Quadrennial Technology Review 2015

Chapter 1: Energy Challenges

Supplemental Information

Additional Information on Energy Challenges

Agency Information

Representative DOE Energy and Science Program Workshops

U.S. DEPARTMENT OF
ENERGY

Quadrennial Technology Review 2015

Additional Information on Energy Challenges

Chapter 1: Supplemental Information

This Supplemental Information appendix expands on the discussion of energy challenges in Chapter 1 of the Quadrennial Technology Review 2015 (QTR).[1] Issues explored here include: (1) how energy use impacts U.S. and global energy security, economic vitality, and environmental quality; (2) the time required to conduct the Research, Development, Demonstration, and Deployment (RDD&D) of and transition existing and new capital stock to energy systems that are secure, economic, and clean;[2] and (3) public and private roles in conducting this RDD&D. These are detailed in the three main sections below.

As discussed in the QTR and its Technology Assessments and Supplemental Information appendices, energy technologies are entering a period of dramatic change due to such factors as: increasing attention to energy system design and system dynamics; transitioning from analog to digital communications and control technologies; and after decades of development, new clean energy supply and end-use technologies are becoming more cost-competitive and entering energy markets at scale. These fortuitous factors can help enable a more rapid response to U.S. and global energy challenges.

Clean energy supply and end use energy technologies entering the market today can do much to address U.S. and global energy-related challenges, and continuing the evolutionary development and scaling up the deployment of these technologies is critical for their continued cost reductions. Yet these changes alone are not sufficient to meet today's energy challenges. Substantial further improvements are needed in the cost and performance of key energy technologies to accelerate, broaden, deepen, and strengthen their ability to meet U.S. energy challenges.

Mechanisms for accelerating RDD&D are needed to reduce the costs and risks of this transition to clean energy systems. Addressing these issues within resource constraints also encourages ongoing evaluation of appropriate public and private roles, and identification of opportunities to leverage scarce resources.

Security, Economic, and Environmental Challenges of Conventional Energy Use

The national energy enterprise has served the U.S. well in many ways, driving unprecedented economic growth and prosperity and supporting our national security. To maintain U.S. energy security requires reducing the risks of physical and cyber attack, improving system resilience, and reducing the risks of dependence on uncertain sources of energy commodities, critical materials, and capital equipment. Maintaining U.S. economic security requires further reductions in vulnerability to economic shocks of energy price volatility. Energy systems will also need to further reduce pollutants that impact human health and the environment, including greenhouse gas (GHG) emissions that impact global climate change and ocean acidification. These require a transition to energy systems and technologies that significantly address all these needs—energy security, economic vitality, and environmental quality—simultaneously while providing better energy services.

Security Challenges

Energy-related threats to national security can broadly be categorized as physical, cyber, economic, and conflict-related, though many of these are inter-related and, in some cases, linked with economic and environmental challenges. Fuel and material supplies—such as critical materials and oil—impact several of these issues, particularly physical and economic threats.

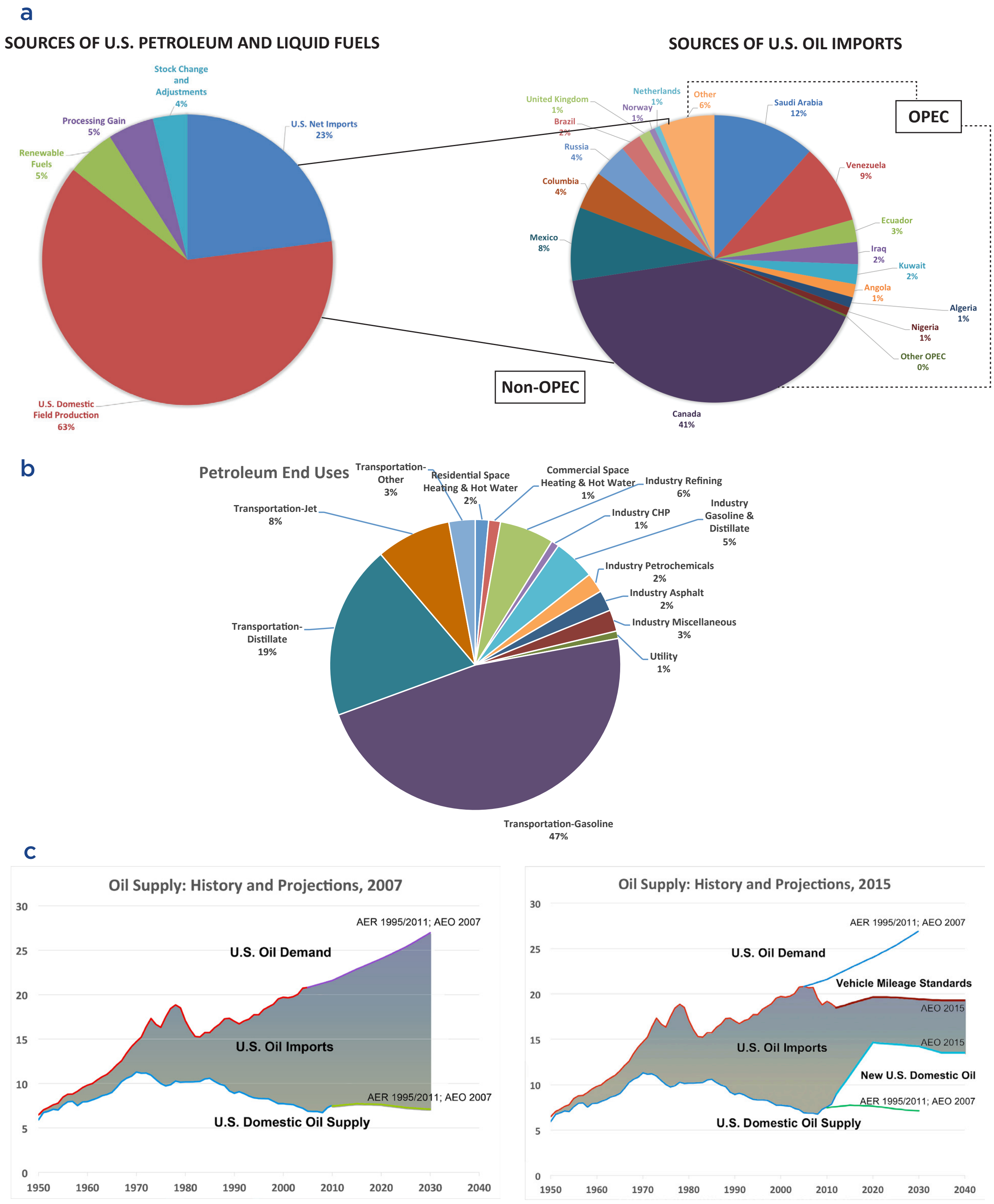
Physical security threats are generally related to potential damage to energy infrastructure.[3] Infrastructure systems of concern include: electricity generation, transmission, and distribution; natural gas and oil pipelines and storage; railroads for coal and crude oil shipments; marine systems; and energy-linked water supply, treatment, and distribution.[4] Damage to these systems could be caused by extreme weather, natural hazards such as earthquakes, or malicious actors[5] (domestic or foreign, state- or non-state-sponsored). Extreme weather, increasingly impacted by climate change, poses growing risks to energy generation (e.g., shortages of water and other resources) and energy infrastructure (e.g., due to heat, drought, or flooding, compounded by sea level rise in coastal areas), as well as changing energy needs (seasonal energy demands and population changes across regions).[6] Storms such as hurricanes Katrina and Sandy, for example, have increased attention to issues such as reliability and resiliency.[7]

A related energy security threat is the availability of energy supplies, particularly oil imports. Oil imports have long supply lines, price volatility, and geopolitical aspects that can impact physical and economic security. The increase in Corporate Automobile Fuel Economy (CAFE) standards and increased domestic production of oil from unconventional sources such as shale are significantly reducing U.S. oil imports. This proportionately reduces U.S. vulnerability to oil disruptions and price spikes. Figure 1, below, shows: (a) sources of U.S. oil supplies; (b) oil use by sector; and (c) the past and projected changes in overall oil supply and demand from 1950 to 2040. Yet even if the U.S. were completely self-sufficient in oil production, U.S. oil prices would still be linked to global oil prices because oil is a globally traded commodity. Although oil prices have recently been low (2015-2016), global pressures on oil are expected to increase in the longer term, as indicated by the growth of overall energy use shown in QTR Figure 1.5. The development of new supplies has largely kept up with demand in the past (sometimes with lags and price volatility), but increasingly is tapping more challenging resources, such as deep offshore, tar sands, and oil shales.[8]

Cyber security vulnerabilities are generally related to the compromise of computer-based systems in their various activities of data inputs and analysis, and their coordination and control of energy supply, delivery, and end-use systems. Malicious actors (domestic or foreign, state- or non-state-sponsored) could introduce malware through a variety of channels to disrupt the production, transmission, or distribution of energy. For example, power outages in western Ukraine on December 23, 2015, have reportedly been attributed to a cyber attack.[10] The challenges of maintaining the integrity of these systems are related to the number of access points to these systems, the need to validate and manage data inputs and responses, the need to monitor the systems for intrusion, and the need to address other vulnerabilities. Private networks also face cybersecurity challenges that increase with access to the Internet. The QTR provides additional information (e.g., see p. 38).

Economic security threats are related to price shocks and supply disruptions or vulnerabilities of energy commodities, critical materials, and/or capital equipment, particularly when the supplies and sources are not diversified. Globally traded energy commodities can be subject to rapid price swings as a result of a wide range of geopolitical factors. Such energy price shocks have led to significant economic disruptions in the past.[11] These price shocks—both up and down—create uncertainty for energy-dependent businesses which, in turn, can reduce investment and productivity. Additionally, the manufacturing of large energy infrastructure components can be dependent on global supply chains that may be subject to long lead times, long-range shipping logistics, price volatility, or availability. Major energy commodity or equipment suppliers could manipulate markets by shifting output levels.

Figure 1 (a) Sources of U.S. oil and liquid fuel supplies (not including liquefied petroleum gas) in 2015, with the sources of U.S. oil imports expanded; (b) U.S. oil use by sector in 2013; and (c) U.S. domestic oil supply and demand from 1950 to 2040 as projected by the Energy Information Administration (EIA). Figure 1.c illustrates the dramatic recent and projected reduction in U.S. oil imports due to new CAFE standards for vehicles, and new U.S. domestic oil production from unconventional supplies, showing the changes in EIA projections between 2007 and 2015. The actual domestic supply will depend on oil prices over time and domestic production is currently challenged (in 2016) by low oil prices.[9]



Critical materials enable important energy technology capabilities in, for example, high performance gas turbines, high performance magnets used in important types of generators and motor drives, and many others.[12] A lack of domestic supply or trusted suppliers could expose economic vulnerabilities as new energy systems that require particular critical materials significantly scale up their installations. Important efforts related to critical materials include the Critical Materials Institute, an energy innovation hub now in place at Ames National Lab.[13]

Conflict-related energy security threats include those that are linked to military or political unrest in locations important to global energy commodities or equipment supplies.[14] Unrest driven by poverty, corruption, inadequate civil institutions, and other factors may be exacerbated by energy price increases or decreases, crop failures, water shortages, or extreme weather. Increasing pressures from climate change—on water, food, ecosystems, and others—have prompted the U.S. Department of Defense[15] to identify climate change as a potentially serious risk that could contribute to political instability, as has the State Department.[16] The same has been found by the United Kingdom and others.[17] The Syrian uprising beginning in 2011 was influenced by many factors, one of which was the most severe drought on record.[18] For the period 1980-2010, a recent study found a "coincidence rate of 9% regarding armed-conflict outbreak and disaster occurrence such as heat waves or droughts", and that "about 23% of conflict outbreaks in ethnically highly fractionalized countries robustly coincide with climate calamities."[19] Some studies have also linked conflict with high temperatures.[20] More broadly, there is a need in developing countries for access to modern energy systems and supplies at reasonable prices to help enable economic development, without which there can be social and political stress.

Many issues are raised by these energy security challenges, including: how to reduce the risk of disruption of global energy supplies; how to develop a diversity of suppliers—particularly with trusted sources; how to reduce dependence on foreign supplies of energy; how to increase system robustness and resilience to physical or cyber attack, or to extreme weather or other natural disasters; and more. Similar issues arise in connection with critical materials as well as key energy technologies. To help respond to these challenges energy science and technology RDD&D is needed on: electricity grid and power supply technologies; advanced fuel and transportation technologies; high efficiency end-use technologies in the buildings and industry sectors; computational methods for the development of advanced materials; and more, as detailed throughout the QTR and its appendices.

Economic Challenges

Energy plays a central role in the U.S. economy, enabling electric power, manufacturing, transport, buildings services, communications, and more. The total cost of energy supplies to end users in the U.S. was roughly $1.2 trillion in 2010,[21] or about 8% of total GDP; this does not include many of the large expenditures on the equipment and systems in the buildings, industry, and transportation sectors[22] that use this energy, and it does not fully include the externality costs of producing, transporting, and using this energy on human health, the environment, or the global climate.

Energy Prices, Price Volatility, and Import Costs. The costs of energy are determined by a complex interplay of the energy supplies available at a given price, the capital and operating costs of converting these supplies into energy services, and the demand for these energy services. In general, demand for energy is often not very sensitive to changes in the price of energy—over the short term. This can cause substantial changes—volatility—in energy prices with small changes in supply. Factors as diverse as inventory adjustments, economic activity, geopolitical events, natural disasters, and market speculation can drive volatility on various timescales. This volatility complicates business planning, which could negatively impact the economy. Over the longer term, higher prices can lead to competition among energy resources and services, opening markets to alternatives (but the volatility of energy markets and the risk of lower prices may constrain investment). When energy is produced domestically, price increases raise producer incomes at the expense of higher consumer expenditures for other goods and services; conversely, price decreases save consumers money, but at a cost to domestic energy exploration and production companies and workers. For energy imports, price increases go to external producers and can impact our national trade balance.

Over the past several decades, a boom-bust cycle has sometimes been observed in energy markets, particularly oil. Higher energy prices encourage an investment boom in new production. As additional supplies become available, prices can fall and lead to a bust in investment—potentially setting up the next round of higher prices. For oil, recent sharp price drops occurred around 1986, 1997, 2008, and 2015.

Energy System Investments. Energy systems are generally capital intensive and have long lifetimes, so they can be relatively inflexible in handling short term changes in the availability of energy supplies or energy prices, contributing to energy price volatility. In the longer-term, however, RDD&D and the gradual replacement of lower performance equipment, together with market responses and mode shifts, can moderate price changes. For example, investments in hydraulic fracturing RDD&D have increased supply in a time of high demand to reduce market prices for natural gas and oil; investments in technologies such as vehicle fuel efficiency improvements can reduce fuel demand (see Figure 1.c), which would in turn reduce market pressures on fuel prices. Such technology advances on both the supply and the demand sides can change energy market conditions over the long term. Having a diversified portfolio comprised of different energy supply and use technologies provides "options" value[23] and can help hedge the risk of being dependent on a single energy supply with potentially large swings in price or disruption of supply. For example, renewable energy technologies that do not use fuel, such as wind and solar, can provide an important natural hedge against fuel price volatility or overall escalation in fuel prices. Diversity also provides a broader spectrum of opportunities for science and technology advances to improve energy technology performance. These considerations help motivate a broad RDD&D portfolio, both to improve the likelihood that some RDD&D pathways are successful, and also to build a portfolio of alternatives for deployment that have independent energy sources (see QTR Chapter 10).

The high capital costs of new energy technologies generally require RDD&D to lower costs and/or improve performance, manufacturing scale-up to capture economies of scale in producing the technology, and substantial production over time to capture economies of learning for both the technology and in rationalizing its supply chains (e.g., see QTR Section 1.4.4); together, these can drive sharp cost reductions in new technologies. This is illustrated in Figure 2 which shows 40-90% cost reductions from 2008-2014 for solar photovoltaic (PV) energy, wind energy, electric vehicle batteries, and LEDs.

Such cost reductions are particularly important for renewable technologies such as solar and wind energy, which have no fuel costs but have relatively high capital costs due to the large area over which they collect diffuse renewable energy and the correspondingly large amount of capital equipment. The upfront capital cost for solar and wind energy systems is effectively paying for the equipment to collect "free" fuel over the lifetime of the system. Although this front-loaded capital cost has often generated a substantial barrier to investment, it also provides a strong hedge against the risk of future fuel price escalation that conventional technologies have and can reduce the overall system sensitivity to volatility in the price of energy. On the demand side, increasing energy efficiency provides protection against future energy price changes and reduces investment in upstream energy supply equipment; for example, doubling efficiency reduces energy use by half with associated cost benefits (not considering any possible rebound effect[25]), and also correspondingly reduces the impact of energy price changes.

To the extent that advances in energy supply or end-use technologies reduce the future demand for conventional fuels and power, this could moderate price increases—benefiting consumers but slowing investment in new energy technologies, particularly those with higher initial costs. Lower prices may also discourage investment in R&D, contrary to long-term strategic interests in energy R&D to help meet national and global energy challenges.

