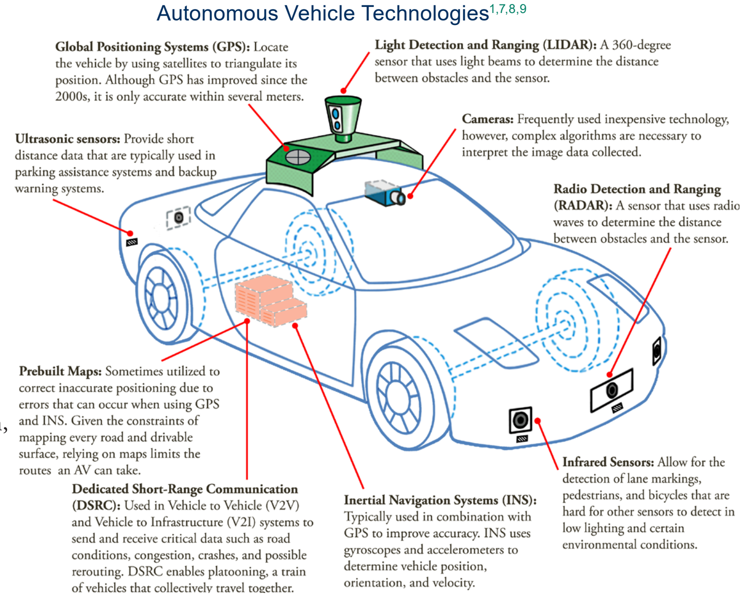
The SAE AV classification system is broken down by level of automation:[2, 3]

Level 0	Vehicles equipped with no automated features, requiring the driver to be in complete control of the vehicle.
Level 1	Vehicles equipped with one or more primary automated features such as cruise control, but requires the driver to perform all other tasks.
Level 2	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.
Level 3	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.
Level 4	Vehicles equipped with features that allow the driver to relinquish control of the vehicle's safety-critical functions. The vehicle can perform all aspects of driving even if the driver does not respond to a request to intervene.
Level 5	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.

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.[1] 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.[1] No vehicles successfully finished the 2004 Grand Challenge, but five completed the course in 2005.[1] In 2007, six teams finished the third DARPA challenge, which consisted of a 60-mile course navigating an urban environment obeying normal traffic laws.[1] In 2015, the University of Michigan built Mcity, the first testing facility built for autonomous vehicles. Research is conducted there into the safety, efficiency, accessibility, and commercial viability of AVs.[4] Unmanned aircraft systems (UAS), or drones, are being deployed for commercial ventures such as last-mile package delivery, medical supply transportation, and inspection of critical infrastructure.[5]

Autonomous Vehicle Technologies[1,7,8,9]



Autonomous Vehicle Technologies

AVs use combinations of technologies and sensors to sense the roadway, other vehicles, and objects on and along the roadway.[6]

Current and Projected Market

Market Leaders

- Waymo has tested its vehicles by driving over 20 million miles on public roads and tens of billions of miles in simulation.[10]
- Teslas have driven over 3 billion miles in Autopilot mode since 2014.[11]
- Other major contributors include Audi, BMW, Daimler, GM, Nissan, Volvo, Bosch, Continental, Mobileye, Valeo, Velodyne, Nvidia, Ford, as well as many other OEMs and technology companies.[6,12]

Regulations, Liability, and Projected Timeline

- Regulation will directly impact the adoption of AVs. There are no national standards or guidelines for AVs, allowing states to determine their own.[13] In 2018, Congress worked to pass the AV Start Act that would have implemented a framework for the testing, regulating, and deploying of AVs. The legislation failed to pass both houses.[14] As of February 2020, 29 states and D.C. have enacted legislation regarding the definition of AVs, their usage, and liability, among other topics.[15]
- 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 appropriately to its level of automation.[16,17]
- Although many researchers, OEMs, and industry experts have different projected timelines for AV market penetration and full adoption, the majority predict Level 5 AVs around 2030.[18,19]

Current Limitations and Barriers

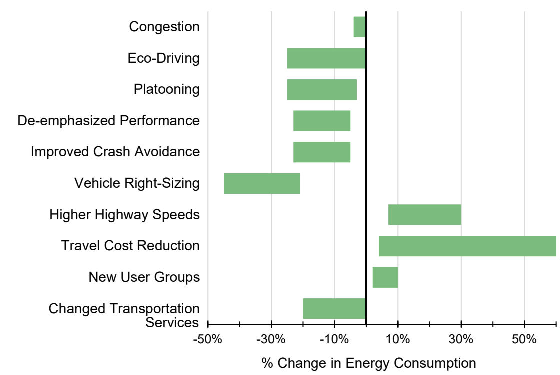
- There are several limitations and barriers that could impede adoption of AVs, including: the need for sufficient consumer demand, assurance of data security, protection against cyberattacks, regulations compatible with driverless operation, resolved liability laws, societal attitude and behavior change regarding distrust and subsequent resistance to AV use, and the development of economically viable AV technologies.[6]
- 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.[12]

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.[20,21] 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%.[22]

Metrics and Associated Impacts

Projected Fuel Consumption Impact Ranges[20,24]



- **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.[20]
- **Eco-Driving**: Eco-Driving, a set of practices that reduce fuel consumption, are predicted to reduce energy consumption by up to 20%. However, if AV algorithms do not prioritize efficiency, fuel efficiency may actually decrease.[20,23]
- **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 vehicle characteristics.[20]
- **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.[20]
- **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%.[20]
- **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.[20]
- **Higher Highway Speeds**: Increased highway speeds are likely due to improved safety, increasing fuel consumption by 7-30%.[20,24]
- **Travel Cost Reduction**: AVs are predicted to reduce the cost of travel 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%.[20]
- **New User Groups**: AVs are likely to increase VMT, especially for elderly and disabled users, and fuel consumption from new users by 2-10%.[20]
- **Changed Mobility Services**: Ride-sharing on-demand business models are likely to utilize AVs due to the significant reduction of labor costs.[25] The adoption of a ride-sharing model is estimated to reduce energy consumption by 0-20%.[20]
- Although an accurate assessment of these interconnected impacts cannot currently be made, 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.[20]

Potential Benefits and Costs

- In 2021, U.S. annual vehicular fatality rate was 42,915; 94% of crashes are due to human error. AVs have the potential to remove/reduce human error and decrease deaths.[26,27] AVs have the potential to reduce crashes by 90%, potentially saving approximately $190 billion per year.[28]
- Potential benefits include improvements in safety and public health; increased productivity, quality of life, mobility, accessibility, and travel, especially for the disabled and elderly; reduction of energy use, environmental impacts, congestion, and public and private costs associated with transportation; and increased adoption of car sharing.[1,13,29,30]
- 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.[1,13,24,30,31]

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Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Autonomous Vehicles Factsheet." Pub. No. CSS16-18. **July 2023**

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 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 warm the surface. Anthropogenic (human-caused) GHG emissions are modifying the Earth's energy balance between incoming solar radiation and the heat released into space, amplifying the greenhouse effect and resulting in climate change.[1]

Greenhouse Gases

- There are ten primary GHGs; of these, water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are naturally occurring. Perfluorocarbons (CF_6, C_2F_6), hydrofluorocarbons (CHF_3, CF_3CH_2F, CH_3CHF_2), and sulfur hexafluoride (SF_6) are only present in the atmosphere due to industrial processes.[3]
- 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.[1]
- CO2 is the primary anthropogenic greenhouse gas, accounting for 64% of the human contribution to the greenhouse effect in 2019.[4]
- Global Warming Potentials (GWPs) indicate the relative effectiveness of GHGs in trapping the Earth's heat over a certain time horizon. CO_2 is used as the reference gas and has a GWP of one.[1] For example, the 100-year GWP of nitrous oxide (N2O) is 273, indicating that its radiative effect on a mass basis is 273 times that of CO2 over the same time horizon.[1]
- GHG emissions are discussed in terms of mass of carbon dioxide equivalents (CO_2e), which are calculated by multiplying the mass of emissions by the GWP of the gas.[5]

The Main Greenhouse Gases[1,2]

Compound	Pre-industry Concentration	Concentration in 2019	Atmospheric Lifetime (years)	Main Human Activity Source	GWP**
Carbon dioxide (CO_2)	278 ppm	416 ppm*	Variable	Fossil fuels, cement production, land use change	1
Methane (CH_4)	729 ppb	1908 ppb*	12	Fossil fuels, Rice paddies, waste dumps, livestock	30 (fossil fuel), 27 (non fossil fuel)
Nitrous Oxide (N_2O)	270 ppb	335 ppb*	109	Fertilizers, combustion industrial processes	273
HFC-134a (CF_3CH_2F)	0 ppt	108 ppt	14	Refrigerant	1,526
HFC-32 (CH_2F_2)	0 ppt	20 ppt	5	Refrigerant	771
CFC-11 (CCl_3F)	0 ppt	226 ppt	52	Refrigerant	6,226
PFC-14 (CF_4)	34 ppt	86 ppt	50,000	Aluminum production	7,380

*Concentration in 2021, ** GWP = 100-year global warming potential.