Figure 2 Cost reductions (vertical bars) and increased market penetration (orange lines) for: (a) utility-scale PV; (b) distributed PV systems; (c) onshore wind turbines; (d) batteries for electric vehicles; (e) LED lighting; and (f) indexed cost reductions for these clean energy technologies, 2008-2014.[24]

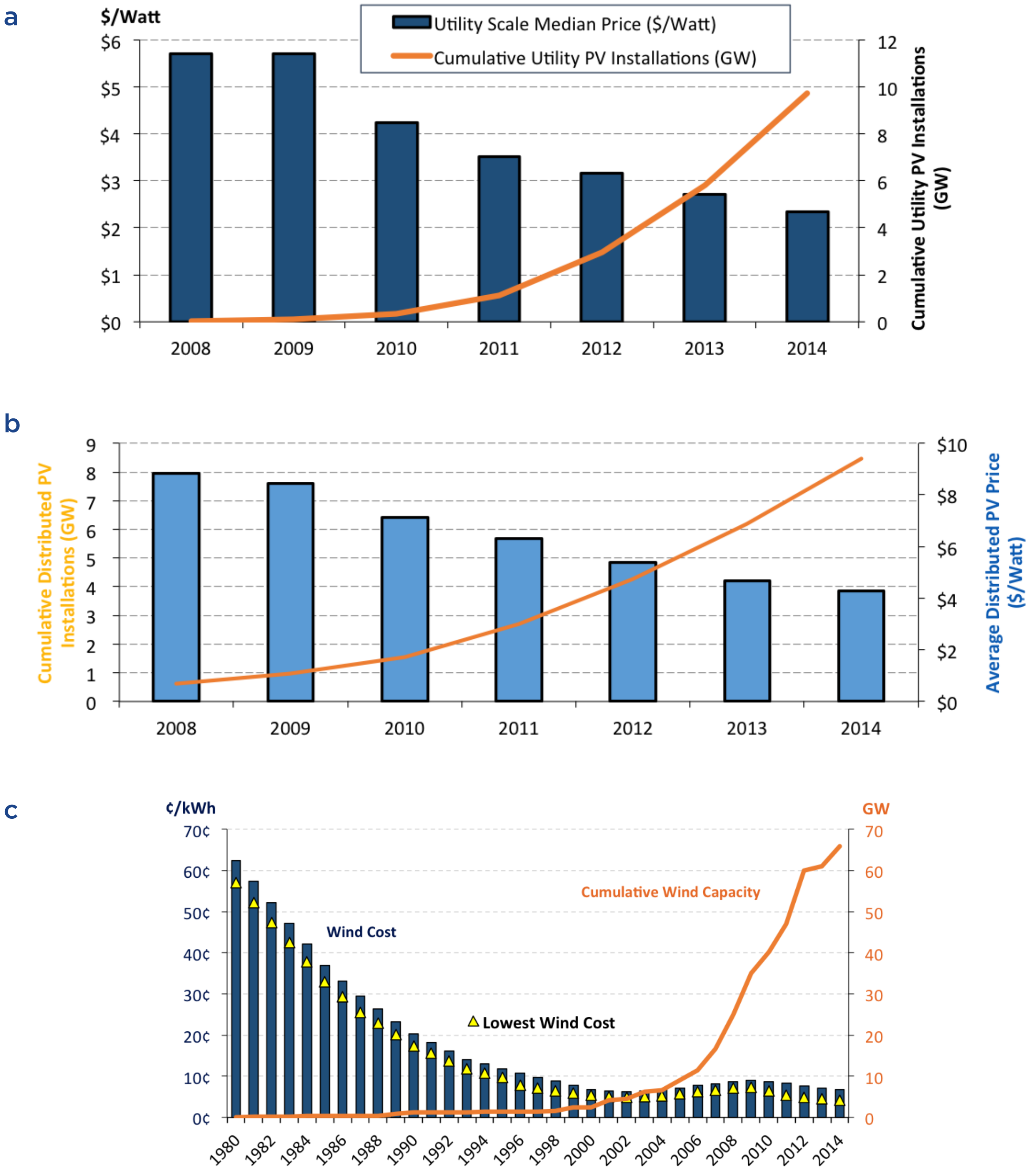
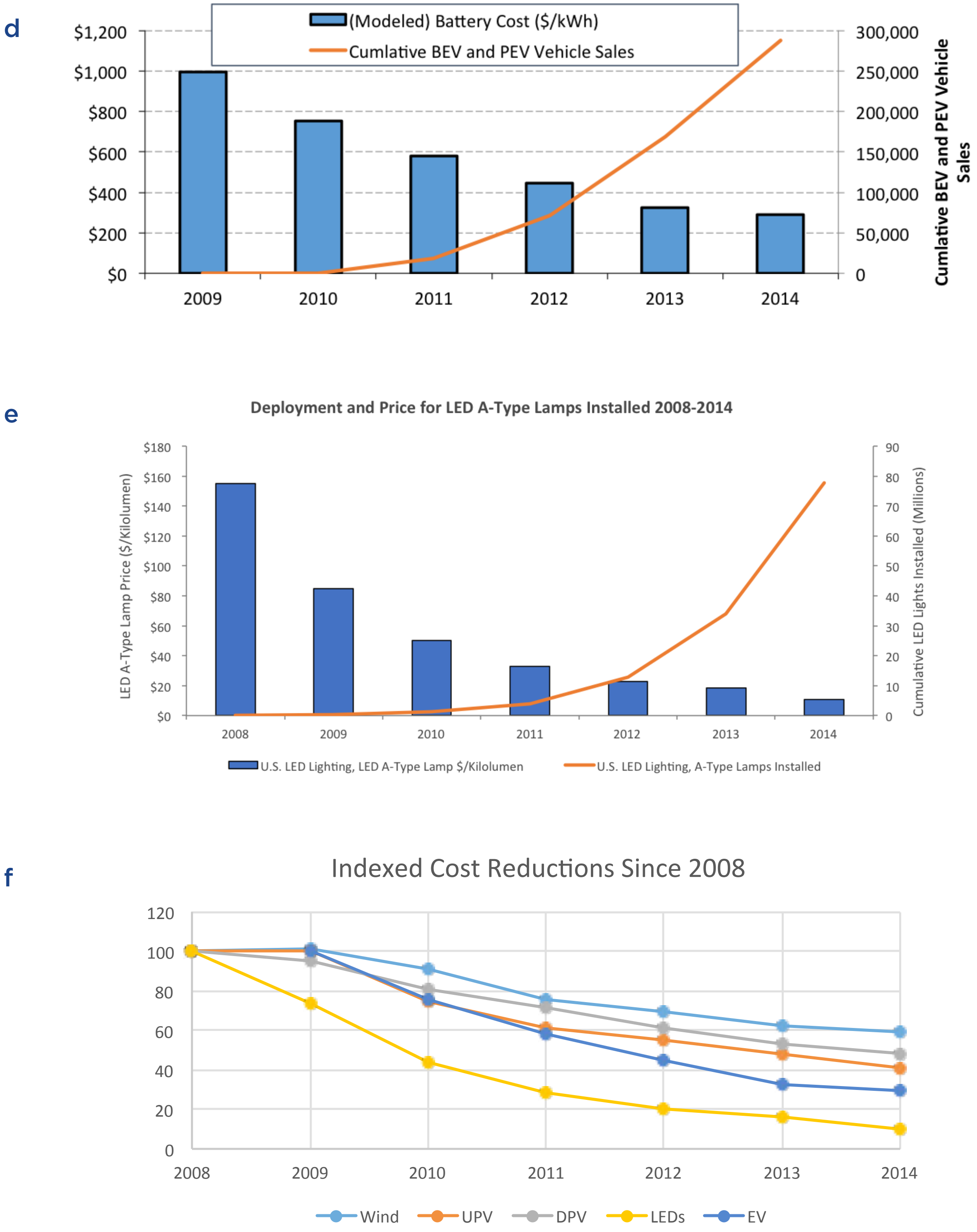


Figure 2, continued Cost reductions (vertical bars) and increased market penetration (orange lines) for: (a) utility-scale PV; (b) distributed PV systems; (c) onshore wind turbines; (d) batteries for electric vehicles; (e) LED lighting; and (f) indexed cost reductions for these clean energy technologies, 2008-2014.[24]



Disruption-related Costs: Outages of the aging U.S. electric power system can impose substantial economic costs on the impacted customer as well as society-wide. A 2006 study by LBNL estimated that disruptions to the U.S. electric power system cost roughly $80 billion per year due to normal weather events, trees falling, equipment failures, and other such events.[26] A more recent study put costs at $20-50 billion per year for weather-related outages, with costs increasing over time; these do not include the damage from extreme weather events such as Hurricane Katrina in 2005 or Hurricane Sandy in 2012.[27] The Quadrennial Energy Review found that widespread power outages due to severe weather cost "the U.S. Economy $18 billion to $33 billion each year between 2003 and 2013."[28] Such costs will rise if climate change further drives increased frequency and severity of extreme weather events (see section below on environmental challenges), if maintenance lags infrastructure aging, or if grid modernization does not keep up with the challenges from new requirements imposed by changing generation and end-use technologies and markets. Improvements in the transmission and distribution system could reduce these costs.[29] These issues indicate a growing challenge to and need for modernization of the electric power system.

Infrastructure Costs: The American Society of Civil Engineers recently reported its analysis of the impact of low levels of investment in infrastructure, finding substantial losses to the U.S. economy.[30] The International Energy Agency review of U.S. energy policy similarly identified a need for infrastructure investment.[31] There are also substantial costs associated with inadequate infrastructure for the transport of coal on railways and for natural gas pipelines and storage; these are addressed in the 2015 Quadrennial Energy Review.[32]

Energy Imports. Oil (petroleum) accounts for most of the energy imported into the U.S.; expenditures for energy imports go to external producers and can be a substantial component of the U.S. trade deficit. Net petroleum imports cost the U.S. economy approximately $190 billion in 2014,[33] nearly half our total trade deficit. The increase in domestic production of oil cut imports in 2015, and together with the global slump in oil prices, reduced the U.S. oil import bill to a still substantial $80 billion.[34] These imports also impose additional macroeconomic costs on our economy.[35] Sharp oil price increases in the past have been important contributors to U.S. recessions,[36] and sharp oil price declines have impacted states and regions, as well as companies, that receive substantial income from oil production.

Global Oil Markets. Over the next 20 years, the International Energy Agency projects that global oil demand will continue to grow, but that production from currently-producing conventional oil fields will decline sharply.[37] Separately, the EIA reference case projects that global oil demand will increase from 93 million barrels per day (MMBbl/d) in 2015 to 121 MMBbl/d in 2040.[38] For the United States, however, the EIA projects that oil demand will not grow at all, remaining at 2015 levels of 19.3 MMBbl/d (Figure 1.c). For U.S. oil supply, the 2015 EIA Annual Energy Outlook (AEO) projects a domestic production peak[39] around 2020 in the reference case but growing slowly at least to 2040 in the high oil supply scenario, although even then oil imports will continue at a reduced level and U.S. oil prices will be tied to global prices.[40] These projections depend on the ability of R&D to keep production ahead of any decline in the quality of the remaining resource at a competitive price. This could provide the opportunity for the U.S. to successfully develop and put into place technologies to more efficiently refine, produce, and use petroleum, as well as reduce demand by transitioning to clean sustainable alternatives. Alternative energy sources for vehicles include electricity or hydrogen that can be produced without releasing CO_2 into the atmosphere (although most current technology for electricity and hydrogen production does generate CO_2 emissions), that do not release polluting emissions when used in the vehicle, and that reduce U.S. dependence on global transport fuel markets. These energy sources would also be particularly useful as their prices are set domestically and can thus side-step the price volatility of current petroleum-based fuels that are traded globally at prices tied to world markets.[41]

Technology advances. RDD&D can reduce costs and diversify energy supplies and end-use systems to help address these economic challenges. On the supply side, one recent example is the set of technologies that enable extraction of gas and oil at competitive prices from previously unrecoverable (shale and tight) reserves, thereby increasing domestic supplies of gas and oil—resulting in the highest domestic oil production in 3 decades.[42] On the end-use side, examples include advances in engines and other vehicle technologies which maintain or improve performance while increasing vehicle fuel economy, resulting in lower overall ownership costs.

Environmental Challenges

Energy production, delivery, and end use can impact human health, ecosystem health, the climate, land, water quality and availability, and more through pathways such as the following:

- **Atmosphere**. The atmosphere is impacted by: release of pollutants—such as sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs), air toxics such as lead and mercury, and many others—and by release of greenhouse gases (GHGs)—such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), black carbon (BC), and fluorinated gases (e.g., refrigerants, certain industrial process gases, and others)—from energy supply and use. In turn, chemical reactions among these can occur, such as between NO_x and VOCs in sunlight to produce ground-level ozone.
- **Water**. Water resources can be impacted: by pollution—such as acid run-off from mining, deposition of air pollutants, or absorption of CO_2; by climate change; by thermal discharges—such as from power plant cooling; by withdrawal of water from ground or surface sources; by physical disruption—such as due to soil displacement, dams, infrastructure, and others; and by other impacts.
- **Land**. Land resources can be impacted: by pollutants; by physical disruption due to fuel extraction or production; by solid waste (coal ash, nuclear waste, etc.); by energy plant or infrastructure siting; and others.

These pathways and their impacts—such as on human health, ecosystems, the environment, and global climate—will be briefly summarized here in the context of energy systems and energy RDD&D. More extensive literature on aspects of these issues is referenced in the endnotes.

Particular attention is given to GHGs, and particularly CO_2, because the potential scale of their impacts are much larger by several important measures than for other environmental challenges. The relatively long lifetime in the atmosphere of CO_2 results in its potential impact as a GHG scaling with its cumulative emissions over time and its corresponding atmospheric concentrations.[43] The planetary-wide scale of impacts from CO_2 and other GHGs impacts the global population to varying degrees. Many other (not all) environmental challenges have relatively short lifetimes and thus scale linearly with emissions rates rather than with cumulative emissions, and the populations impacted are those in the specific emissions plume rather than the global community. This is the case for BC, which is a GHG with a short (a few weeks) atmospheric lifetime that also has substantial human health impacts and regional impacts. Because of its short atmospheric lifetime, reductions in BC emissions quickly reduce atmospheric concentrations, with benefits for both human health and the climate.

Atmosphere

Emissions from energy-related activities are grouped here into two sets: (a) Pollutants such as SO_x, NO_x, PM (which includes BC), VOCs, mercury, and others; and (b) GHGs such as CO_2, CH_4, N_2O, BC, and fluorinated gases, with a particular focus on CO_2.[44]

Pollutant Emissions.[45] Pollutants such as SO_x, NO_x, PM, VOCs, air toxics (mercury, etc.), and others are released into the atmosphere by combustion of fossil fuels in power plants, vehicles, industry, and building equipment, with the quantities of particular pollutants emitted varying by the fuel, the combustion process, the emission controls in place, and other factors. The combustion of biomass, municipal solid wastes, and other materials also generate polluting emissions. Numerous analyses have been done of the serious human health and other environmental impacts from these emissions, resulting in a number of actions to control them. These include catalytic converters to control emissions from cars, flue gas desulfurization systems ("scrubbers") to control emissions from power plants, and thermal oxidizers used to control VOCs from certain manufacturing operations. There remain substantial health and environmental costs. One analysis, published in 2011, estimated economic damages at about $60 billion per year in 2002 from the utility sector due to SO2, NO_x, VOCs, NH_3, $PM_{2.5}$, and $PM_{10\text{-}2.5}$, mostly due to coal-fired power plants.[46] The National Academies of Sciences, Engineering, and Medicine's National Research Council (NRC) found similar costs of about $60 billion for 2005 due to SO_2, NO_x, and PM.[47] Some other studies incorporated a wider range of emissions and damages and found higher values.[48] The NRC study, for example, did not include toxics such as mercury which bioaccumulates in the food chain and is a neurotoxin. Coal-fired power plant emissions are the major source of mercury emissions within the United States and the Mercury and Air Toxics Standards are projected to reduce power sector mercury emissions by approximately 75% when implemented, providing net benefits of $37 billion to $90 billion per year.[49] PM and NO_x exposure have been found to contribute significantly to atherosclerosis and heart disease.[50] There are also studies beginning to explore such issues as the impacts of polycyclic aromatic hydrocarbons (PAH) on children's health.[51] Conversely, studies of children in areas where air pollution has been reduced have found improved health.[52] Refineries also emit pollutants, including petroleum refineries[53] as well as ethanol refineries[54] which release ethanol, a VOC that can contribute to ground level ozone. Some fuel efficient vehicle engines have also been implicated as increasing very small particulate emissions.[55] And geothermal energy systems can release pollutants such as hydrogen sulfide. There are, of course, varying degrees of uncertainty around these estimates, as detailed in the references, due to the estimation of emissions, populations and exposures, translation of exposures into mortality and morbidity rates, and conversion to dollar values.

For energy RDD&D, these considerations motivate attention to emissions over the lifecycle of all energy technologies, not just conventional energy operations but also including those assumed to be clean. These considerations also motivate RDD&D on systems that can control these emissions or to develop alternatives that do not lead to such emissions. An example in the electricity sector would be controlling emissions from coal power plants such as by using advanced selective catalytic reduction or other technologies[56] or by avoiding such emissions by using nuclear or renewable power. An example in the transportation sector would be controlling emissions from vehicle engines with advanced engine design or by avoiding such direct emissions by using electric or hydrogen fuel cell vehicles. In all cases, controlling emissions is also needed in the production of the materials used in the technologies through their recycling or final disposition.

Greenhouse Gas (GHG) Emissions.[57] The greenhouse effect is the result of greenhouse gases (GHGs) in the atmosphere such as CO_2, CH_4, BC, nitrous oxide (N_2O), fluorinated gases, and others absorbing infrared radiation that is leaving the earth's surface and re-radiating some of it back towards earth, raising the average surface temperature. This effect is readily measured in the laboratory and has been measured in the atmosphere.[58] CO_2 is the principal control of this effect; water (H_2O) is also an important contributor to such radiative forcing but would quickly condense out of the atmosphere in the absence of CO_2-driven warmth.[59] The greenhouse effect was first described by Joseph Fourier in 1824; the radiative properties of the most important GHGs were first experimentally verified in the laboratory by John Tyndall in 1863; and the impact of increasing GHGs in the atmosphere was first quantified by Svante Arrhenius in 1896.[60] Without the greenhouse effect, the average temperature of the Earth would be about 59°F (33°C) lower than it is and the earth would be largely frozen.[61]

Mankind is increasing the greenhouse effect by the release of additional greenhouse gases (GHGs) above the levels present before the industrial revolution; these GHGs result from the combustion of fossil fuels, cutting down forests, and the degradation of soil on agricultural lands—all of which release CO_2 to the atmosphere; the release of methane from fossil energy operations and from agricultural activities, particularly from livestock; the release of synthetic fluorinated gases such as those used in air conditioning and refrigeration; and other sources. CO_2 emissions are the largest driver of climate change, accounting for about two-thirds of total radiative forcing.[62] The concentration of CO_2 in the atmosphere has increased from about 280 parts per million by volume (ppmv) during pre-industrial times to just over 400 ppmv today.[63] Figure 3 shows the change in atmospheric CO_2 concentration over time and the corresponding average global temperature. U.S. fossil fuel use currently results in about 5.4 billion metric tonnes (GT) of CO_2 emitted to the atmosphere each year for energy, non-energy (e.g. feedstocks), and manufacturing process-related emissions, such as those from cement production. QTR figure 1.7 shows U.S. energy-related emissions of CO_2 by source and sector. Methane is the next largest radiative forcing GHG, accounting for about one-sixth of the total anthropogenic increase in forcing; energy-related activities account for about one-fourth of global methane emissions and nearly half of U.S. methane emissions.[64] Annual and cumulative emissions by country can be found elsewhere.[65]

The signature of climate change from this increase in GHGs is already widely observed, including, for example:

- higher atmospheric and oceanic temperatures;[66]
- warmer nights, and reduced day-night temperature swings;[67]
- warmer winters, and reduced winter-summer temperature swings;[68]
- warmer lower atmosphere and cooler upper atmosphere temperatures, and reduced radiant heat transfer to space,[69] and
- reduced sea ice and land ice.[70]

These observations from around the world document changes in the earth's temperature and its distribution that are the expected result of increased GHGs in the atmosphere.[71]

The increase in GHGs, particularly CO_2, in the atmosphere is having a number of impacts, which will increase with continued emissions of GHGs. These include the following:[77]