Atmospheric Greenhouse Gas Emissions

- Since 1750, atmospheric concentrations of CO2, CH4, and N2O increased by 149%, 262%, and 124%, respectively, to levels that are unprecedented in the past 800,000 years.[1,2]
- Before the Industrial Revolution, the concentration of CO2 remained around 290 parts per million (ppm) by volume.[1] In January 2023, the global monthly average concentration increased to 419.31 ppm, which is about 2.1 ppm higher than in 2022.[6]

Sources of Greenhouse Gas Emissions

- Anthropogenic CO2 is emitted primarily from fossil fuel combustion. Iron and steel production, cement production, and natural gas systems are other significant sources of CO2 emissions.[5]
- The U.S. oil and gas industry emits 2.3% of its gross natural gas production annually, equivalent to 13 million metric tons (Mt) of methane—nearly 60 percent higher than the U.S. Environmental Protection Agency (EPA) estimates.[7]
- 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 75% of anthropogenic N2O. Other significant sources include mobile and stationary combustion and wastewater treatment.[5]
- Hydrofluorocarbons (HFCs) are the fastest growing category of GHG and are used in refrigeration, cooling, and as solvents in place of ozone-depleting chlorofluorocarbons (CFCs).[8]

Emissions and Trends

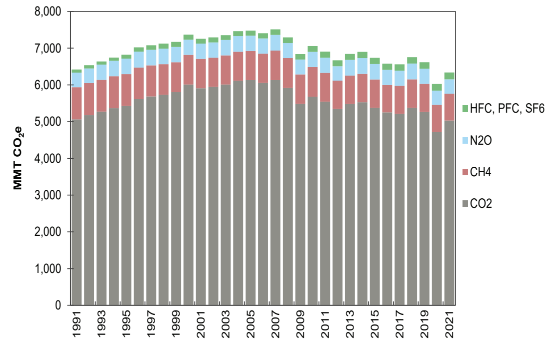
Global

- In 2019, total global anthropogenic GHG emissions were 51.7 Gt CO_2e. Since 1990, annual anthropogenic GHG emissions increased by 57%.[9]
- Average annual GHG emissions were 56 Gt CO2e from 2010-2019. This is the highest decadal average on record and almost 10 Gt CO2e more than the previous decade (2000-2009).[4]
- Emissions from fossil fuel combustion are a majority (73%) of global anthropogenic GHG emissions.[10] In 2021, global emissions of CO2 from energy use totaled 35.3 Gt CO2.[11]
- From 2000 to 2021, global CO2 emissions from energy use increased 45%.[11]
- Since 2005, China has been the world's largest source of anthropogenic CO_2 emissions, surpassing the U.S.[11]

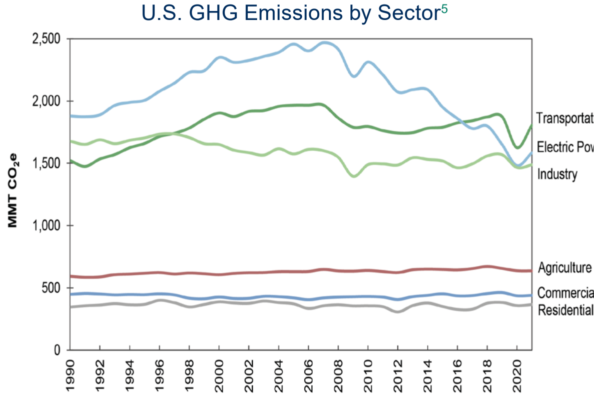
United States

- The U.S. represents less than 5% of the world's total population, but was responsible for 13.5% of total anthropogenic GHG emissions in 2021.[12,13]
- GHG emissions in 2021 were 2.1% lower than in 1990, with an average annual decline rate of 0.02 percent.[5]
- Fossil fuel combustion is the largest source of U.S. GHGs, 73% of total emissions. Since 1990, fossil fuel consumption has decreased at a rate of 0.06%. However, both GHG emissions and fossil fuel consumption have decreased since 2005 by 15% and 19% respectively, while GDP kept growing.[5]
- CO2 emissions accounted for 79.4% of total U.S. GWP-weighted emissions (CO2e) in 2021, 1.7% lower than in 1990 and 17.9% lower than in 2005.[5]
- The electric power industry produces 25% of total U.S. GHG emissions. Emissions from this sector have decreased 16% since 1990 and 36% since 2005.[5]
- Transportation is the largest contributor of U.S. GHG emissions, responsible for 28% of total emissions in 2021, (19% higher than in 1990 and 8% lower than 2005). Passenger cars and light-duty trucks accounted for 374 and 672 Mt CO2e, respectively, together making up 58% of U.S. transportation emissions and 16% of total U.S. emissions.[5]
- Urban sprawl, increased travel demand, population growth, and low fuel prices drive the growth of transportation GHG emissions.[5]
- Land use and forestry in the U.S. sequester CO2 in growing plants and trees, removing 12% of the GHGs emitted by the U.S. in 2021.[5]
- As a result of 2008 federal legislation, sources that emit over 25,000 metric tons (t) of CO_2e are required to report emissions to the U.S. EPA.[14]

U.S. GHG Emissions by Gas[5]



U.S. GHG Emissions by Sector[5]



Emissions by Activity

Use of a 100W light bulb for 10 hours: 0.90 lbs CO2e.[15]

1 mile driven in a car (31.8 mpg): 0.60 lbs CO_2.[16]

1 mile driven in a light-duty vehicle (23.0 mpg): 0.86 lbs CO_2.[16]

Future Scenarios and Targets

- Stabilizing global temperatures and limiting the effects of climate change require more than just slowing the growth rate of emissions; they require absolute emissions reduction to net-zero or net-negative levels.[17]
- Based on current trends, global energy-related CO2 emissions are anticipated to increase by 25% from 2020 to 2050.[18]
- Non-OECD countries' CO_2 emissions are expected to grow by 1.0% annually, while OECD countries' emissions are expected to grow by 0.2% annually. Despite this difference, OECD countries will still have per capita emissions 2.2 times higher than non-OECD countries in 2050.[18]
- Under the Kyoto Protocol, developed countries agreed to reduce their GHG emissions on average by 5% below 1990 levels by 2012. When the first commitment period ended, the Protocol was amended for a second commitment period with a new overall reduction goal of 18% below 1990 levels by 2020.[19]
- In 2015, UNFCCC parties came to an agreement in Paris with a goal to limit global temperature rise to less than 1.5°C above pre-industrial levels, in order to avoid the worst effects of climate change.[20]
- Global CO2 emissions would need to decline 48% from 2019 levels by 2030 and reach net-zero by around 2050 followed by net negative CO2 emissions to avoid temperature rise beyond 1.5° C.[21]

1 Teragram (Tg) = 1000 Gigagrams (Gg) = 1 million metric tons (Mt) = 0.001 Gigatons (Gt) = 2.2 billion pounds (lbs)

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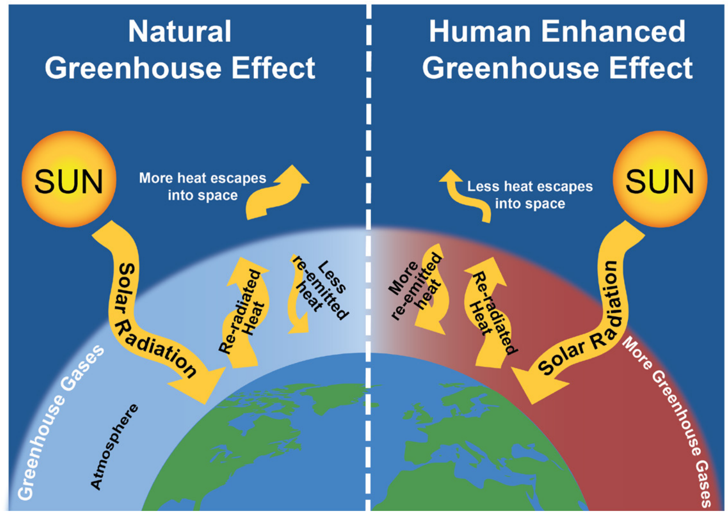
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Greenhouse Gases Factsheet." Pub. No. CSS05-21. **August 2023**