- **Temperature increases.** As noted above, atmospheric and oceanic temperature increases have been extensively documented (See Figure 3).[78] Increasing temperatures above a certain range reduce the human ability to work outdoors,[79] a particular challenge for many developing countries. This is expected to impose a significant cost on national GDPs, both in developed and developing countries,[80] and increasing globalization can connect and enhance economic losses from heat stress-induced reductions in productivity.[81] Extreme heat (and humidity) due to continued business-as-usual carbon emissions could challenge habitability in some regions,[82] with portions of the Middle East and North Africa at particular risk by mid-century.[83] There is also a risk of feedback effects (e.g., an increase in solar absorption resulting from reduced ice cover) that could further accelerate climate change. A number of other potential feedback effects have been identified,[84] as well as a number of potential "tipping" points where abrupt changes in regional climate conditions could occur.[85]
- **Increased Drought in Many Areas; Heavier Precipitation in Others.** As atmospheric concentrations of greenhouse gases increase and temperatures rise, precipitation patterns will shift and evaporation will increase, with the likely result that there will be increased drought in many subtropical and mid-latitude regions, and increased wet conditions in some mid-latitude and many high latitude regions.[86] For the United States, continued global emissions on the business-as-usual trajectory are projected to lead to severe drought in the southwest U.S., beyond what has been seen in the past 1000 years.[87] Figure 4 illustrates expected global changes from a compilation across 22 different climate models, with the overall impact increasing over time with higher concentrations of GHGs in the atmosphere. Groundwater will not likely be able to compensate for reduced precipitation, as it is already under stress in many areas.[88] Further, the observed melt of glaciers in the Himalayas, the Andes, and elsewhere, and early melt and smaller snowpacks in many areas may reduce the availability of water in neighboring agricultural areas during the summer. Other mechanisms will be needed to cope with this increasing

Figure 3 (a) Global average atmospheric CO_2 concentrations and temperature change since 1880.[72] (b) Atmospheric CO_2 concentrations from -800,000 BC to the present, showing the sharp rise over the past 100 years to 400 ppmv at present (in red).[73] For atmospheric CO_2 concentrations since 1958, at Mauna Loa, Hawaii, Observatory and elsewhere, and for global temperature maps, see references:[74] Additional data can be found in the IPCC reports.[75,76]

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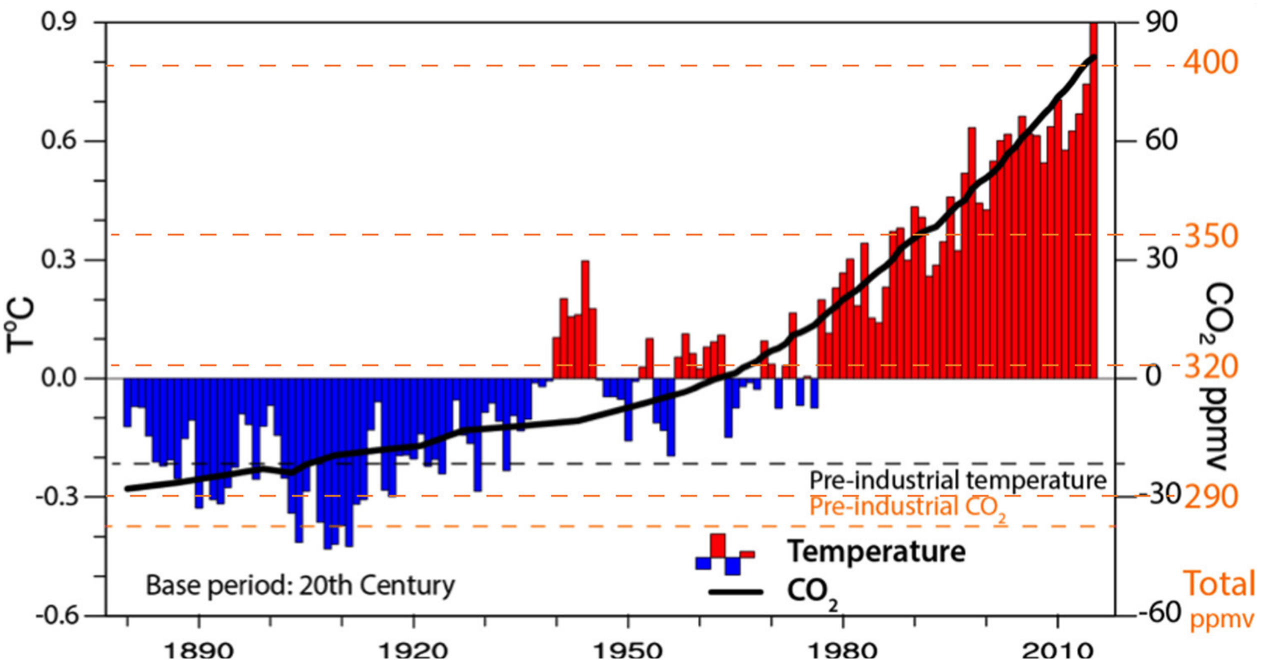

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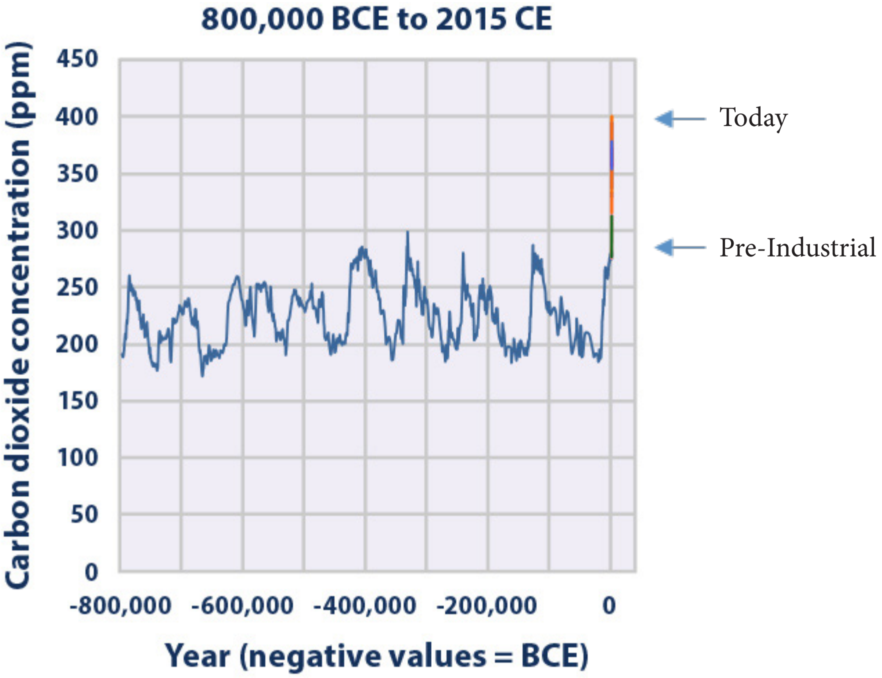
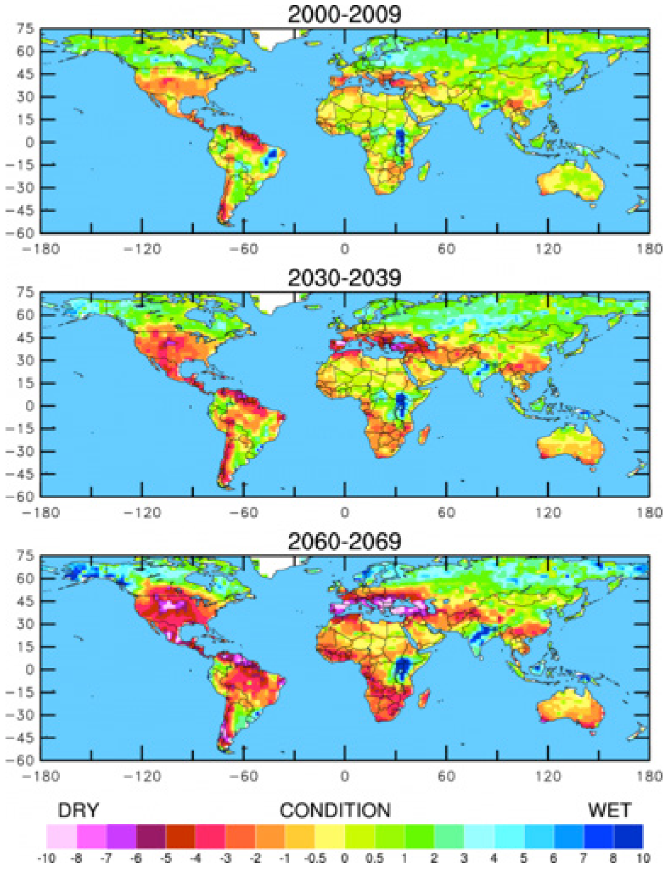


water stress, particularly for impacted lower-income regions in the world, many of which already face serious water supply variability and risk.[89] The UN has warned that the world could face a 40% shortfall in water by 2030 unless there is a dramatic change in water use practices,[90] and the World Bank has warned of serious economic losses from water shortages driven by climate change.[91]

- **Agriculture Impacts.** Higher temperatures and more extreme weather will generally lower agricultural yields, and projected increases in drought (Figure 4) will also challenge agriculture in many areas.[93] For some species, such as rice and soy, increases in atmospheric CO_2 can make up for losses due to higher temperatures for a range of conditions; for others, such as maize and wheat, both increased CO_2 and temperature can reduce yields.[94] Further, increasing atmospheric CO_2 levels have been found to reduce the nutritional value of C3 grains and legumes, although their yield and water use efficiency can increase for a range of CO_2 levels.[95]
- **Health Impacts.** Potential human health impacts of global warming include heat stress, respiratory disorders, increase in infections due to water and vector borne diseases, and others, as examined in detail in the references.[96]
- **Extreme Weather Events.** Increased atmospheric CO_2 levels and consequent increased temperatures have been observed and are expected to lead to more extremes in weather patterns.[97] Higher atmospheric and ocean temperatures fuel convection and provide increased energy and moisture, resulting in more intense storms.[98] Due to the rise in sea surface temperatures, the peak intensity of storms such as tropical cyclones has been observed to move to higher latitudes, increasing their impact on mid-latitude areas and cities.[99] The number of extremely hot days is projected to increase over much of the United States.[100] Summer temperatures are projected to continue rising, and a reduction of soil moisture, as projected for much of the western and central U.S. in summer, can amplify heat waves.

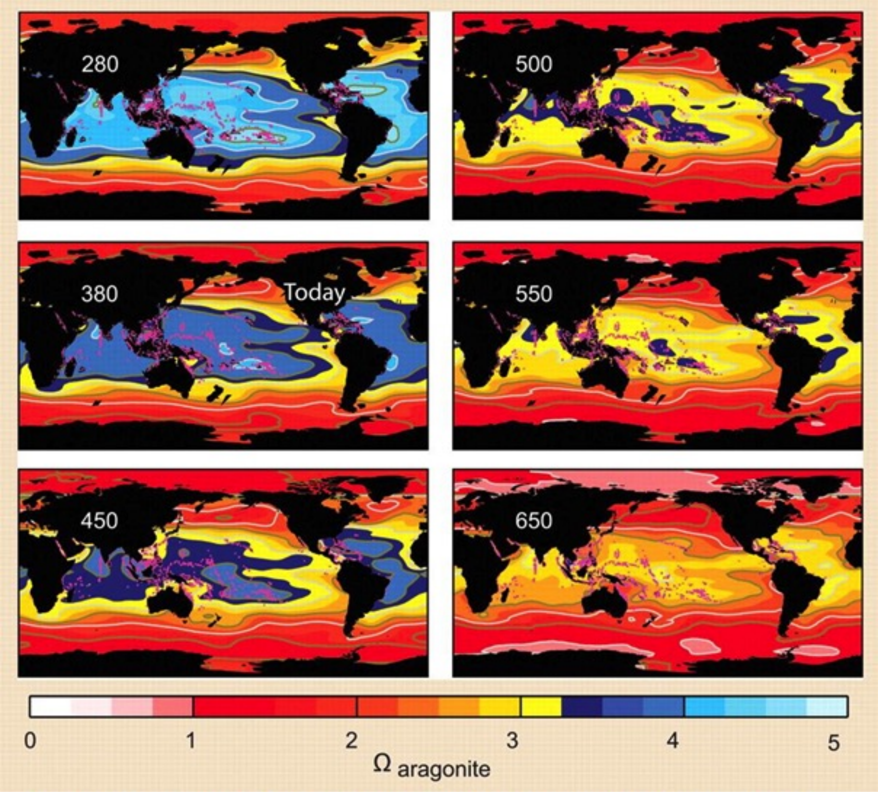
Figure 4 Modeled changes in the Palmer Drought Severity Index on an annual basis for the world.[92]



- **Ecosystems Shift Poleward.** Higher atmospheric temperatures will shift ecosystem temperature zones to higher latitudes, but many species, such as trees and the ecosystems that depend on them, may not be able to spread to these area sufficiently rapidly to keep up with rising temperatures and will face extinction.[101] Similar impacts are observed in marine ecosystems, which currently face rising temperatures, increasing acidification (see below), reduced oxygen, and other stressors.[102] It should be noted, however, that at present the largest drivers of biodiversity decline overall are: the taking of animals faster than they can reproduce, and the taking of land they need to live on for agriculture, livestock, or forestry (or of water bodies for aquaculture).[103]

- **Sea Level Rise**. Climate change impacts sea levels by raising ocean temperatures and thus causing expansion of the water (observed ocean temperatures for the top 700 meters of ocean have warmed about 0.17 °C [0.30 °F] since 1969[104]) and by raising atmospheric temperatures and thus increasing melting of land-based ice. These are projected to result in a 0.5-1 meter rise in sea levels by 2100, without considering large-scale loss of ice from Greenland or Antarctica.[105] However, the geological record indicates the potential for large increases in sea level.[106] In Antarctica, ocean-grounded ice shelves buttress and slow glacier movement into the oceans; higher ocean temperatures are now melting these ocean-grounded ice sheets,[107] reducing this barrier.[108] Two recent independent studies reported that the West Antarctic Ice Sheet may have entered irreversible collapse, which would result in more than 4 meters of sea level rise if completed—in several hundred years or perhaps sooner.[109] Recent studies of the Totten glacier, which has the most rapidly thinning ice in East Antarctica, indicate a potential for up to a 3.5 meter contribution to sea level rise[110] and found that its geological record of large-scale retreats indicate that it is more vulnerable to climate change than previously recognized.[111] Other recent studies have found that the loss of ice from Greenland may be larger and more rapid than expected.[112] An analysis of the long term impacts (hundreds to a few thousand years when equilibrium is reached), considering both the geological record and detailed modeling, estimated that historic cumulative carbon emissions[113] of about 500 GT up to the year 2000 have already committed the world to a Global Mean Sea Level (GMSL) rise of about 1.7 meters (range 1.2-2.2 meters), while the release of another roughly 500 GT would commit the Earth to a GMSL rise of about 9 meters in the long term (with current emissions of 10 GT of carbon per year and growing, 500 more GT will be released before 2050).[114] How much and how fast sea levels rise will determine how severe this challenge will be for coastal cities[115] and for other low lying areas, such as island nations, estuaries, and agricultural areas—particularly during storm surge.[116] There are large uncertainties around how much GMSL will rise—the primary determinant of this will be how much CO_2 is ultimately released into the atmosphere, as well as how fast GMSL will rise.
- **Ocean Acidification and Warming.** About a quarter of the CO_2 that is released into the atmosphere by burning fossil fuels is absorbed by the oceans on an annual basis;[117] the fraction ultimately absorbed by the ocean over time is much higher, perhaps 70-80% of total emissions.[118] The increase in CO_2 in the oceans is making the oceans more acidic.[119] So far, the surface levels of the ocean have become about 30% more acidic[120] since the industrial revolution began[121] and isotope measurements demonstrate that the source of the CO_2 is from fossil fuels.[122] This increasing oceanic acidity is already impacting ocean ecosystems.[123] Figure 5 illustrates expected impacts for coral. If atmospheric CO_2 levels continue to climb from fossil fuel emissions, the result will be fundamental and long-term (thousands of years) change[124] in the chemistry of the oceans with severe impacts on ocean ecosystems. For example, in areas with natural seeps of CO_2 from volcanic activity similar to the concentrations expected from anthropogenic climate change during this century on a business-as-usual trajectory, high biodiversity coral reefs have been found to shift to macroalgae dominated areas.[125] Further, increases in temperature from climate change also challenge ocean ecosystems, including increasing coral bleaching. A 2°C [3.6°F] temperature increase is itself likely to kill most coral reefs, and the impact of temperature on coral is compounded by increased ocean acidification (although some types of coral are able to withstand some acidification).[126] Observed losses of the Great Barrier Reef are an early indicator of the potential impact of warming and acidification.[127] In addition, increased ocean temperatures reduce ocean dissolved oxygen content and increase thermal stratification, leading to larger anoxic dead zones.[128] There is no agreed-upon approach to control ocean acidification other than controlling atmospheric CO_2 levels.[129,130,131]

Figure 5 CO_2-driven changes in ocean chemistry are damaging to many coral, shellfish, and other calcifying organisms. Atmospheric concentrations of CO_2 in ppmv are shown in the upper left of each panel—e.g. 280, 380, 450, ...--and the area of the ocean with chemistry supportive of calcifying organisms is shown in blue and decreasing as the atmospheric CO_2 levels increase from the upper left panel to the lower right. The world is currently at just over 400 ppmv, and on a business-as-usual trajectory, the world, will cross 450 ppmv in the early 2040s. The chemistry shown is for aragonite, a form of calcium carbonate often used by calcifying organisms to create shells and skeletons. Areas indicated in shades of blue have sufficient aragonite for these species, but normal growth becomes increasingly difficult in areas shaded in yellow and red. In areas where the aragonite saturation state is below 1, most exposed aragonite structures will dissolve. However, the growth of calcifying organisms may decrease with declining saturation state, even if it remains above 1.[132]



Overall projected impacts at 1.5°C [2.7°F] and 2°C [3.6°F] temperature increases above pre-industrial levels are examined by Schleussner, et al.[133] Their review includes the increased probability of days with extreme temperatures; the increase in extreme precipitation events; the share of tropical coral reefs at risk of long-term degradation; the long-term global sea-level rise; the change in agricultural yields for corn, wheat, rice, and soy in tropical areas; the impacts on ocean ecosystems, and others. The analysis indicates substantially greater impacts at 2°C [3.6°F] than at 1.5°C [2.7°F] in most cases.