Climate Change: Science and Impacts

The Earth's Climate

The Earth's Greenhouse Effect[1]



Climate change is altering temperature, precipitation, and sea levels, and will adversely impact human and natural systems, including water resources, human settlements and health, 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.[2]

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.[3] Under a stable climate, there is an energy balance between incoming short wave solar radiation and outgoing long wave infrared radiation. Solar radiation passes through the atmosphere and most is absorbed by the Earth's surface. The surface then re-emits energy as infrared radiation, a portion of which escapes into space. Increases in the concentrations of greenhouse gases in the atmosphere reduce the amount of energy the Earth's surface radiates to space, thus warming the planet.[4]

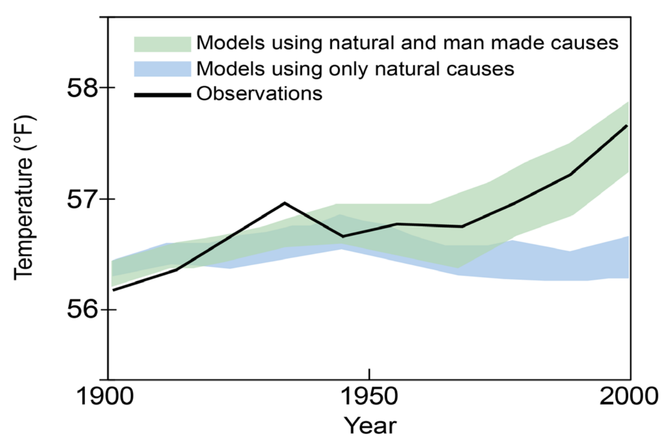
Climate Forcings

- Disturbances of the Earth's balance of incoming and outgoing energy are referred to as positive or negative climate forcings. Positive forcings, such as GHGs, exert a warming influence on the Earth, while negative forcings, such as sulfate aerosols, exert a cooling influence.[5]
- Increased concentrations of GHGs from anthropogenic sources have increased the absorption 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.[5]
- 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.[6]

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 further increases surface warming and evaporation, as water vapor is a powerful GHG.[5]
- The volume of the ocean results in large thermal inertia that slows the response of climate change to forcings; energy balance changes result in delayed climate response with high momentum.[7]
- As polar ice melts, less sunlight is reflected and the oceans absorb more solar radiation.[5]
- Due to increasing temperature, large reserves of organic matter frozen in subarctic permafrost will thaw and decay, releasing additional CO_2 and methane to the atmosphere.[8] June 2020 was tied for the warmest on record and extreme temperatures in the Artic (especially Siberia) contributed to large wildfires and further thawing of permafrost. The fires alone were estimated to have released 59 million metric tons (Mt) of CO_2 into the atmosphere.[9]
- If GHG emissions were completely eliminated today, climate change impacts would still continue for centuries.[10] The Earth's temperature requires 25 to 50 years to reach 60% of its equilibrium response.[11]
- Today's emissions will affect future generations; CO_2 persists in the atmosphere for hundreds of years.[12]

Modeled and Observed Global Average Temperatures[15]



Human Influence on Climate

- Separately, neither natural forcings (e.g., volcanic activity and solar variation) nor anthropogenic forcings (e.g., GHGs and aerosols) can fully explain the warming experienced since 1850.[13]
- Climate models most closely match the observed temperature trend only when natural and anthropogenic forcings are considered together.[13]
- In 2023, the Intergovernmental Panel on Climate Change (IPCC) concluded that: "human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020."[14]

Observed Impacts

Physical Systems

Northwestern Glacier melt, Alaska, 1940-2005[21]

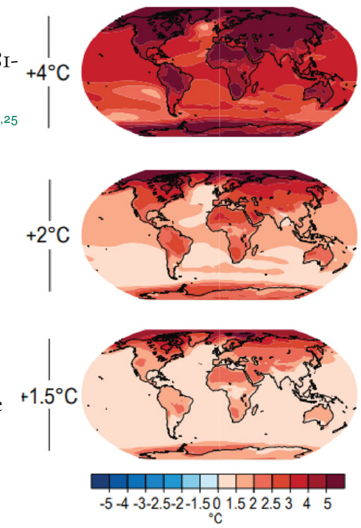
- Global average temperatures in 2022 were 0.86°C (1.55°F) higher than the 20th century average.[16]
- The warmest year on record since records began in 1880 was 2016, with 2020 ranking second. In 2020 global average land temperatures experienced a record high, while 2016 global ocean temperatures remain the highest on record.[17] The nine warmest years on record since 1880 have all occurred within the last nine years (2014-2022), and in 2022 annual global temperatures were above average for the 46th consecutive year.[16]
- Annual 2022 arctic temperatures rose to 0.73°C above the 1991-2020 average. Arctic sea ice is younger, thinner, and less expansive than in the 1980s and 90s.[18] The 2021 extent of ice reached the twelfth lowest annual cover on record since 1979, 4.92 million square kilometers.[19]
- U.S. average annual precipitation has increased by 4% since 1901, but the intensity and frequency of extreme precipitation events has increased even more, a trend that is expected to continue.[20]
- Global mean sea level has rose between 15 and 25 cm since 1901. Due to deep ocean warming and ice sheet melt, sea level rise is unavoidable and will continue for centuries to millennia.[14]
- Snow cover has noticeably decreased in the Northern Hemisphere. Current temperatures have risen 1.1°C and snow cover has decreased 1% relative to 1850-1900. Under a 4°C warming scenario, snow cover is predicted to decrease by 15%-30%.[10]

Biological Systems

- Warming that has already occurred is affecting the biological timing (phenology) and geographic range of plant and animal communities.[22]
- Often biological responses are not sufficient to handle the rapid spatial and temporal shifts that climate change is causing. Globally, approximately half of the species assessed have shifted polewards or to higher elevations.[14]
- Relationships such as predator-prey interactions are affected by these shifts, especially when changes occur unevenly between species.[23]
- Since the start of the 20th century, the average growing season in the contiguous 48 states has lengthened by nearly two weeks.[24]

Predicted Changes

Projected Near Surface Temperature Change Based on Warming Scenarios[10]



Increased Temperature

- IPCC predicts global temperature will rise by 1.5°C (2.7°F) by the early 2030s.[10] 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. Since 1970, global average temperatures have been rising at a rate of 1.7°C per century, significantly higher than the average rate of decline of 0.01°C over the past 7,000 years.[5,25]

Ocean Impacts

- Models anticipate sea level rise between 26 and 77 cm for a 1.5°C increase in temperature by 2100. The rise is a result of thermal expansion from warming oceans and water added to the oceans by melting glaciers and ice sheets.[25]
- The oceans absorb about 31% of anthropogenic CO_2 emissions, resulting in increased acidity. Coral reefs are projected to decline by 70–90% under a 1.5°C global warming senario.[14,26]

Implications for Human and Natural Systems

- This century, an unprecedented combination of climate change, associated disturbances, and other global change drivers will likely exceed many ecosystems' capacities for resilience.[27] Risks associated with a warming scenario of 4°C include more frequent and intense hot and cold extreme temperatures, precipitation events, droughts, and hurricanes.[10]
- In 2023, the IPCC stated with very high confidence that "There is a rapidly closing window of opportunity to secure a livable and sustainable future for all."[14]
- With an increase in average global temperatures of 2°C, nearly every summer would be warmer than the hottest 5% of recent summers.[28]
- Increased temperatures, changes in precipitation, and climate variability have increased the occurrence of food-borne and water-borne diseases. Vector-borne diseases are also occurring more often and in new geographic regions.[14,28]
- Although higher CO_2 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.[28]

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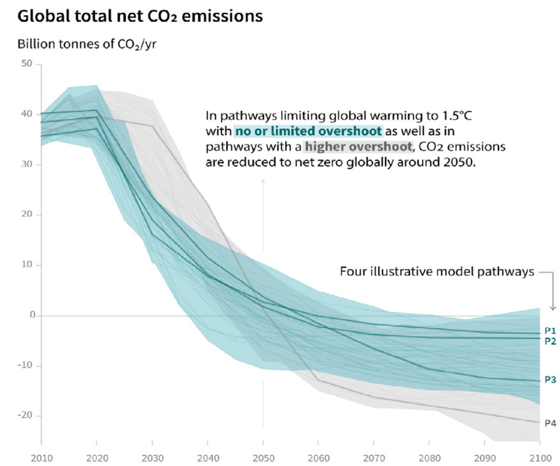
Cite as: Center for Sustainable Systems, University of Michigan. 2023. "Climate Change: Science and Impacts Factsheet." Pub. No. CSS05-19. **August 2023**