Energy Sector Impacts. The changes described above due to GHG emissions will impact energy systems in a variety of ways, including the following:

- **Increased temperatures.** Higher average temperatures will reduce average space heating demands while at the same time increasing the need for space cooling and hence summer electricity production. Higher temperatures will also impact (generally reduce slightly) the performance of thermal power plants and energy infrastructure. Warmer high-latitude temperatures are melting permafrost regions, increasing the difficulty of extracting some energy resources, while longer periods of ice-free coasts in the high latitudes are opening new areas for oil and gas exploration.[134]

- **Increased drought.** Changing rainfall patterns will require thermal power plants in many areas to adjust to altered availability conditions for the water they rely on for cooling.[135] Those same altered hydrologic patterns will affect hydroelectric generation facilities. Bioenergy production will need to adjust to altered weather patterns, particularly rainfall and soil moisture, and higher concentrations of CO_2.
- **Extreme weather events.** Extreme weather poses substantial challenges to energy infrastructure.[136]
- **Sea level rise.** Energy infrastructure located near coasts and in open water will be affected by rising sea levels and more damage due to storm surge and more severe storms.[137]

As noted above, the potential impacts of CO_2 as a GHG, in particular, scales with its cumulative emissions over time and its resulting atmospheric concentrations, with corresponding impacts on the dimensions identified above—higher temperatures, more extreme weather, ecosystem shifts, rising sea levels, ocean acidification, and others. Many of these changes will be substantially irreversible for thousands of years, even after net CO_2 emissions stop.[138] This will require efforts to improve resiliency as well as adaptation.

Health Sector Benefits. Reducing GHG emissions can also benefit health both directly and by the co-benefits of simultaneously reducing the emission of other pollutants. One study of the climate and health impacts that would be associated with U.S. emissions reductions consistent with a 2°C [3.6°F] target, for example, estimated roughly 175,000 premature deaths could be prevented by 2030;[139] another study calculated global average marginal co-benefits of avoided mortality from PM and ozone associated with carbon emissions of $50-380 per tonne of CO_2.[140]

Water

Energy-related environmental impacts on water include the following.

- **Pollutants**. Pollutants entering water include: acids and toxins from deposition of air pollution, described above, or CO_2 absorption leading to acidification; acid run-off or other contamination from energy resource extraction (e.g., mining) operations; release of coal ash or other materials from energy operations; and others.[141]
- **Thermal.** Thermal impacts include thermal discharges of waste heat into water bodies (such as from power plants) and higher temperatures from climate change.
- **Water withdrawals.** Water is withdrawn from surface or ground water for power plant cooling or other energy operations. Cooling thermoelectric power plants accounts for about 38% of U.S. freshwater withdrawals, most of which is returned to the water body, but at a higher temperature due to waste heat discharges.[142]
- **Disruption.** The construction and operation of hydropower reservoirs and other facilities can modify the river or lake itself or otherwise disrupt it, change stream flows, or have other impacts.

All of these can impact aquatic life. Figure 5, for example, describes the impact of increasing atmospheric levels of CO_2 on coral, shellfish, and certain other sea life.

Land

Environmental impacts on land include:

- **Pollutants**. Pollutants impacting the land include: deposition of atmospheric pollutants or direct discharge of pollutants from operations (e.g., coal ash);[143]
- **Disruption.** Physical disruptions can result from fuel extraction/production or energy plant or infrastructure siting. Physical disruption and related impacts on human health and the environment can take many forms, from mountaintop mining,[144] to land used for oil and gas operations,[145] to use

of agricultural or other land to grow bioenergy crops, to placing wind turbines on farm or ranchland, each with differing degrees of disruption and other impacts.[146] Another potential impact is induced seismicity (i.e., earthquakes) caused by injecting water into the subsurface associated with oil and gas extraction (hydraulic fracturing) or wastewater disposal, as well as geothermal energy operations.[147]

Responses to Environmental Challenges.

Responses to these environmental challenges include: planning and developing resilience to or adapting to the changes underway; and mitigation to slow or stop further changes—for example, by reducing net emission of pollutants into the air, water, and land; reducing emission of GHGs; reducing thermal discharges into water bodies by reducing the need for powerplant cooling or through generators that don't need cooling; reducing water body disruptions by using run-of-river systems that don't require reservoirs and reducing land disruptions from mining or system siting; and others. For GHGs, with an emphasis here on CO_2 because its climate impact scales with cumulative emissions and climate change has global scope, these responses include the following:

- **Mitigation**. To constrain the increasingly serious impacts that will occur with continued release of GHGs, the net anthropogenic emission of GHGs (particularly CO_2) into the atmosphere must go to zero; to control ocean acidification, the net anthropogenic emission of CO_2 must go to zero. To do this requires the deployment of energy supply technologies that either control emissions, such as through carbon capture, utilization, and storage (CCS), or that do not release GHG emissions, such as nuclear or renewable energy. Energy efficiency is important for reducing demand and thus reducing the required build-out of clean energy supply systems (and to reduce costs for consumers, as efficiency is often the lowest cost option). It is also important to significantly reduce fugitive emissions of methane from fossil fuel extraction, transport, and use, as well as emissions of other GHGs such as N_2O and methane from agriculture and livestock, and refrigerants such as CFCs and HFCs. Increasing uptake of atmospheric CO_2 is also important, such as through reforestation. For the energy supplying or using technologies themselves, changes in the materials used and their production processes, fabrication, and lifecycle are also needed to reduce the associated GHG emissions, as well as other impacts (lifecycle emissions are discussed in QTR chapter 10 and its Supplementary Information appendix, and in Technology Assessment 6.L: Sustainable Manufacturing: Flow of Materials Through Industry).

  Clean energy technologies available today can significantly reduce GHG emissions. Further RDD&D – as detailed in the 2015 QTR Technology Assessments[148] – can improve the cost and performance of these and other energy supply, infrastructure, and end use technologies to accelerate and strengthen their ability to ultimately end GHG emissions while improving the robustness and resilience of our energy systems.
- **Resilience**. Resilience and adaptation of energy systems and infrastructure are also needed for the changes that are already underway and will continue. This includes identifying systems most at risk to climate change—such as those that are highly vulnerable to temperature increases, water shortages, severe storms, and/or sea level rise—and correspondingly strengthening their resilience or identifying alternatives.[149]

Over the last several decades, significant progress has been made in reducing many forms of pollution in the United States—impacting the atmosphere, water, and land—from energy-related activities. Energy-related atmospheric emissions of conventional pollutants such as particulates, sulfur, and nitrogen compounds have been reduced through improved fuels and combustion strategies, and by "end-of-pipe" (e.g., scrubbers, catalytic converters) emissions controls. Additional progress has occurred by transitioning to cleaner fuels and renewable resources. These successes indicate what can be accomplished with RDD&D and policy. Advanced technologies can have a significant impact on the next generation of challenges, especially deep reductions in GHG emissions. RDD&D to advance these technologies is the focus below.

Research, Development, Demonstration, and Deployment Challenges

The levels of public RDD&D funding for energy technologies, any associated policies, and any other public role to address the energy-linked challenges described above are informed by rigorous analysis. As investment decisions are made, it is useful to consider issues associated with RDD&D, including: (a) capital stock inertia; (b) RDD&D gestation times; and (c) public and private activities in RDD&D. These issues influence the type of RDD&D that is done, the timeframe in which it is done, how it is done, the balance across the various elements of RDD&D, and other considerations. These issues are examined below.

Capital Stock Inertia

The existing U.S. capital stock of buildings, factories, power plants, vehicles, and infrastructure will continue to use conventional fuels and to emit pollution and GHGs over their lifetimes.[150] This existing capital stock thus embodies a large conventional energy and carbon commitment and will require long periods of time to replace with new capital stock using clean energy technologies.[151] The scale of change required can be usefully visualized using a wedge framework (see QTR Chapter 10).[152] Should a rapid response to the above security, economic, or environmental challenges be needed, some portion of this capital stock might require retirement before its economic (and technical) life is complete—thus resulting in a "stranded asset". The number of assets at risk of being stranded could grow over time as additional conventional technologies are installed with, for example, their high levels of oil use, GHG emissions, or other problematic characteristics, thus locking these factors in over the lifetime of the equipment. Studies have found that the most important factor in limiting climate change, for example, is the reduction of emissions in the near term.[153] Examination of these capital stocks and their inertia identifies a number of RDD&D challenges.

Energy supply capital stock. The United States currently has about 1000 GW of power plants (net summer capacity),[154] with just over 19,000 electric generation facilities and many more small distributed facilities providing power to the U.S.; about 142 petroleum refineries and almost 200 ethanol plants;[155] and the associated infrastructure of mines, wells, pipelines, railroads, powerlines, and more.[156]

End-use capital stock. In the U.S. in 2012 there were more than 5.6 million commercial buildings with a total of 87 billion square feet of floor space;[157] about 115 million residential households;[158] about 350,000 industrial facilities;[159] and about 250 million light-duty vehicles,[160] which traveled a total of almost 2.7 trillion miles that year. The global vehicle fleet now stands at roughly 1 billion units with a projection of 2 billion by 2035.[161]

Typical lifetimes for several types of capital equipment are listed in Table 1. These range from 10-20 years typical of building appliances, to 50-100 years or longer for many buildings, to perhaps hundreds of years for urban form—many cities largely keep the same layout of buildings and streets over their history. These lifetimes reflect the inertia of the existing system, with its associated security, economic, and environmental impacts. Long lifetimes slow the transition to improved technologies, but at the same time, long lifetimes reduce the turnover and loss of the energy embodied in the materials and manufacture of the building, plant, or other capital stock.[162] Thus, speeding replacement of capital stock with new technologies to improve energy performance can carry a corresponding embodied energy cost for the new technology and retirement of the old system that needs to be taken into consideration.

Table 1 Approximate lifetime ranges for various capital stocks in the United States.

Capital Stock	Approximate Lifetimes, Years
Cars[163]	~ 15-20
Building Appliances[164]	~ 10-20
Industrial Equipment	~ 10-30+
Power Plants[165]	~ 40-60
Buildings[166]	~ 50-100+
Urban Form	~ 100s

Buildings. Given building lifetimes of 50-100 years or more, RDD&D on technologies to retrofit existing buildings for much higher efficiency at low cost will be important to capture significant near- to mid-term energy savings and emissions benefits from the existing building stock that would otherwise wait decades before the existing building stock was replaced with new, more efficient buildings. RDD&D on energy technologies for new buildings is also very important, so that new buildings can be built for optimal efficiency to start with and provide long lifetimes of savings. In contrast, the furnaces, appliances, and other equipment within buildings will typically turn over in 10-20 years, so RDD&D on them can be focused on advancing new equipment rather than retrofits. Electricity accounts for about 72% of building primary energy use (Figure 1.3a of the QTR) and the associated challenges for electricity will be addressed below. Fuel use in buildings poses particular challenges, however, as it would be quite expensive and logistically difficult to capture the emissions from these small-scale and widely distributed fossil fuel systems. Yet these account for about 11% of total U.S. energy-related CO_2 emissions (Figure 1.7 of the QTR). RDD&D is therefore needed to identify ways to reduce distributed use of fossil fuels in the buildings sector by using clean electricity or fuels with no associated on-site CO_2 emissions.

Industry. In the industrial sector, the high manufacturing energy intensities of commodity materials (see QTR Figure 6.1) encourages the introduction of new processes, plants, and equipment to capture energy and emissions savings as well as productivity and performance benefits in the production process; retrofits that can capture an appropriate share of these benefits are also of interest. However, replacing commodity material production capital equipment is difficult given the low profit margins on commodity products. The time required to build entirely new plants can also be long. RDD&D to develop clean processes or new, better materials that also lower capital costs and increase productivity and performance are particularly important, as is a shift from a linear economy to a circular economy where waste is minimized through reuse, remanufacture, and recycling approaches that can dramatically reduce the energy requirements to manufacture commodities and products.[167] Industrial fuel use, accounting for 18% of U.S. energy-related CO_2 emissions (Figure 1.7 of the QTR), may be addressed for some large-scale plants with carbon capture, utilization, and storage technologies (CCS—as described in the QTR Technology Assessment 4.D-Carbon Dioxide Capture for Natural Gas and Industrial Applications), but it will likely be expensive and logistically difficult to apply CCS to small and medium size plants. For these plants, RDD&D to reduce distributed use of fossil fuels is needed, such as by electrifying currently fuel-based processes or by using fuels, such as hydrogen, with no on-site CO_2 emissions, and in both cases producing the electricity and fuel that is used with no net GHG emissions.

Transportation. For road transportation, the lifetime of vehicles of roughly 15-20 years means that the vehicle stock in the U.S. will turn over a couple times by 2050, allowing the introduction of new generations of technology, but also requiring substantial changes in the manufacturing system and supply chains to produce them, and in the refueling/recharging and service infrastructures to sustain them—which also require substantial time to change. For national energy security, use of petroleum products for transportation will need to be sharply reduced—increased domestic production helps (Figure 1c), but still leaves the domestic transportation system subject to global oil markets and the associated risks of supply availability and price volatility. Reducing oil use can also help address associated economic and air pollution challenges. The CO_2 emissions from onboard transportation fuels cannot practically be captured and stored for disposal at a central site.[168] Therefore, RDD&D on systems that have no net carbon emissions over their entire energy production and use lifecycle is needed, such as can potentially be provided by electric battery, hydrogen, or biomass-fueled vehicles (QTR Chapter 8). Similar considerations apply to other parts of the transportation sector, including air, rail, water, and pipelines.

Electric Power. For the power sector, as described in QTR Chapter 3, changes in supply and demand technologies are changing fundamental characteristics of the electric power system and impacting system reliability and performance. This motivates installation of new equipment that can better meet these new and rapidly changing system requirements. RDD&D on, for example, new grid architectures, flexible and smart systems, power flow controllers, and others can help address these challenges and could lead to substantial system improvements.

Infrastructure. The energy infrastructure developed over the past century has been optimized around today's conventional technologies. New fuels and systems that are not adequately compatible with the existing infrastructure, such as hydrogen fuel cell vehicles, will require new infrastructures for fuel production and delivery, as well as new supply chains for equipment manufacture; others, such as for electric vehicles, will require upgrading and expansion. This poses a "chicken-and-egg" dilemma: without a widely distributed fueling infrastructure it is harder to convince potential vehicle purchasers to buy, and without sufficient vehicles it is hard to pay for a large refueling infrastructure. This can impede technology introduction. Consumer preference also plays a very large role in technology choice, with style, space, acceleration, and many other factors often taking precedence over energy efficiency or GHG emissions. Together, all these factors pose barriers to deployment of cleaner, more efficient vehicles and require particular attention.[169]

Stakeholders. Implementing new technologies faces the challenge of the number of actors that must be engaged, ranging from over 600,000 firms involved in the construction industry, to 250,000 companies across the manufacturing sector (with associated plants, above), to 17,000 firms across the supply chains for appliances and vehicles.[170] On the supply side, as indicated above, there are about 19,000 generation facilities, more than 3,000 electric utilities and cooperatives, and about 142 petroleum refineries and almost 200 ethanol plants. And, of course, there are more than 300 million consumers in the U.S. whose preferences determine product choice and impact upstream technology RDD&D.

RDD&D Gestation

As noted, advanced energy technologies becoming available today can significantly help address the energy challenges described above (see, for example, Figure 2), but RDD&D is needed to further improve the cost and performance of these and other energy technologies to accelerate, broaden, deepen, and strengthen their ability to meet these challenges.

RDD&D can require substantial gestation time to significantly impact the energy sector, as described below. In comparison, significant impacts from some of the security, economic, or environmental challenges identified above also potentially become increasingly acute in the same time frame of the next several decades (see, for example, Figures 4 and 5).[171] This motivates the following two questions: (1) how long does RDD&D take; and (2) how can RDD&D be accelerated?

RDD&D involves a number of interwoven steps requiring various amounts of time:[172]

- **Decision to Invest.** First, a decision to invest in a particular area of RDD&D is required, typically requiring a minimum of a couple years (for public support), often longer.

- **Research and Development (R&D).** The R&D itself, particularly that with public support which generally focuses on mid to longer term R&D, will typically require perhaps five years or more to do and move to the next stage of work.
- **Demonstration Scale-up.** Large-scale technologies, such as for centralized plant electricity generation or fuels production, will typically need to be demonstrated at successively larger sizes to address scale-up challenges as it develops economies of scale.
- **Commercial Demonstration.** For large-scale technologies, demonstration of a plant that can validate performance at a commercial scale is needed.
- **Regulatory Issues.** Regulatory issues, if any, also need to be addressed, such as for the environment, health, and safety of the technology or for siting it. These issues need to be considered early and often throughout the RDD&D process and may help guide early stages of the R&D itself.
- **Finance.** Finance must be mobilized to build the first energy plants or for the technology production facilities. Financial issues should also be considered early in the RDD&D process and may influence aspects of the technology design.
- **Market Penetration.** Finally, the new technologies must penetrate their respective markets and gradually displace sales of the conventional technologies. Market deployment enables cost reductions by economies of scale and learning, as described in QTR Section 1.4.4 on page 25. The results of RDD&D and economies of scale and learning can be seen above in the technology cost reductions shown in Figure 2; much more extensive reviews are provided elsewhere.[173] In turn, these cost reductions aid further market deployment. (For a discussion of the intersection of technology, economics, and decision science as related to market penetration, see Section 10.2, pp.395-396, of the QTR.) Overall, market penetration can take decades. For example, a detailed analysis by Plotkin, et al., found market penetration times for major technology rollouts in the transportation sector of 23-33+ years after market entry.[174]

The above steps are summarized in Table 2. These interwoven RDD&D activities face further challenges that can slow progress, such as the "valley-of-death" in mobilizing financial support at various stages (see Sections 1.4.3 and 1.4.5 of the QTR).[175] Energy price volatility can also pose challenges for RDD&D investments, with higher energy prices encouraging RDD&D investment and lower energy prices reducing interest in and the resources available for investment.

Table 2 Approximate Gestation Times for RDD&D.

RDD&D Activity	Timeframes (years)
Decision to Invest in RDD&D[176]	~ 2+
Research & Development[177]	~ 5-20+
Demonstration Scale-up of the Technology and System	~ 2-10+
Demonstration of the Commercial Production Model	~ 2-5+
Resolution of Regulatory Issues[178]	~ 0-5+
Financing Manufacturing Facilities for Equipment or Installed Energy Plant	~ 2-5+
Market Penetration[179]	~ 10-20+

Together, even though some energy technologies are not subject to each of the above steps and some of the above steps can and should be done in parallel, they can quickly add up into a decades-long process before having a significant impact in a particular technology market. An example can be seen in Figure 2.c for onshore wind, which has just begun to enter the electricity supply market at scale after 30+ years of RDD&D. The huge scale of U.S. energy systems, embedded in virtually every aspect of the economy, means that to make substantial changes also require large investments over these long periods.

Accelerating Action

The above discussion identifies the following:

1. The national energy-linked security, economic, and environmental challenges, especially from climate change (e.g., see Figures 4 and 5), are likely to pose substantial and increasing costs over the next three decades and motivate significant near-term action to transition to secure, economic, and clean energy systems. The IPCC Assessment Reports 4 and 5 identified a reduction of 80-95% in GHG emissions (carbon equivalent) in 2050 relative to 1990 for Annex I countries to meet a 450 ppmv CO_2-eq target to keep global temperature increases to less than 2°C [3.6°F].[180] The United Nations Framework Convention on Climate Change under the Paris Agreement[181] states in Article 2.1.a, agreement to *"Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."*[182]
2. The existing capital stock of buildings, industry, power, transportation, and their associated infrastructure have long lifetimes (Table 1), however, and represent large commitments of pollution and CO_2 emissions, oil consumption, and/or other contributors to our national energy challenges. This capital stock requires substantial time to reach its economic lifetime and be replaced, and thus will slow the transition to clean energy systems, directly conflicting with the time pressures for action posed by our energy-linked challenges.[183]
3. RDD&D to develop new clean energy technologies and significantly impact the market can require decades (Table 2), which can slow the replacement of existing capital stock or new builds with these improved clean energy technologies, thus conflicting with both our energy-linked challenges and the need for new technologies as capital stock turns over.

Together, these three factors pose substantial challenges to the transition to secure, economic, and clean energy technologies: climate change motivates significant near-term action, but capital stock turn-over and R&D can take substantial time to do. These factors motivate developing mechanisms to accelerate the deployment of secure, economic,[184] clean energy technology available today, and to more rapidly conduct RDD&D of clean energy systems. Opportunities for accelerating RDD&D include the following:

- **Deployment**. Significant clean energy technologies, such as shown in Figure 2, are entering the market. Policy mechanisms can assist in more rapidly realizing economies of scale and accelerating learning-by-doing. Such technologies can make an important impact in the near to mid term.
- **System Integration.** Throughout the QTR, the importance of energy system integration and the notable transition from analog to increasingly digital systems is emphasized, from specific energy technologies all the way to large-scale systems such as the electric grid. This increasing integration and use of digital technologies (e.g., sensors, communications, control, computation, and software) may improve performance and utilization of capital for a range of conditions more rapidly (e.g., by the introduction of successive generations of more advanced software operating systems) and at a lower cost than traditional approaches of building out expensive physical plant. The integration and use of digital technologies can also improve the manufacturing of these clean energy technologies and the competitiveness of companies using them.[185]

- **Smaller Systems.** Many of the advances today are in relatively small technologies, such as those shown in Figure 2. A first advantage of these small systems is that they can be mass produced in factories,[186] enabling economies of scale and learning for rapid cost reductions, rather than being site-built in large central plants with less opportunity for such learning. Second, evolutionary advances in these small technologies may be more rapidly implemented in production, rather than go through the steps indicated in Table 2 that may be required for a substantially new large-scale technology system. Third, implementation of these smaller systems may be closer to energy users, reducing the amount of long lead-time large-scale infrastructure change required (but may increase smaller local infrastructure changes required). The more rapid introduction, mass production, evolution, and implementation of these smaller systems can potentially accelerate their widespread use and ability to respond to U.S. and global energy challenges.
- **Computational RDD&D.** As described in the QTR (see especially Technology Assessment 6.B Advanced Materials Manufacturing), advanced computational capabilities are beginning to enable the first principles computational design of materials, which can be combined with testing and validation using high throughput combinatorial experiment and other techniques.[187] This has the potential to dramatically reduce the time to develop advanced materials. Advanced computational capabilities are also becoming increasingly capable for technology design and system integration.[188] Together, with further development these have the potential to substantially accelerate the RDD&D process.

These can be supported by analysis—including improved metrics, data, analytical tools, and processes such as technology roadmapping or portfolio analysis—to more effectively and efficiently target RDD&D activities, and evaluate lessons learned (see QTR Chapter 10 "Concepts in Integrated Analysis" and Chapter 10 Supplemental Information, "Additional Information on Concepts in Integrated Analysis"). It is also important to broaden the scope of analysis to include the full lifecycle of integrated systems and identify the full range of materials and energy inputs and outputs through the entire lifecycle of the technology and the capital stock.

Public and Private RDD&D

Private investment in energy science and technology RDD&D faces substantial challenges, including the following:

1. **Long Time Frames for RDD&D**. Directed basic research[189] and early applied R&D can require as much as a decade or more before demonstration of a new technology begins. This is too long for most private companies or investors to support without a return on investment, especially smaller innovative companies.
2. **Appropriability**. Once a technology is demonstrated to be viable, it is much easier for a competitor to copy it or find alternative approaches to achieve the same thing. This can sharply reduce the financial return for the innovator. Standard intellectual property protections may not always be sufficient to protect these interests, particularly in international markets.
3. **Risk**. Energy RDD&D activities face many risks, including technical, managerial, financial, market, regulatory, and policy risks; these can pose substantial challenges for companies and investors.
4. **Capital Cost and Returns**. Capital costs for new energy supply and end use technologies are generally higher per unit than their conventional competitors due to the cost of the performance advantages they offer and because they are just starting down the learning curve (new technologies may need many years to decades to capture economies of scale and learning to lower their costs and be competitive). However, energy technologies typically produce or save low margin commodity fuels or power, resulting in long time frames before they earn a return. Further, purchasers are generally wary of high capital costs, and this sensitivity is increased for a relatively new technology which may have performance risk due to immaturity. This sensitivity to capital cost is compounded in many cases

by structural disconnects, such as between an owner and a renter—the owner would have to pay the higher capital costs of the improved technology but the renter would benefit from the reduced energy and operating costs.[190] Finally, some technologies require multi-hundred million to billion dollar investments for a single energy supply plant, such as for large-scale electricity generation or fuels production. Similarly large investments may be required for a manufacturing facility to produce a new energy technology. A sufficiently strong company may be able to make or mobilize such investments, but this is often not the case, with the result that promising technologies face substantial challenges in accessing needed capital.

5. **Infrastructure.** The existing energy infrastructure has developed around incumbent fuels and technologies over the past century. New technologies requiring new infrastructures can face the "chicken-and-egg" challenge noted above. Vehicle purchasers want confidence that they will have ready access to fueling stations and will often hesitate in purchasing a vehicle that does not have such support; but without a large base of vehicles using such infrastructure, it is difficult to purchase and maintain this refueling capacity. Similarly, the conventional infrastructure of manufacturing facilities, supply chain networks, operations and maintenance facilities, trained manpower, and other important elements have developed over many decades, and innovative technologies with different requirements then face their own "chicken-and-egg" challenges.

Most new technologies face elements of these challenges, but they are often more acute for energy technologies. For example, capital costs for new energy supply technologies are often very high and must be amortized over many years, but returns for the commodity fuels or power services they provide are generally low, resulting in long payback periods. These factors can reduce private returns. In addition, there are few high value market niches in energy to enable early investment, in contrast to semiconductors, information technology, or biotechnology where advanced technologies are readily introduced into high-value markets. Similar problems face new energy efficient end-use technologies, which may have significantly higher costs than their conventional lower efficiency counterparts, in order to save low cost commodity fuels or power. For both energy supply and end-use technologies, this limits early deployment and the opportunity to begin driving costs for new energy technologies down the learning curve, which ultimately requires substantial deployment over time (see Figure 2 and QTR Figure 1.9). The result is a low level of R&D investment in energy compared to other important sectors, as shown in QTR Figure 1.8(a). Corporate investments in clean energy R&D have remained roughly in the range of $3 billion to about $3.8 billion from 2006-2014; venture capital (VC) funding has generally declined from its peak (in dollars) in 2008 (QTR Figure 1.8(b)).[191] A review of the VC industry experience in clean energy technologies from 2006-2011 found that the overall returns were poor, and that other financial structures may be better suited to the clean energy industry.[192]

Although private investment in energy RDD&D may be low, there can be very substantial public returns for energy technology RDD&D. The following identify some of the public returns and challenges for RDD&D investment.

6. **Public Returns.** Numerous studies have found that public returns on R&D investment are much larger than private returns, dating back to Solow's work in 1957 and numerous studies since.[193] This has been often highlighted for basic research,[194] but can also be the case for applied RDD&D. For example, a retrospective analysis by the National Academies of Sciences, Engineering, and Medicine found returns of about 20 to 1 for public investment in energy efficiency RDD&D for the portfolio of work they examined.[195] Subsequent analyses across a wide range of energy RDD&D investments have also generally found large returns.[196] The 31 new or updated appliance standards (substantially enabled by RDD&D) put in place from 2009 to 2015 are projected to cumulatively save by 2030 over $500 billion for consumers, 39 quads of energy, and 3 billion metric tons of CO_2 emissions.[197]

7. **Research Capability Costs.** Advanced research capabilities, such as synchrotron light sources or spallation neutron sources, and supporting expertise are too expensive for private sector development, and these capabilities would not be available without public support. Examples are described in QTR Chapter 9 where user facilities have been developed for these and other advanced research capabilities.
8. **Externality Costs:** Conventional energy technologies typically address only part of the environmental, security, and other costs that they cause,[198] with the public incurring substantial additional costs, such as health costs from air pollution. That conventional energy technologies don't pay for all the costs that they impose on the public reduces the price of energy from them and thus undercuts the market viability of advanced energy technologies that could help address these challenges. These costs are known as externalities and are recognized as a fundamental market failure.[199]
    a. **Externalities—Environmental:** Advanced energy technologies can reduce the environmental impacts caused by pollution of air, land, and water, and GHGs. As noted above and in the cited literature, pollution imposes substantial costs. Further, the benefits to public health from reducing emissions of conventional air pollutants associated with GHG emissions can offset much of the cost of controlling the GHGs themselves for a range of conditions.[200]
    b. **Externalities—Security**: Global oil supplies have been a particular concern for energy security in the past, and the oil supply system often does not function as a normal market because of the power of the Organization of Petroleum Exporting Countries (OPEC). However, RDD&D in energy efficiency and supply technologies for oil, together with policy, are substantially constraining U.S. oil imports (Figure 1.c) and are currently helping control the market power of OPEC, contributing to recent oil price reductions. This provides a substantial public benefit even as the oil industry has to adjust to the much lower prices.
    c. **Externalities—Services:** Energy systems must reliably provide essential services; these are the foundation of the modern economy with large public benefits. Important aspects of the reliability of these energy services are covered, for example, by state regulatory compacts in the electricity sector, but others may not be or are insufficient. Adversely, risks (or perceived risks) that new technologies may raise for reliability may slow development and adoption of important new technologies.
9. **Information Access:** There can be substantial differences in public and private access to information about energy impacts and energy technologies and a corresponding public need for information. Public RDD&D and information dissemination can assist this.
10. **Market Failures and Friction:** Many market failures and frictions have been documented in the energy sector, particularly for energy efficiency, resulting in substantially lower levels of investment in energy efficiency technologies than economically appropriate. These include: (a) split incentives between the purchaser of equipment and the payer of the energy bill, as noted above; (b) frequent lack of energy metering by location (e.g., multiple users with a single meter) or by time, impeding knowledge of energy costs; (c) high personal transaction costs for low levels of savings by individual devices; and others. The costs of conventional fuels and risks of cost increases are often largely passed through to consumers by utilities, reducing the incentive for utilities to invest in energy technologies that use nuclear energy or renewables that have lower or no fuel cost, respectively.

The high public returns for RDD&D, externality costs, information needs, market failures and friction, and other factors,[201] and the observed high returns found in retrospective studies of energy RDD&D raise important considerations for policy maker decisions about RDD&D. A discussion of some of the modalities for conducting RDD&D can be found in QTR Chapter 9 Supplemental "*A Comparison of Research Center Funding Modalities*", and other key aspects of public RDD&D on energy technologies can be found in the DOE Science and Energy Plan.[202]

Endnotes

[1] U.S. Department of Energy, "Quadrennial Technology Review 2015", http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015

[2] By "clean", this refers to systems that are moving towards near-zero CO$_2$ emissions and pollution from operation of the technology. Manufacturing of the systems is discussed separately below.

[3] An overall review of infrastructure issues is provided in:

- U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", April 2015. http://energy.gov/epsa/quadrennial-energy-review-qer

There is also a large literature specifically on grid vulnerabilities, including:

- U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, http://www.energy.gov/oe/office-electricity-delivery-and-energy-reliability
- B. A. Carreras, D.E. Newman, Ian Dobson, "Does Size Matter?", Chaos: An Interdisciplinary Journal of Nonlinear Science 24, 023104 (2014)
- B. A. Carreras, V.E. Lynch, I. Dobson, D.E. Newman, "Complex Dynamics of Blackouts in Power Transmission Systems", Chaos 14, 643-652 (2004).
- Scott Backhaus, Michael Chertkov, "Getting a Grip on the Electrical Grid", Physics Today, 66(5), pp.42-48 (May, 2013)
- Sergey V. Buldyrev, Roni Parshani, Gerald Paul, H. Eugene Stanley, Shlomo Havlin, "Catastrophic cascade of failures in interdependent networks", Nature, V.464, 15 April 2010, pp.1025-1028.
- Reka Albert, Istvan Albert, Gary L. Nakarado, "Structural Vulnerability of the North American Power Grid", Physical Review E 69, 025103(R) (2004)
- Adilson E. Motter, "Cascade Control and Defense in Complex Networks", Physical Review Letters, V.03, N.9, 27 August 2004
- Peter Fairley, "The Unruly Power Grid", IEEE Spectrum, August 2004.

[4] U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", April 2015. http://energy.gov/epsa/quadrennial-energy-review-qer

[5] The Wall Street Journal, "Assault on California Power Station Raises Alarm on Potential for Terrorism." February 5, 2014. Accessed June 22, 2015, http://www.wsj.com/articles/SB10001424052702304851104579359141941621778.

[6] See, for example:

- "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather," U.S. Department of Energy, 2013. http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather.
- U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", April 2015. http://energy.gov/epsa/quadrennial-energy-review-qer
- Thomas J. Wilbanks, Steven J. Fernandez, "Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the US Department of Energy in Support of the National Climate Assessment," Oak Ridge National Laboratory, 2012. http://www.esd.ornl.gov/eess/Infrastructure.pdf
- J. Dell, S. Tierney, G. Franco, R. G. Newell, R. Richels, J. Weyant, and T. J. Wilbanks, 2014: Ch. 4: "Energy Supply and Use", in: Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 113-129. doi:10.7930/J0BG2KWD. http://nca2014.globalchange.gov/report/sectors/energy

[7] U.S. Department of Energy, "Hurricane Sandy and Our Energy Infrastructure." December, 2012. Accessed June 22, 2015: http://energy.gov/articles/hurricane-sandy-and-our-energy-infrastructure

[8] International Energy Agency, "World Energy Outlook", various years.

Another projection indicates a 4.5% rate of decline for producing fields rather than IEA's 6.7%. See:

- Emmanuel Gallezot, "Oil Demand and Well Decline Rates Ensure Strong Outlook for Oil Industry", Oil & Gas Monitor, Nov. 5, 2014. http://www.oilgasmonitor.com/oil-demand-and-well-decline-rates-ensure-strong-outlook-for-oil-industry/8075/
- "No Evidence of Precipitous Fall on Horizon for World Oil Production: Global 4.5% Decline Rate Means No Near-Term Peak: CERA/HIS Study", January 17, 2008, Business Wire. http://press.ihs.com/press-release/corporate-financial/no-evidence-precipitous-fall-horizon-world-oil-production-global-4

Other perspectives can be round in a large body of literature, such as:

- Richard G. Miller and Steven R. Sorrell, "The future of oil supply", Phil Trans Royal Society A, 2014, 372, 2 Dec. 2013, Also, see other articles in this special issue.

[9] DOE, developed from EIA data in Monthly Energy Review, April, 2016; Annual Energy Review, 1995 and 2011; and Annual Energy Outlook, 2007 and 2015.

[10] Dustin Volz, "U.S. government concludes cyber attack caused Ukraine power outage", Reuters, Feb 25, 2016, http://www.reuters.com/article/us-ukraine-cybersecurity-idUSKCN0VY30K

[11] Lutz Kilian, Rovert J. Vigfusson, "The Role of Oil Price Shocks in Causing U.S. Recessions", Board of Governors of the Federal Reserve System, International Finance Discussion Papers, Number 11114, August 2014. https://www.federalreserve.gov/pubs/ifdp/2014/1114/ifdp1114.pdf.

[12] DOE analysis of these issues can be found in:

- U.S. Department of Energy, "Critical Materials Strategy", December 2010, http://energy.gov/sites/prod/files/piprod/documents/cms_dec_17_full_web.pdf
- U.S. Department of Energy, "The Department of Energy's Critical Materials Strategy", http://energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy

[13] Critical Materials Institute, Ames Laboratory, U.S. Department of Energy, https://cmi.ameslab.gov/

[14] U.S. Department of Defense, "Quadrennial Defense Review," http://www.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf

See also:

- Solomon M. Hsiang, Marshall Burke, Edward Miguel, "Quantifying the Influence of Climate on Human Conflict", Science, v. 341, 13 Sept. 2013, #1235367-1to14
- John O'Loughlin et al., "Climate variability and conflict risk in East Africa, 1990-2009". Proc.Nat. Acad. Sci, PNAS.12051301009

[15] U.S. Department of Defense, "Quadrennial Defense Review 2014", http://www.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf

See also:

- The CNA Corporation, Military Advisory Board, "National Security and the Threat of Climate Change", 2007.
- The CNA Corporation, Military Advisory Board, "National Security and the Accelerating Risks of Climate Change", May 2014

[16] "Enduring Leadership in a Dynamic World: Quadrennial Diplomacy and Development Review 2015", U.S. Department of State, http://www.state.gov/s/dmr/qddr/

[17] United Kingdom, Ministry of Defence, "Global Strategic Trends – Out to 2045", https://www.gov.uk/government/publications/global-strategic-trends-out-to-2045

See also, for example:

- Global Military Advisory Council on Climate Change, http://gmaccc.org/ . "Climate Change & Security in South Asia: Cooperating for Peace", GMACC Paper No.2, May 2016, http://gmaccc.org/wp-content/uploads/2016/05/Climate_Change_and_Security_in_South_Asia.pdf

[18] Colin P. Kelley, Shahrzad Mohtadi, Mark A. Cane, Richard Seager, Yochanan Kushnir, "Climate change in the Fertile Crescent and implications of the recent Syrian drought", PNAS, V.112, N.11, March 17, 2015, pp.3241-3246

[19] Carl-Friedrich Schleussner, Jonathan F. Donges, Reik V. Donner, Hans Joachim Schellnhuber, "Armed-Conflict risks enhanced by climate-related disasters in ethnically fractionalized countries", PNAS early edition, 2016, www.pnas.org/cgi/doi/10.1073/pnas.1601611113

[20] See, for example:

- Solomon M. Hsiang, Marshall Burke, Edward Miguel, "Quantifying the Influence of Climate on Human Conflict", Science, V.341, 13 September 2013, p.1212. See also: John Bohannon, "Study Links Climate Change and Violence, Battle Ensues", Science V.341, 2 August 2013, p.444-445, citing dissenting perspectives.
- John O'Loughlin, et al., "Climate variability and conflict risk in East Africa, 1990-2009", Proceedings of the National Academy of Sciences, 2012 (early edition)
- Marshall Burke, Solomon M. Hsiang, Edward Miguel, "Climate and Conflict", National Bureau of Economic Research Working Paper No. 20598, October 2014. http://www.nber.org/papers/w20598.