Climate Change: Policy and Mitigation

The Challenge

Climate change is a global problem that requires 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."[1] Due to the persistence of some GHGs in the atmosphere, significant emissions reductions must be achieved in coming decades to meet the UNFCCC objective. In 2023, the Intergovernmental Panel on Climate Change (IPCC) published its Sixth Assessment Report. The report details the impacts of climate change and mitigation and adaptation strategies. To limit warming to 1.5°C based on 2019 emission levels, global carbon dioxide (CO_2) emissions need to be reduced by 48% by 2030 and reach net zero in the early 2050s, followed by net negative CO_2 emissions. This requires deep and rapid emission reductions in all sectors.[2] Current national targets under the Paris Agreement would lead to 52–58 billion metric tons or gigatons (Gt) CO_2-equivalents (CO_2e) per year by 2030—not enough to meet the 1.5°C target. 2018 GHG emissions were approximately 42 $GtCO_2$ and would need to drop to between 25-30 $GtCO_2$ per year by 2030 to remain on target.[3] In 2021, U.S. GHG emissions were 6.3 $GtCO_2e$.[4]

Carbon Emission Pathways to Achieve 1.5ºC Target[3]



General Policies

Market-Based Instruments

- Market-based approaches include carbon taxes, subsidies, and cap-and-trade programs.[5]
- In a tradable carbon permit system, permits equal to an allowed level of emissions are distributed or auctioned. Parties with emissions below their allowance are able to sell their excess permits to other parties that have exceeded their emissions allowance.[5]
- Market-based instruments are recognized for their potential to reduce emissions by allowing for flexibility and ingenuity in the private sector.[5]

Regulatory Instruments

- Regulatory approaches include non-tradable permits, technology and emissions standards, product bans, and government investment.
- In 2007, the U.S. Supreme Court ruled that CO_2 and other GHG emissions meet the Clean Air Act's definition of air pollutants, which are regulated by the U.S. Environmental Protection Agency (EPA).[6] After several appeals, the U.S. Court of Appeals upheld the ruling in 2012.[7]
- In the U.S., the Safer Affordable Fuel-Efficient (SAFE) vehicles rule, administered by NHTSA, was implemented in 2020.[8] NHTSA revised the SAFE standards in 2022, setting the Corporate Average Fuel Economy (CAFE) standard to approximatly 49 mpg for passenger cars and light trucks by MY2026.[9] The new CAFE standards are projected to reduce fuel use by more than 200 billion gallons through 2050, saving Americans money and cutting CO_2 emissions by 2.5 Gt.[10]

Voluntary Agreements

- Voluntary agreements are generally made between a government agency and one or more private parties to "achieve environmental objectives or to improve environmental performance beyond compliance."[11] EPA partners with the public and private sectors to oversee a variety of voluntary programs aimed at reducing GHG emissions, increasing clean energy adoption, and adapting to climate change.[12]

The Kyoto Protocol

- The Kyoto Protocol came into force on February 16, 2005, and 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 by 2012. When the first commitment period ended in 2012, the Protocol was amended for a second commitment period; the new overall reduction goal is 18% below 1990 levels by 2020.[13]

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 the global temperature increase (from pre-industrial levels) below 2°C.[14]
- The Paris Agreement entered into force on November 4, 2016. As of May 2023, The Paris Agreement had 198 signatories, 195 of which have ratified the agreement.[15]

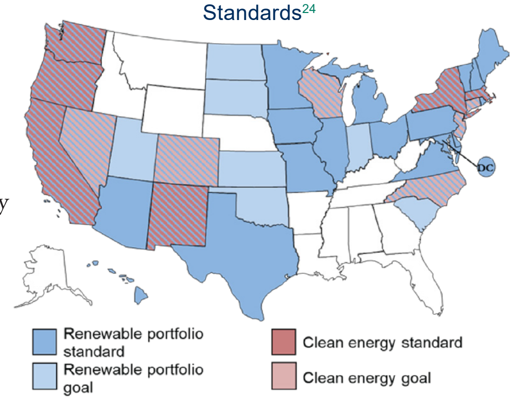
Government Action in the U.S.