[21] Energy Information Administration, "Consumer Expenditures for Energy by End-Use Sector, 1970-2010", http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0306

[22] Note that the figure shows the cost of electricity and fuels to end-users. Thus, most of the costs for power plants and refineries are included in the cost of electricity and fuels to end-users, but the costs to end-users do not include what they pay for their vehicles, household furnaces, or other such equipment that use this energy to provide services.

[23] Discussions of Options Values can be found in the QTR Chapter 10 and its Supplemental Information Appendix "Additional Information On Concepts In Integrated Analysis." See also:

- Afzal S. Siddiqui, Chris Marnay, Ryan H. Wiser, "Real Options Valuation of US Federal Renewable Energy Research, Development, Demonstration, and Deployment", Lawrence Berkeley National Laboratory, LBNL-5800, 2005. https://emp.lbl.gov/publications/real-options-valuation-us-federal
- Avinash K. Dixit, Robert S. Pindyck, "Investment under Uncertainty", Princeton University Press, 1994.
- Tom Copeland, Vladimir Antikarov, "Real Options: A Practitioner's Guide", Texere, 2003.

[24] U.S. Department of Energy, "Revolution … Now: The Future Arrives for Five Clean Energy Technologies – 2015 Update", November, 2015, http://energy.gov/sites/prod/files/2015/11/f27/Revolution-Now-11132015.pdf

[25] Steven Nadel, "The Rebound Effect: Large or Small?", American Council for an Energy-Efficient Economy, Washington, DC, August 2012. http://aceee.org/files/pdf/white-paper/rebound-large-and-small.pdf.

[26] LaCommare, Kristina Hamachi, and Joseph H. Eto, “Cost of Power Interruptions to Electricity Consumers in the United States (U.S.)”, Berkeley: LBNL, 2006. https://emp.lbl.gov/sites/all/files/report-lbnl-58164.pdf. This study found a mean of $79B/year, with a range of $22B to $135B depending on sensitivity assumptions used.

[27] Richard J. Campbell, “Weather-Related Power Outages and Electric System Resiliency”, Congressional Research Service, August 28, 2012. See also:

- Executive Office of the President, “Economic Benefits Of Increasing Electric Grid Resilience To Weather Outages” August 2013. http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf

[28] “Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure.”Washington, DC: U.S. Department of Energy, 2015. http://energy.gov/epsa/quadrennial-energy-review-qer

[29] Ibid

[30] American Society of Civil Engineers, “Failure to Act: Closing the Infrastructure Investment Gap for America’s Economic Future”, http://www.infrastructurereportcard.org/wp-content/uploads/2016/05/ASCE2016FailuretoActReport5.10.161.pdf

- American Society of Civil Engineers, “2013 Report Card for America’s Infrastructure”, http://www.infrastructurereportcard.org/

[31] International Energy Agency, “Energy Policies of IEA Countries: The United States, 2014 Review” http://www.iea.org/publications/freepublications/publication/USA_2014.pdf

[32] U.S. Department of Energy, “Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure”, April 2015. http://energy.gov/epsa/quadrennial-energy-review-qer

[33] “U.S Trade in Petroleum and Non-Petroleum Products by End-Use,” U.S. Census Bureau, 2015. Accessed August 5, 2015: https://www.census.gov/foreign-trade/Press-Release/current_press_release/exh9.pdf.

[34] Energy Information Administration, “Monthly Energy Review, April 2016”, http://www.eia.gov/totalenergy/data/monthly/previous.cfm gives average net imports of 4.65 Million Barrels per day in 2015, at an average price of $46.40 for imported oil, leading to a cost of about $78 billion for 2015.

[35] See, for example:

- D. L. Greene and S. Ahmad. 2005. Costs of U.S. Oil Dependence: 2005 Update, ORNL/TM-2005/45, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March
- D.L. Greene and P.N. Leiby, The Oil Security Metrics Model: A Tool for Evaluating the Prospective Oil Security Benefits of DOE’s Energy Efficiency and Renewable Energy R&D Programs, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May. Report No. ONRL/TM-2006/505 (2006). http://www-cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2006_505.pdf.
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[36] Lutz Kilian, Rovert J. Vigfusson, “The Role of Oil Price Shocks in Causing U.S. Recessions”, Board of Governors of the Federal Reserve System, International Finance Discussion Papers, Number 11114, August 2014. http://www.federalreserve.gov/pubs/ifdp/2014/1114/ifdp1114.pdf

[37] International Energy Agency, “World Energy Outlook”, various years.

Another projection indicates a 4.5% rate of decline for producing fields rather than IEA’s 6.7%. See:

- Emmanuel Gallezot, “Oil Demand and Well Decline Rates Ensure Strong Outlook for Oil Industry”, Oil & Gas Monitor, Nov. 5, 2014. http://www.oilgasmonitor.com/oil-demand-and-well-decline-rates-ensure-strong-outlook-for-oil-industry/8075/
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[38] Energy Information Administration, “International Energy Outlook, 2016”, http://www.eia.gov/forecasts/ieo/

[39] Energy Information Administration, “Annual Energy Outlook 2015”, See also the online table 11 at http://www.eia.gov/forecasts/aeo/tables_ref.cfm

[40] Energy Information Administration, Annual Energy Outlook, 2014, Table A1, D8 http://www.eia.gov/forecasts/aeo/pdf/0383%282014%29.pdf

[41] U.S. Department of Energy, “Strategic Plan –2014-2018”, http://energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf and U.S. Department of Energy, “Quadrennial Technology Review 2011”, http://energy.gov/sites/prod/files/ReportOnTheFirstQTR.pdf

[42] Michael Shellenberger, Ted Nordhaus, Alex Tembath, Jesse Jenkins, “Where the Shale Gas Revolution Came From: Government’s Role in the Development of Hydraulic Fracturing in Shale”, Breakthrough Institute Energy & Climate Program, May, 2012, http://thebreakthrough.org/archive/shale_gas_fracking_history_and

[43] Numerous studies have found global warming is approximately linear with cumulative CO_2 emissions, with the range currently extended up to at least 5 trillion tonnes of carbon, which is 10 times cumulative emissions to date, and would result in an average temperature increase of 6.4–9.5 C. See: Katarzyna B. Tokarska, Nathan P. Gillett, Andrew J. Weaver, Vivek K. Arora, Michael Eby, “The climate response to five trillion tonnes of carbon”, Nature Climate Change, online 23 May 2016.

[44] A complete list of GHGs and their various contributions to radiant forcing can be found in Intergovernmental Panel on Climate Change, Assessment Report 5, Working Group 1, Summary for Policy Makers, Figure 5, page 14. https://www.ipcc.ch/report/ar5/. Some emissions from energy-related activities, such as sulfur oxides (SOx) reduce radiant forcing, as detailed in the IPCC review.

[45] There is a very large body of literature on pollution emissions, their impacts, and their costs. The following only touch on a very few of these:

- NRC, "Hidden Costs of Energy Use: Unpriced Consequences of Energy Production and Use", National Academy Press, Washington, DC, 2010, http://www.nap.edu/catalog.php?record_id=12794
- United National Environment Program, "Global Mercury Assessment 2013: Sources, Emissions, Releases, and Environmental Transport", UNEP Chemicals Branch, Geneva, Switzerland. http://www.unep.org/publications/contents/pub_details_search.asp?ID=6282
- David P. Krabbenhoft, Elsie M. Sunderland, "Global Change and Mercury", Science, V.341, 27 Sept. 2013, pp.1457-1458;
- Naomi Lubick, David Malakoff, "With Pact's Completion, the Real Work Begins", Science, V.341, 27 Sept. 2013, pp.1443-1445;
- Dennis Normile, "In Minimata, Mercury Still Divides", Science, V.341, 27 Sept. 2013, pp.1446-1447. Note that the mercury poisoning in Minimata was not specifically connected with energy production or use, but is an example of the neurotoxicity of mercury.
- Francesca Dominici, Michael Greenstone, Cass R. Sunstein, "Particulate Matter Matters", Science, V.344, 18 April 2014, pp.257-259;
- Neal Fann, Kirk R. Baker, Charles M. Fulcher, "Characterizing the PM2.5-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S.," Environment International 49 (2012) 141-151;
- Thomas J. Grahame, Rebecca Klemm, Richard B. Schlesinger, "Public Health and Components of Particulate Matter: The Changing Assessment of Black Carbon", Air & Waste Management Association, June 2014, pp.41-47
- James F. Fox, J.Elliott Campbell, "Terrestrial Carbon Disturbance from Mountaintop Mining Increases Lifecycle Emissions for Clean Coal", Environ. Sci. Technol. 2010, 44, 2144-2149
- Karen C. Rice, Janet S. Herman, "Acidification of Earth: An Assessment Across Mechanisms and Scales", Applied Geochemistry 27 (2012) pp.1-14
- U.S. Environmental Protection Agency, Energy and the Environment, http://www.epa.gov/cleanenergy/energy-and-you/affect/water-discharge.html
- U.S. Environmental Protection Agency, Air & Radiation, "Criteria Air Pollutants", https://www.epa.gov/criteria-air-pollutants
- Frederica P. Perera, et al., "Early-Life Exposure to Polycyclic Aromatic Hydrocarbons and ADHD Behavior Problems", PLOS ONE, November 2014, V.9, No.11, e111670. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0111670

[46] Nicholas Z. Muller, Robert Mendelsohn, William Nordhaus, "Environmental Accounting for Pollution in the United States Economy", American Economic Review 101, August 2011, pp.1649-1675. SO_2 is sulfur dioxide; NO_x are nitrogen oxides; VOCs, are volatile organic compounds; NH_3, is ammonia; $PM_{2.5}$ is fine particulate matter with a size of 2.5 microns; and $PM10_{-2.5}$ is particulate matter with a size in the range of 2.5 to 10 microns.

[47] NRC, "Hidden Costs of Energy Use: Unpriced Consequences of Energy Production and Use", National Academy Press, Washington, DC, 2010, http://www.nap.edu/catalog.php?record_id=12794

[48] See, for example:

- Drew T. Shindell, "The social cost of atmospheric release", Climatic Change, online 25 February 2015, 130: 313-326.
- Paul R. Epstein, et al., "Full cost accounting for the life cycle of coal", Annals of the New York Academy of Sciences, 1219 (2011) 73-98.

[49] See, for example:

- EPA, "Mercury and Air Toxics Standards", "Healthier Americans", http://www.epa.gov/mats/
- Amanda Giang, Noelle E. Selin, "Benefits of mercury controls for the United States", PNAS, V.113, N.2, Jan. 12, 2016, pp.286-291, http://www.pnas.org/content/113/2/286.full.pdf
- Elsie M. Sunderland, et al., "Benefits of Regulating Hazardous Air Pollutants from Coal and Oil-Fired Utilities in the United States", Environmental Science & Technology, V.50, 2016, 2117-2120

As a separate analysis, primarily not energy-related, but providing a detailed analytical approach, see:

- Scott D. Grosse, Thomas D. Matte, Joel Schwartz, Richard J. Jackson, "Economic Gains Resulting from the Reduction in Children's Exposure to Lead in the United States", Environmental Health Perspectives, V.110, N.6, June 2002, pp.563- 569. With the removal of lead from gasoline, primary sources of lead exposure are now such things as lead in the paint of old housing, water pipes in some areas, and others. Nevertheless, it is useful to note that estimated benefits from reducing children's exposure to lead in the U.S. since 1976 for each year's cohort of about 3.8 million 2-year-old children, 1976-1980, totaled $110 billion to $319 billion due to the decline in blood lead levels from 1976-1999.

[50] Joel D. Kaufman, et al., "Association between air pollution and coronary artery calcification within six metropolitan areas in the USA (the Multi-Ethnic Study of Atherosclerosis and Air Pollution): a longitudinal cohort study", Lancet, online May 24, 2016, http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(16)00378-0/abstract

[51] See, for example:

- Julia Vishnevetsky, et al., "Combined effects of prenatal polycyclic aromatic hydrocarbons and material hardship on child IQ", Neurotoxicology and Teratology, in press, 2015.
- Deliang Tang, et al., "Molecular and Neurodevelopmental Benefits to Children of Closure of a Coal Burning Power Plant in China", PLOS ONE, March 2014, V.9, Nbr.3, e91966. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0091966

Particulates are also implicated in a recent study of neurological health of adults:

- Wilker, et al, "Long-Term Exposure to Fine Particulate Matter, Residential Proximity to Major Roads and Measures of Brain Structure," Stroke, 2015, 46, 1161-1166. http://stroke.ahajournals.org/content/early/2015/04/23/STROKEAHA.114.008348.full.pdf+html

[52] See, for example:

- W. James Gauderman, "Air Pollution and Children—An Unhealthy Mix", New England Journal of Medicine, July 6, 2006.
- W. James Gauderman et al, "Association of Improved Air Quality with Lung Development in Children," New England Journal of Medicine, V.372, N.10, March 5, 2015, pp.905-913.
- Deliang Tang, et al., "Molecular and Neurodevelopmental Benefits to Children of Closure of a Coal Burning Power Plant in China", PLOS ONE, March 2014, V.9, Nbr.3, e91966. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0091966

[53] Nicholas Z. Muller, Robert Mendelsohn, William Nordhaus, "Environmental Accounting for Pollution in the United States Economy", American Economic Review 101, August 2011, pp.1649-1675.

[54] J.A. de Gouw, et al., "Airborne measurements of the atmospheric emissions from a fuel ethanol refinery", Journal of Geophysical Research: Atmospheres, 2015. V.129, N.9, 8 May 2015, pp.4385-4397.

[55] John M. Storey, et al, "Novel Characterization of GDI Engine Exhaust for Gasoline and Mid-Level Gasoline-Alcohol Blends", SAE International J. Fuels Lubr., V.7, N.2 (June 2014)

[56] Others might include advanced electrostatic precipitators, flue gas desulfurization, dry sorbent injection, powdered activitated carbon injection to control mercury, and others. A.L. Moretti, C.S. Jones, "Advanced Emissions Control Technologies for Coal-Fired Power Plants", Babcock & Wilcox, Technical Paper BR-1886, Power-Gen Asia, Bangkok, Thailand, Oct. 3-5, 2012, http://www.babcock.com/library/Documents/BR-1886.pdf

[57] For a detailed review of the state of knowledge of climate change and its impacts, see the materials below as developed by the Intergovernmental Panel on Climate Change; this is the most complete review available. In addition, in the following pages and endnotes, specific studies highlighting particular issues, most of which were published subsequent to the completion of the literature review for the IPCC Assessment Report 5 in about 2012, provide additional information from a few of the studies that have been more recently published.

- Climate Change 2014 Synthesis Report. Geneva, Switzerland: Intergovernmental Panel on Climate Change https://www.ipcc.ch/report/ar5/
- Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC AR5): https://www.ipcc.ch/report/ar5/
    - o IPCC AR5 Working Group 1, "Climate Change 2013: The Physical Science Basis"
    - o IPCC AR5 Working Group 2, "Climate Change 2014 : Impacts, Adaptation, and Vulnerability"
    - o IPCC AR5 Working Group 3, "Climate Change 2014: Mitigation of Climate Change"

For U.S.-specific state of knowledge on climate change and its impacts, see:

- J.M. Melillo; T.C. Richmond, G. W. Yohe, (Eds). Climate Change Impacts on the United States, Washington, DC: U.S. Global Change Research Program, 2014. http://www.globalchange.gov/what-we-do/assessment

[58] D.R. Feldman, W.D. Collins, P.J. Gero, M.S. Torn, E.J. Mlawer, T.R. Shippert, "Observational determination of surface radiative forcing by CO_2 from 2000 to 2010", Nature, v., 2015

[59] Andrew A. Lacis, Gavin A. Schmidt, David Rind, Retro A. Ruedy, "Atmospheric CO_2: Principal Control Knob Governing Earth's Temperature", Science, V.330, 15 October 2010, pp.356-359. Note that non-condensing GHGs account for about 25% of the greenhouse effect, with water vapor and clouds, etc, accounting for 75%, but without the temperature change generated by non-condensing GHGs, the water would condense and come out of the atmosphere.

[60] American Institute of Physics, "The Discovery of Global Warming", https://www.aip.org/history/climate/co2.htm

[61] NASA, Earth Observatory, Global Warming, "This absorption and radiation of heat by the atmosphere—the natural greenhouse effect—is beneficial for life on Earth. If there were no greenhouse effect, the Earth's average surface temperature would be a very chilly -18°C (0°F) instead of the comfortable 15°C (59°F) that it is today.", http://earthobservatory.nasa.gov/Features/GlobalWarming/page2.php

- Some calculations indicate there would be some areas near the equator that would not freeze, but the long-term stability of these unfrozen areas has not been confirmed. See: Andrew A. Lacis, Gavin A. Schmidt, David Rind, Reto A. Ruedy, "Atmospheric CO_2: Principal Control Knob Governing Earth's Temperature", Science , V.330, 15 Oct. 2010, pp.356-359

[62] EPA, Climate Change Indicators in the United States, "Climate Forcing", "Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979-2014", https://www3.epa.gov/climatechange/science/indicators/ghg/climate-forcing.html

[63] Atmospheric concentrations of CO_2 can be found for various time periods in the following, among others: http://www.esrl.noaa.gov/gmd/ccgg/trends/

- C.D. Keeling, R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, and L.S. Waterman, (1976), "Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii," Tellus, vol. 28, 538-551
- K.W. Thoning, P.P. Tans, and W.D. Komhyr, (1989), "Atmospheric carbon dioxide at Mauna Loa Observatory 2. Analysis of the NOAA GMCC data, 1974-1985", J. Geophys. Research, vol. 94, 8549-8565
- T. R. Karl, J. T. Melillo, and T. C. Peterson, 2009: "Global Climate Change Impacts in the United States." T.R. Karl, J.T. Melillo, and T.C. Peterson, Eds. Cambridge University Press, 189 pp
- IPCC AR5 Working Group 1, "Climate Change 2013: The Physical Science Basis", https://www.ipcc.ch/report/ar5/
- National Atmospheric and Oceanic Administration, Earth System Research Laboratory, Global Monitoring Division, Global Greenhouse Gas Reference Network, "Trends in Atmospheric Carbon Dioxide", http://www.esrl.noaa.gov/gmd/ccgg/trends/
- Carbon Dioxide Information Analysis Center, "800,000-year Ice-Core Records of Atmospheric Carbon Dioxide (CO_2)," http://cdiac.ornl.gov/trends/co2/ice_core_co2.html

[64] See, for example:

- Global Methane Initiative, "Global Methane Emissions and Mitigation Opportunities", https://www3.epa.gov/climatechange/ghgemissions/gases/ch4.html

For the United States, see:

- EPA, "Overview of Greenhouse Gases", https://www3.epa.gov/climatechange/ghgemissions/gases/ch4.html
- Eric A. Kort, et al, "Four corners: The largest US methane anomaly viewed from space", Geophysical Research Letters, October 2014.
- Oliver Schneising, et al., "Remote sensing of fugitive methane emissions from oil and gas production in North American tight gelologic formations", Earth's Future, September 2014. http://science.nasa.gov/science-news/science-at-nasa/2014/09oct_methanehotspot/

There have also been analyses that black carbon is a larger radiant forcer than methane. See:

- T.C. Bond, et al., "Bounding the role of black carbon in the climate system: A scientific assessment", Journal of Geophysical Research: Atmospheres, V.118, 5380-5552, 2013. From the abstract: "…The best estimate of industrial-era climate forcing of black carbon through all forcing mechanisms, including clouds and cryosphere forcing, is +1.1 W/m² with 90% uncertainty bounds of +0.17 to +2.1 W/m². Thus, there is a very high probability that black carbon emissions, independent of co-emitted species, have a positive forcing and warm the climate. We estimate that black carbon, with a total climate forcing of +1.1 W/m², is the second most important human emission in terms of its climate forcing in the present-day atmosphere; only carbon dioxide is estimated to have a greater forcing…." http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50171/full

[65] See, for example:

- Carbon Dioxide Information Analysis Center, "Fossil Fuel CO_2 Emissions by Nation", http://cdiac.ornl.gov/trends/emis/tre_coun.html
- Höhne, N., Blum, H., Fuglestvedt, J., Skeie, R.B., Kurosawa, A., Hu, G., Lowe, J., Gohar, L., Matthews, B., de Salles, A.C.N., Ellermann, C., "Contributions of individual countries' emissions to climate change and their uncertainty", (2011) Climatic Change, 106 (3), pp. 359-391. Source: PBL Netherlands Environmental Assessment Agency: http://www.pbl.nl/en/publications/countries-contributions-to-climate-change

[66] NASA, "Global Climate Change, Vital Signs of the Planet, Global Temperature": http://climate.nasa.gov/vital-signs/global-temperature/ See also the references cited below for atmospheric and oceanic temperature increases.

[67] US Department of Commerce, National Oceanic and Atmospheric Administration, Climate.gov, "Climate change rule of thumb: cold "things" warming faster than warm things", https://www.climate.gov/news-features/blogs/beyond-data/climate-change-rule-thumb-cold-things-warming-faster-warm-things

[68] Ibid.

[69] Benjamin D. Santer, et al., "Human and natural influences on the changing thermal structure of the atmosphere", PNAS, Oct 22, 2013, V.110, N.43, 17235-17240, http://www.pnas.org/content/110/43/17235.full.pdf

Another important aspect of this is observed changes in global cloud distributions and heights that align with expected impacts due to climate change. See:

- Joel R. Norris, Robert J. Allen, Amato T. Evan, Mark D. Zelinka, Christopher W. O'Dell, Stephen A. Klein, "Evidence for climate change in the satellite cloud record," Nature, 2016. V.536, 11 July 2016, pp.72-75.

[70] NASA, Global climate Change, Vital Signs of the Planet, Global Ice Viewer: http://climate.nasa.gov/interactives/global_ice_viewer see also: http://nsidc.org/arcticseaicenews/

[71] No other known physical phenomenon fits these and other data, only anthropogenic increases in atmospheric concentrations of greenhouse gases explain the data. See: Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC AR5), IPCC AR5 Working Group 1, "Climate Change 2013: The Physical Science Basis" https://www.ipcc.ch/report/ar5/ See Chapter 10, and, in particular, pages 894-895.

For an illustration of some of the factors, see also:

- National Oceanic and Atmospheric Administration, "Ten indicators of a warming world." NOAA 2009 State of the Climate Highlights Report; http://nca2014.globalchange.gov/highlights/overview/overview#tab2-images

For visualizations of some of these various data see:

- National Air and Space Administration, Global Climate Change, Vital Signs of the Planet, "Global Temperature", http://climate.nasa.gov/vital-signs/global-temperature/
- National Oceanic and Atmospheric Administration, National Centers for Environmmental Information, "ASOS Temperature Departure and Degree Day Maps", "Temp, Precip, and Drought", http://www.ncdc.noaa.gov/temp-and-precip/asos/
- National Air and Space Administration, "Global Ice Viewer: Sentinels of Climate Change", http://climate.nasa.gov/interactives/global_ice_viewer

[72] Image credit: Kevin Trenberth/John Fasullo, National Oceanic and Atmospheric Administration.

[73] Environmental Protection Agency, Climate Change Indicators in the United States, "Atmospheric Concentrations of Greenhouse Gases, Figure 1. Global Atmospheric Concentrations of Carbon Dioxide Over Time", https://www3.epa.gov/climatechange/science/indicators/ghg/ghg-concentrations.html See also:

- Carbon Dioxide Information Analysis Center, "800,000-year Ice-Core Records of Atmospheric Carbon Dioxide (CO_2)", http://cdiac.ornl.gov/trends/co2/ice_core_co2.html

[74] Scripps Institute of Oceanography, "The Keeling Curve", https://scripps.ucsd.edu/programs/keelingcurve/

See also:

- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Earth System Research Laboratory, http://www.esrl.noaa.gov/gmd/ccgg/trends/
- National Oceanic and Atmospheric Administration, National Centers for Environmental Information, State of the Climate, "Global Summary Information – April 2016", https://www.ncdc.noaa.gov/sotc/

[75] Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC AR5): 2014, https://www.ipcc.ch/report/ar5/.

[76] Source: U.S. Environmental Protection Agency, Climate Change Indicators in the United States, "Atmospheric concentrations of Greenhouse Gases": https://www3.epa.gov/climatechange/science/indicators/ghg/ghg-concentrations.html

[77] The Intergovenmental Panel on Climate Change Assessment Report Five (IPCC AR5) has estimated expected ranges for many of the factors listed here reflecting current understanding of the science as well as uncertainties in population and economic growth, carbon emissions by energy systems, and many other factors. For a detailed review of the state of knowledge for climate change and its impacts, see:

- Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC AR5), 2014, https://www.ipcc.ch/report/ar5/

See also:

- U.S. Global Change Research Program, U.S. National Climate Assessment, "Climate Change Impacts on the United States", 2014. Op cit.

[78] For atmospheric temperature increases, in addition to the above reports by the IPCC, U.S. National Climate Assessment, and others already cited, it is useful to see:

- Visualization of global temperature difference from 1884 to 2014 from NASA's Goddard Institute for Space Studies - http://climate.nasa.gov/vital-signs/global-temperature/

In addition, studies have been conducted concerning the potential impacts of temperatures above the current 2C goal set by the Paris accord, such as the following:

- Benjamin M. Sanderson et al., "The response of the climate system to very high greenhouse gas emission scenarios", Environ. Res. Lett., 6 (2011)
- Andreas Sterl, Camiel Severijns, et al., "When can we expect extremely high surface temperatures?" Geophysical Research Letters, 2008. V.35, N.14, 19 July 2008, L14703.
- Todd Sanford, Peter C. Fumhoff, Amy Luers, Jay Gulledge, "The climate policy narrative for a dangerously warming world", Nature Climate Change, V.4, March 2014, pp.164-166
- Kevin Anderson, Alice Bows, "Beyond 'dangerous' climate change: emission scenarios for a new world", Phil. Trans. Royal Society A, 2011, 369, 20-44
- Fai Fung, Ana Lopez, Mark New, "Water availability in +2C and +4C Worlds", Phil. Trans. Royal Society A, 2011, v.369, 99-116
- M.G. Sanderson, D.L. Hemming, R.A. Betts, "Regional temperature and precipitation changes under high-end (>=4°C) global warming", Roy. Phil Trans. A (2011) 369, 85-98
- Francois Gemenne, "Climate-induced population displacements in a 4C+ world", Phil Trans. Royal Society A, 2011 369 pp.182-194
- Mark Stafford Smith, Lisa Horrocks, Alex Harvey, Clive Hamilton, "Rethinking adaptation for a 4C world", Phil Trans. Royal Society A, 2011, 369, 196-216

[79] Studies of increase temperature impacts on labor include:

- John P. Dunne, Ronald J. Stouffer, Jasmin G. John, “Reductions in labour capacity from heat stress under climate warming”, Nature Climate Change , V.3, June 2013, pp.563-566.
- Melissa Dell, Benjamin F. Jones, Benjamin A. Olken, “Temperature Shocks and Economic Growth: Evidence from the Last Half Century”, American Economic Journal: Macroeconomics 2012, 4(3), 66-95.
- Geoffrey M. Heal, Jisung Park, “Feeling the Heat: Temperature, Physiology & the Wealth of Nations”, Harvard Kennedy School, Belfer Center, January 2014, Discussion Paper 14-60
- Frances C. Moore, Delavane B. Diaz, “Temperature impacts on economic growth warrant stringent mitigation policy”, Nature Climate Change Online 12 January 2015, V.5, pp.127-131.
- Steven C. Sherwood, Matthew Huber, “An adaptability limit to climate change due to heat stress”, PNAS, V.107, N.21, 25 May 2010, pp.9552-9555.
- E.M. Fischer, R. Knutti, “Robust projections of combined humidity and temperature extremes”, Nature Climate Change, online 2 September 2012, V.3, February 2013, pp.126-130.
- Solomon M. Hsiang, “Temperature and Cyclones strongly associated with economic production in the Caribbean and Central America”, Proceedings of the National Academy of Sciences, V.107, N.35, August 31, 2010, 15367-15372.
- Tatyana Deryugina, Solomon M. Hsiang, “Does the Environment Still Matter? Daily Temperature and Income in the United States”, Working Paper 20750, National Bureau of Economic Research, 2014

[80] Marshall Burke, Solomon M. Hsiang, Edward Miguel, “Global non-linear effect of temperature on economic production”, Nature, V.527, 12 November 2015, pp.235-239

[81] Leonie Wenz, Anders Levermann, “Enhanced economic connectivity to foster heat stress-related losses”, Science Advances 2016, 2, 10 June 2016, 10.1126/sciadv.1501026 http://advances.sciencemag.org/content/2/6/e1501026

[82] See, for example:

- Steven C. Sherwood, Matthew Huber, “An adaptability limit to climate change due to heat stress”, PNAS, V.107, N.21, 25 May 2010, pp.9552-9555.
- E.M. Fischer, R. Knutti, “Robust projections of combined humidity and temperature extremes”, Nature Climate Change, online 2 September 2012, V.3, February 2013, pp.126-130.
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- Todd Sanford, Peter C. Fumhoff, Amy Luers, Jay Gulledge, “The climate policy narrative for a dangerously warming world”, Nature Climate Change, V.4, March 2014, pp.164-166
- Kevin Anderson, Alice Bows, “Beyond ‘dangerous’ climate change: emission scenarios for a new world”, Phil. Trans. Royal Society A, 2011, 369, 20-44

[83] J. Lelieveld, Y. Proestos, P. Hadjinicolaou, M. Tanarhte, E. Tyrlis, G. Zittis, “Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century”, Climatic Change, 23 April 2016.

[84] Potential feedback effects that have been raised include: reductions in ice cover and the resulting increase in solar absorption; changes in land cover and impacts on albedo; melting of permafrost and emission of CO_2 and CH_4 (note that CH_4 has radiant forcing about 80 times stronger than CO_2 per molecule for periods of 20 years, declining to about 20 times over a 100 year period); and many others. There remain large uncertainties in these and the extent to which they may have an impact or not. See, for example:

- YongYang Cai, Timothy M. Lenton, Thomas S. Lontzek, “Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction”, Nature Climate Change, online 21 March 2016, V.6, May 2016, pp.520-525.
- Timothy M. Lenton, “Environmental Tipping Points”, Annual Review Environmental Resources 2013.
- Lawrence, David M.; Slater, Andrew G.; Tomas, Robert A.; Holland, Marika M.; Deser, Clara (2008). “Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss”. Geophysical Research Letters 35 (11): L11506. Bibcode:2008GeoRL..3511506L. doi:10.1029/2008GL033985.
- Suzanne B. Hodgkins, et al., “Changes in peat chemistry associated with permafrost thaw increase greenhouse gas production”. PNAS, 2014, V.111 (16) 5819-5824.
- Jennifer W. Harden, et al., “Field Information links permafrost carbon to physical vulnerabilities of thawing”, Geophysical Research Letters, V.39, L15704, 7 August 2012
- Kevin Schaefer, Tingjun Zhang, Lori Bruhwiler, Andrew P. Barrett, “Amount and timing of permafrost carbon release in response to climate warming”, Tellus B, V.63, N.2, pp.165-180, April 2011.

- O'Connor, F. M., et al. (2010), "Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: A review," Rev. Geophys., 48, RG4005, doi:10.1029/2010RG000326.
- Peter U. Clark, et al., "Consequences of twenty-first-century policy for multi-millennial climate and sea-level change", Nature Climate Change, V.6, April 2016, pp.360-369

[85] Sybren Drijfhout, et al., "Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models", PNAS, Published online Oct.12, 2015, www.pnas.org/cgi/doi/10.1073/pnas.1511451112

[86] As atmospheric concentrations of greenhouse gases increase and temperatures rise, evaporation will increase and precipitation patterns will shift, with the likely result that there will be widespread drying and increased drought in many low and mid-latitude regions, and increased wet conditions in many high latitude and other mid-latitude regions. This could have significant impacts on agriculture in dryer regions. Areas with reductions in available moisture may also face challenges due to stresses on available groundwater. Useful references include:

- Alexis Berg, et al., "Land-atmosphere feedbacks amplify aridity increase over land under global warming", Nature Climate Change, 16 May 2016 online, DOI: 10.1038/NCLIMATE3029.
- Emily Underwood, "Models predict longer, deeper U.S. droughts", Science 13 Feb. 2015, V.347, N.6223, pp.707.
- Benjamin I. Cook, Toby R. Ault, Jason E. Smerdon, "Unprecedented 21st Century drought risk in the American Southwest and Central Plains", Science Advances 12 February 2015.
- Aiguo Dai, "Increased drought under global warming in observations and models", Nature Climate Change V.3, Jan. 2013, pp.52-58
- Jonathan T. Overpeck, "The challenge of hot drought", Nature, V.503, pp.350-351, 21 Nov. 2013
- Steven Sherwood, Qiang Fu, "A Drier Future", Science V.343, pp.737-739, 14 Feb. 2014
- Richard Seager, et al., "Model projections of an imminent transition to a more arid climate in Southwestern North America", Science, V.316, 25 May 2007, pp.1181-1184.
- Benjamin I. Cook, Jason E. Smerdon, Richard Seager, Sloan Coats, "Global Warming and 21st Century Drying", Climate Dynamics, 2014
- Kevin E. Trenberth, et al., "Global warming and changes in drought", Nature Climate Change, V.4, pp.17-22, Jan. 2014
- Sloan Coats, et al., "Megadroughts in Southwestern North America in ECH-G Millennial Simulations and Their Comparison to Proxy Drought Reconstructions", Journal of Climate, 1 Oct 2013, pp.7635-7649
- Richard G. Taylor, et al., "Ground water and climate change", Nature Climate Change 25 Nov 2012, p.322-329.
- Walter W. Immerzeel, et al., "Climate Change will affect the Asian Water Towers", Science V.328, 2010, pp.1382-1385.
- Shilong Piao, et al, "The impacts of climate change on water resources and agriculture in China", Nature 2 Sept. 2010, V.467 pp.43-51
- Rong Fu, et al, "Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection", PNAS early edition October 2013, V.110 (45) pp.18110-18115.
- Sonia I. Seneviratne, "Historical drought trends revisited", Nature 15 November 2012, V.491, pp.338-339, But see Dai, and Trenberth, above.
- Quirin Schiermeier, "Climate models fail to predict US droughts", Nature V.496, 18 April 2013, pp.284
- R. Quentin Grafton, et al., "Global insights into water resources, climate change and governance", Nature Climate Change 25 Nov 2012, pp.315-321
- Justin Sheffield, Eric F. Wood, Michael L. Roderick, "Little change in global drought over the past 60 years", Nature V.491, 15 November 2012, pp.435-438. Argue that PDSI simplified model of potential evaporation is insufficient. But see Trenberth, Dai above
- Peter J. Fawcett, et al., "Extended megadroughts in the southwestern United States during the Pleistocene interglacials", Nature V.470, 24 Feb 2011, pp.518-521
- Jian Liu et al, "Divergent global precipitation changes induced by natural versus anthropogenic forcing", Nature , V.493, 31 Jnuary 2013, pp.656-659
- Richard G. Taylor, et al., "Ground Water and Climate Change", Nature Climate Change, online 25 November 2012, V.3, pp.322-329.
- Fai Fung, Ana Lopez, Mark New, "Water availability in +2°C and +4°C Worlds", Phil. Trans. Royal Soc.A, 2011, v.369, 99-116
- Sloan Coats, et al., "Megadroughts in Southwester North America in ECHO-G Millenial Simulations and Their Comparison to Proxy Drought Reconstructions", Journal of Climate, 1 October 2013, pp.7635-7649
- Mosheng Zhao, Steven W. Running, "Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000-2009, Science, V.329, 20 Aug 2010, pp.940-943.
- Mark E. Ledger, et al., "Drought alters the structure and functioning of complex food webs", Nature Climate Change, online 9 September 2012, V.3, pp.223-227.
- Rong Fu, et al., "Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection", Proc. Nat. Acad. Sci., 1302584110, Oct 2014.
- Richard A. Kerr, "The Greenhouse is Making the Water-Poor Even Poorer", Science, V.336, 27 April 2012, p.405.

- Paul J. Durack, Susan E. Wijfells, Richard J. Matear, "Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000", Science, V. 336, 27 April 2012, pp.455-458.
- R. Quentin Grafton, et al., "Global insights into water resources, climate change and governance," Nature Climate Change V.3, April 2013, pp.315-321.
- Mark Howells, et al., "Integrated analysis of climate change, land-use, energy and water strategies", Nature Climate Change, V.3, July 2013, pp.621-626.
- Martin Jung, et al, "Recent decline in the global land evapotranspiration trend due to limited moisture supply", Nature, V.467, 21 Oct 2010, pp.951-954
- T. Zhao, and A. Dai, 2015: The magnitude and causes of global drought changes in the 21st century under a low-moderate emissions scenario. J. Climate, doi: http://dx.doi.org/10.1175/JCLI-D-14-00363.1, in press.
- Aiguo Dai, "Drought under global warming: a review", Wiley InterDisciplinary Review: Climate Change, 2010, http://onlinelibrary.wiley.com/doi/10.1002/wcc.81/pdf For a correction, see: https://www2.ucar.edu/atmosnews/news/2904/climate-change-drought-may-threaten-much-globe-within-decades
- Benjamin Cook, Jason E Smerdon, Richard Seager, Sloan Coats, et al., "Global Warming and 21st Century Drying", http://www.ldeo.columbia.edu/~bc9z/cook_pdsi_clidyn_REV_v01.pdf)

[87] See, for example,

- NASA video of expected soil moisture (surface down to 30cm) from 1950 to 2095 based on a 10 year moving average of 17 CMIP5 models using a high future emissions scenario (RCP 8.5). The link is: http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4270
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- Benjamin Cook, Jason E Smerdon, Richard Seager, Sloan Coats, et al., "Global Warming and 21st Century Drying", http://www.ldeo.columbia.edu/~bc9z/cook_pdsi_clidyn_REV_v01.pdf)

[88] See, for example:

- J.S. Famiglietti, "The global groundwater crisis", Nature Climate Change, V.4, November 2014, pp.945-948.
- J.W. Hall, et al, "Coping with the curse of freshwater variability", Science, V.346, N.6208, 24 Oct 2014, pp.429-430
- United Nations Convention to Combat Desertification, "Desertification: the Invisible Frontline", 2014
- United Nations, "World Water Development Report 2015: Water for a Sustainable World", http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2015-water-for-a-sustainable-world/
- Lisa Palmer, "The Next Water Cycle", Nature Climate Change", V.4, Nov. 2014, pp.949-950
- Jan Eliasson, "The rising pressure of global water shortages", Nature V.517, 1 Jan 2015, pp.6
- Moshe Alamaro, "Water politics must adapt to a warming world", Nature 2 October 2014, V.514, p.7

[89] See, for example:

- J.W. Hall, et al, "Coping with the curse of freshwater variability", Science, V.346, N.6208, 24 Oct 2014, pp.429-430
- United Nations Convention to Combat Desertification, "Desertification: the Invisible Frontline", 2014.