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…"[16]

- Due to the Consolidated Appropriations Act of 2008, large emitters of GHGs in the U.S. must report emissions to the EPA.[17]
- In 2023, the EPA proposed a new rule that would set limits for GHG emissions from power plants. This rule includes New Source Performance Standards (NSPS) and emission guidelines for new and existing fossil fuel plants.[18]
- In 2019, a Green New Deal resolution was introduced in the U.S. House. It proposed a 10-year mobilization effort to focus on goals such as net-zero GHG emissions, economic security, infrastructure investment, clean air and water, and promoting justice and equality.[19]
- In April 2021, President Biden held the Leaders Summit on Climate with 40 world leaders and announced the U.S. will "target reducing emissions by 50-52 percent by 2030 compared to 2005 levels."[20]
- The Inflation Reduction Act of 2022 provides resources and loans to organizations including businesses, NGOs, and state, local, and tribal governments to accelerate the clean energy transition.[21]

States with Renewable and/or Clean Energy Standards[24]

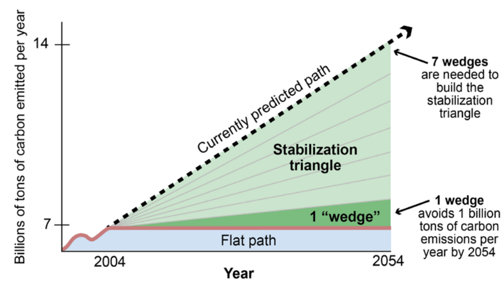


State Policy

- Climate change action plans have been released in 31 states and D.C. and 1 state is updating its plan.[22]
- Twenty five states and D.C. have GHG emissions reduction targets. California is targeting GHG emissions 40% below 1990 levels by 2030 and net zero CO2 emissions by 2045.[23]
- Twenty nine states, D.C., and three U.S. territories have Renewable Portfolio Standards, which specify the percentage of electricity to be generated from renewable sources by a certain date. Six states have Clean Energy Standards, which specify the percentage of electricity to be generated from low-to-no carbon sources and can include renewables, nuclear, and advanced fossil fuel plants with carbon capture and sequestration.[24] A group of governors formed the U.S. Climate Alliance to achieve the GHG reductions outlined in the Paris Agreement. The alliance represents 54% of the U.S. population and 58% of the U.S. economy.[25]

Mitigation Strategies

Stabilization Wedges[26]



Stabilizing atmospheric CO2 concentrations requires changes in energy production and consumption. Effective mitigation cannot be achieved without individual agencies working collectively towards reduction goals and immense GHG emission reductions in all sectors.[11] Stronger mitigation efforts require increased upfront investments, yet the global benefits of avoided damages and reduced adaptation costs exceeds the mitigation expense.[2] Stabilization wedges are one display of GHG reduction strategies; each wedge represents 1 Gt of carbon avoided in 2054.[26]

- *Energy Savings*: Many energy efficiency efforts require an initial capital investment, but the payback period is often only a few years. In 2016, the Minneapolis Clean Energy Partnership planned to retrofit 75% of Minneapolis residences for efficiency and allocated resources to buy down the cost of energy audits and provide no-interest financing for energy efficiency upgrades.[27]
- *Fuel Switching*: Switching power plants and vehicles to less carbon-intensive fuels can achieve emission reductions quickly. For instance, switching from an average coal plant to a natural gas combined cycle plant can reduce CO_2 emissions by approximately 50%.[11]
- *Capturing and Storing Emissions*: CO_2 can be captured from large point sources both pre- and post-combustion of fossil fuels. Once CO_2 is separated, it can be stored underground depending on the geology of a site. Currently, CO_2 is used in enhanced oil recovery (EOR), but long-term storage technologies remain expensive.[28] Alternatively, existing CO_2 can be removed from the atmosphere through Negative Emissions Technologies and approaches such as direct air capture and sequestration, bioenergy with carbon capture and sequestration, and land management strategies.[29]

Individual Action

- There are many actions that individuals can take to reduce their GHG emissions; many involve energy conservation and also save money.
- Choose a fuel-efficient or electric vehicle. Decrease the amount you drive by using public transportation, riding a bike, walking, or telecommuting. For a 20-mile round trip commute, switching to public transit can prevent 4,800 lbs of CO_2 emissions per year.[30]
- Ask your electricity 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 light bulbs use ~90% less energy than standard bulbs, last 15 times longer, and save ~$55 in electricity costs over their lifetimes.[31]
- Space heating is the largest energy use in residential buildings (33%).[32] Ensure that your house is properly sealed by reducing air leaks, installing the recommended level of insulation, and choosing Energy Star windows.[33]

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