[90] United Nations, "World Water Development Report 2015: Water for a Sustainable World", http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2015-water-for-a-sustainable-world/

[91] World Bank Group, "High and Dry: Climate Change, Water, and the Economy", Washington, DC, 2016. http://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy

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- U.S. Global Change Research Program, "The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment", April, 2016, https://health2016.globalchange.gov/ and https://www3.epa.gov/climatechange/impacts/health.html
- Jonathan A. Patz, Howard Frumkin, Tracey Holloway, Daniel J. Vimont, Andrew Haines, "Climate Change: Challenges and Opportunities for Global Health", Clinical Review and Education, JAMA Sept 22. 2014
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- IPCC Assessment Report 5, op cit.
- T. R. Karl, G. A. Meehl, T. C. Peterson, K. E. Kunkel, W. J. Gutowski, Jr., and D. R. Easterling, 2008: Executive Summary. Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and US Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. http://library.globalchange.gov/sap-3-3-weather-and-climate-extremes-in-a-changing-climate
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- James P. Kossin, Kerry A. Emanuel, Gabriel A. Vecchi, "The poleward migration of the location of tropical cyclone maximum intensity", Nature, V.509, 15 May 2014, pp.349-352

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[100] U.S. Global Change Research Program, U.S. National Climate Assessment, "Climate Change Impacts on the United States", 2014. Op cit.

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- Janneke Hille Ris Lambers, "Extinction risks from climate change: How will climate change affect global biodiversity?", Science, V.348, N.6234, 1 May 2015, pp.501-502.
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- Craig Moritz, Rose Agudo, "The Future of Species Under Climate Change: Resilience or Decline?", Science, V. 341, 2 August 2013, pp.504-508.
- Eric Post, et al., "Ecological Consequences of Sea-Ice Decline", Science, V.341, 2 August 2013, pp.519-524
- Michael T. Burrows, et al., "The Pace of Shifting Climate in Marine and Terrestrial Ecosystems", Science, V.334, 4 Nov. 2011, pp.652-655.
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- See also NatureServe for a database of rare and endangered species in the Americas, used as a basis for a Climate Change Vulnerability Index: http://www.natureserve.org/conservation-tools/climate-change-vulnerability-index

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- R.D. Norris, S. Kirtland Turner, P.M. Hull, A. Ridgwell, "Marine Ecosystem Responses to Cenozoic Global Change", Science, 2 August 2013, V.341, pp.492-498.
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[103] Sean L. Maxwell, Richard A. Fuller, Thomas M. Brooks, James E.M. Watson, "The ravages of guns, nets and bulldozers", Nature 14 August 2016, V.536, pp.143-145.

[104] S. Levitus, et al, "Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems," Geophys. Res. Lett. V.36, L07608 (2009).

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- Kenneth G. Miller, et al., "High tide of the warm Pliocene: Implications of global sea level for Antarctic deglaciation", Geology, online 19 March 2012. doi: 10.1130/G32869.1
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- Carys P. Cook, et al., "Dynamic behavior of the East Antarctic ice sheet during Pliocene warmth", Nature Geoscience, 21 July 2013, V.6, pp.765-769.
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- R.M. Cooke, "Quantifying uncertainty on thin ice", Nature Climate Change, V.V.63, N.2, pp.165-180, April 2011.

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- NASA, Global Climate Change, Vital Signs of the Planet, "Land Ice", http://climate.nasa.gov/vital-signs/land-ice/
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- J.S. Greenbaum et al., "Ocean access to a cavity beneath Totten Glacier in East Antarctica", Nature Geoscience, V.8, pp.294-298, 16 March 2015
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[108] Johannes Jakob Furst, et al., "The safety band of Antarctic ice shelves", Nature Climate Change, online 8 February 2016, V.6, pp.479-482.

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- Thomas Sumner, "No stopping the collapse of West Antarctic Ice Sheet", Science V.344, 16 May 2014, pp.683.
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[110] J.S. Greenbaum et al., "Ocean access to a cavity beneath Totten Glacier in East Antarctica", Nature Geoscience, 16 March 2015, V.8, pp. 294-298.

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- Beata M. Csatho, et al., "Laser altimetry reveals complex pattern of Greenland Ice Sheet dynamics", Proceedings of the National Academy of Sciences, V.111, N.52, December 30, 2014, pp.18478-18483;
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[114] Peter U. Clark, et al., "Consequences of twenty-first-century policy for multi-millennial climate and sea-level change", Nature Climate Change, V.6, April 2016, pp.360-369

[115] See, for example:

- Jochen Hinkel, et al., "Coastal flood damage and adaptation costs under 21st century sea-level rise", PNAS 4 March 2014, V.111, N.9, pp.3292-3297.
- Stephane Hallegatte, Colin Green, Robert J. Nicholls, Jan Corfee-Morlot, "Future flood losses in major coastal cities", Nature Climate Change, 18 Aug 2013 online, V.3, pp.802-806.

[116] Higher sea levels and storm surge from tropical cyclones have been projected to cost the U.S. about $1 trillion by 2100. See:

- James E. Neumann, Kerry Emanuel, Sai Ravela, Lindsay Ludwig, Paul Kirshen, Kirk Bosma, Jeremy Martinich, "Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy", Climatic Change, (2015) 129:337–349, http://download.springer.com/static/pdf/258/art%253A10.1007%252Fs10584-014-1304-z.pdf?auth66=1425154940_6fb562b1050636fc1ee2d66bd4787334&ext=.pdf

See also:

- National Oceanic and Atmospheric Administration, National Centers for Environmental Information, "Billion-Dollar Weather and Climate Disasters: Overview", http://www.ncdc.noaa.gov/billions/

[117] Ocean uptake of atmospheric CO_2 is currently about 2 Petagrams (Pg) of carbon per year, according to the IPCC Assessment Report Working Group 1 page 292, and global emissions of carbon were about 9 Pg in 2020, thus in the range of 20-25%.

[118] Kheshgi, H., Smith, S.J., and Edmonds, J. 2005. "Emissions and Atmospheric CO_2 Stabilization: Long-term Limits and Paths," Mitigation and Adaptation Strategies for Global Change, Climate Change and Environmental Policy, 10: 213–220, Springer 2005. http://link.springer.com/article/10.1007/s11027-005-3783-8

[119] Ocean acidification information can be found in many references; see, for example:

- Interacademy Panel on International Issues, "IAP Statement on Ocean Acidification", http://www.interacademies.net/File.aspx?id=9075
- NOAA, Geophysical Fluid Dynamics Laboratory, "Ocean Acidification", "Background", http://www.gfdl.noaa.gov/acidification
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- The Royal Society, "Ocean acidification due to increasing atmospheric carbon dioxide", Policy document 12/05, June 2005, http://www.us-ocb.org/publications/Royal_Soc_OA.pdf

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- James C. Orr, et al., "Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms", Nature V.437, 29 Sept 2005, pp.681-685.
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- John M. Pandolfi, Sean R. Connolly, Dustin J. Marshall, Anne L. Cohen, "Projecting Coral Reef Futures Under Global Warming and Ocean Acidification", Science, V.333, pp.418-422, 22 July 2011

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- Astrid C. Wittman, Hans-O. Portner, “Sensitivities of extant animal taxa to ocean acidification”, Nature Climate Change, V.3, pp.995-1001, November 2013
- Barbel Honisch, et al., “The Geological Record of Ocean Acidification”, Science, V.335, pp.1058-1063, 2 March 2012
- Elvira S. Poloczanska, “Global imprint of climate change on marine life”, Nature Climate Change, 4 August 2013, V.3, pp.919-925.
- K. Frieler et al., “Limiting global warming to 2 °C is unlikely to save most coral reefs”, Nature Climate Change, 16 Sept. 2012, pp.165-170
- Stephen R. Palumbi, Daniel J. Barshis, Nikki Traylor-Knowles, Rachael A. Bay, “Mechanisms of reef coral resistance to future climate change”, Science, 23 May 2014, pp.895-898.
- D. Bernie, J. Lowe, T. Tyrrell, O. Legge, “Influence of mitigation policy on ocean acidification”, Geophysical Research Letters, V.37, L15704, 2010.
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- LongCao, Han Zhang, Meidi Zhang, Shuangjing Wang, “Response of ocean acidification to a gradual increase and decrease of atmospheric CO_2”, Environ. Res. Lett. 9 (2014) 024012 (9pp)

[120] The term “acidity” is used here in order to align with common usage. In fact, the ocean is slightly alkaline, with a pH of about 8.14, so this change is making the ocean less alkaline.

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[122] D. M. Etheridge, et al. “Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn.” Journal of Geophysical Research: Atmospheres (1984–2012) 101.D2 (1996): 4115-4128.

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- Nicolas Gruber, Claudine Hauri, Zouhair Lachkar, Damian Loher, Thomas L. Frolicher, Gian-Kasper Plattner, “Rapid Progression of Ocean Acidification in the California Current System”, Science, V.337, pp.220-223, 13 July 2012
- Eli Kintisch, “Sea Butterflies Are a Canary for Ocean Acidification”, Science, V.344, 9 May 2014, pp.569.
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- Robert F. Service, “Rising Acidity Brings an Ocean of Trouble”, Science V. 337, pp.146-148, 13 July 2012
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- Ulf Riebesell, Jean-Pierre Gattuso, “Lessons learned from ocean acidification research”, Nature Climate Change, Jan. 2015, V.5, pp.12-14

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- Sabine Mathesius, Matthias Hofmann, Ken Caldeira, Haans Joachim Schellnhuber, “Long-term response of oceans to CO_2 removal from the atmosphere”, Nature Climate Change, V.5, Dec. 2015, pp.1107-1113.

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[125] I.C. Enochs, et al., "Shift from coral to macroalgae dominance on a volcanically acidified reef", Nature Climate Change V.5, December 2015, pp.1083-1088.

[126] K. Frieler, M. Meinshausen, A. Golly, M. Mengel, K. Levek, S.D. Donner, O. Hoegh-Guldberg, "Limiting global warming to 2C is unlikely to save most coral reefs", Nature Climate Change, February 2013, V.3, pp.165-170.

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- Tracy D. Ainsworth, et al., "Climate change disables coral bleaching protection on the Great Barrier Reef", Science, 15 April 2016, V.352, N.6283, pp.338-342.
- Bradley D. Eyre, Andreas J. Andersson, Tyler Cyronak, "Benthic coral reef calcium carbonate dissolution in an acidifying ocean", Nature Climate Change, V.4, November 2014, pp.969-976

It is important to note that some types of coral are able to withstand some acidification; see:

- Stephen R. Palumbi, Daniel J. Barshis, Nikki Traylor-Knowles, Rachael A. Bay, "Mechanisms of reef coral resistance to future climate change", Science, 23 May 2014, pp.895-898.
- Shihori Inoue, Hajime Kayanne, Shoji Yamamoto, Haruko Kurihara, "Spatial community shift from hard to soft corals in acidified water", Nature Climate Change, 24 March 2013, V.3, pp.683-687.

[127] There are numerous articles on the current (as of July 2016) bleaching and mortality impacts of the high ocean temperatures on the Great Barrier Reef. See, for example:

- ARC Centre of Excellence, Coral Reef Studies, "Only 7% of the Great Barrier Reef has avoided coral bleaching", 20 April 2016, https://www.coralcoe.org.au/media-releases/only-7-of-the-great-barrier-reef-has-avoided-coral-bleaching
- ARC Centre of Excellence, Coral Reef Studies, "Coral death toll climbs on Great Barrier Reef, 30 May 2016, https://www.coralcoe.org.au/media-releases/coral-death-toll-climbs-on-great-barrier-reef

[128] Ocean hypoxia issues are examined in, for example:

- Lothar Stramma, et al., "Expanding Oxygen-Minimum Zones in the Tropical Oceans", Science V.320, 2 May 2008, pp.655-658
- Phil Berardelli, "Marine Life Gasping for Breath?" ScienceNOW Daily News, 1May2008.
- Gary Shaffer, Steffen Malskaer Olsen, Jens Olaf Pepke Pedersen, "Long-Term Ocean Oxygen Depletion in Reponse to Carbon Dioxide Emissions from Fossil Fuels". Nature Geoscience, V.2, Feb 2009, pp.105-109
- Raquel Vaquer-Sunyer and Carlos M. Duarte, "Thresholds of hypoxia for marine biodiversity", Proceedings of the National Academy of Sciences, V.105, N.40, 7 October 2008, pp.15452-15457
- J.L. Sarmiento, "Response of Ocean Ecosystems to Climate Warming", Global Biogeochemical Cycles, V.18, 2004, GB3003.
- Curtis Deutsch, Holger Brix, Taka Ito, Hartmut Frenzel, LuAnne Thompson, "Climate-Forced Variability of Ocean Hypoxia", Science, V.333, 15 July 2011, pp.336-339

[129] Geoengineering responses broadly are discussed in, for example:

- National Research Council, "Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration", Committee on Geoengineering Climate, National Academies Press, 2015, http://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration
- National Research Council, "Climate Intervention: Reflecting Sunlight to Cool Earth", Committee on Geoengineering Climate, National Academies Press, 2015, http://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth
- UK Royal Society. "Geoengineering the climate: science, governance and uncertainty", London: UK Royal Society. (September 2009), RS Policy document 10/09, https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/8693.pdf
- Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze (2013), "Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification", Geophysical Research Letters, 40(22), 5909-5914, doi:10.1002/2013gl057981

[130] It is important to note that analyses of even large scale CO_2 removal from the atmosphere have found that it does not compensate for the CO_2 now entering the ocean, which leaves a long-term legacy of the above problems. See:

- Sabine Mathesius, Matthias Hofmann, Ken Caldeira, Haans Joachim Schellnhuber, "Long-term response of oceans to CO_2 removal from the atmosphere", Nature Climate Change, V.5, Dec. 2015, pp.1107-1113.
- Long Cao, Han Zhang, Meidi Zheng, Shuangjing Wang, "Response of ocean acidification to a gradual increase and decrease of atmospheric CO_2", IOP Environmental Research Letters, V.9, N.2, 21 February 2014, 024012. http://iopscience.iop.org/article/10.1088/1748-9326/9/2/024012/meta;jsessionid=A133357D153BD1BBDD0D466A1E1D705A.c4.iopscience.cld.iop.org

[131] Note that analyses of planned emissions reductions under the Paris Accord indicate that there will need to be further reductions to moderate damage to ocean ecosystems. See, for example:

- Alexandre K. Magnan, et al., "Implications of the Paris agreement for the ocean", Nature Climate Change, August 2016, V.6, pp.732-734.

[132] O. Hoegh-Guldberg, et al., "Ocean Reefs Under Rapid Climate Change and Ocean Acidification", Science, V.318, pp.1737, 14 Dec. 2007.

[133] Carl-Friedrich Schleussner, Joeri Rogelj, Michiel Schaeffer, Tabea Lissner, Rachel Licker, Erich M. Fischer, Reto Knutti, Anders Levermann, Katja Frieler, William Hare, "Science and policy characteristics of the Paris Agreement temperature goal", Nature Climate Change, online 25 July V.6, pp.827-835, 2016.

[134] Changes in Arctic sea ice are described in:

- L. Polyak, et.al., "History of Sea Ice in the Arctic," in Past Climate Variability and Change in the Arctic and at High Latitudes, U.S. Geological Survey, Climate Change Science Program Synthesis and Assessment Product 1.2, January 2009, chapter 7.
- R. Kwok and D. A. Rothrock, "Decline in Arctic sea ice thickness from submarine and ICESAT records: 1958-2008," Geophysical Research Letters, v. 36, paper no. L15501, 2009 http://nsidc.org/sotc/sea_ice.html

[135] See, for example:

- U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", April 2015. http://energy.gov/epsa/quadrennial-energy-review-qer
- U.S. Department of Energy, "The Water-Energy Nexus: Challenges and Opportunities", June 2014. http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities
- Michelle T. H. van Vliet, David Wiberg, Sylvain Leduc, Keywan Riahi, "Power-generation system vulnerability and adaptation to changes in climate and water resources", Nature Climate Change, V.6, April 2016, pp.375-380.

[136] See references above on extreme weather and impacts on infrastructure, and the following:

- U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", 2015. http://www.energy.gov/epsa/quadrennial-energy-review-qer
- U.S. Department of Energy, "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather," 2013. http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather.
- Thomas J. Wilbanks, Steven J. Fernandez, "Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the US Department of Energy in Support of the National Climate Assessment,"Oak Ridge National Laboratory, 2012. http://www.esd.ornl.gov/eess/Infrastructure.pdf
- J. Dell, S. Tierney, G. Franco, R. G. Newell, R. Richels, J. Weyant, and T. J. Wilbanks, 2014: Ch. 4: Energy Supply and Use. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 113-129. doi:10.7930/J0BG2KWD. http://nca2014.globalchange.gov/report/sectors/energy

[137] See, for example:

- U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", 2015. http://www.energy.gov/epsa/quadrennial-energy-review-qer
- Jochen Hinkel, et al., "Coastal flood damage and adaptation costs under 21st century sea-level rise", PNAS February 2014
- Stephane Hallegatte, Colin Green, Robert J. Nicholls, Jan Corfee-Morlot, "Future flood losses in major coastal cities", Nature Climate Change, 18 Aug 2013, V.3, pp.802-806.
- James E. Neumann, Kerry Emanuel, Sai Ravela, Lindsay Ludwig, Paul Kirshen, Kirk Bosma, Jeremy Martinich, "Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy", Climatic Change, (2015) 129:337–349, http://download.springer.com/static/pdf/258/art%253A10.1007%252Fs10584-014-1304-z.pdf?auth66=1425154940_6fb562b1050636fc1ee2d66bd4787334&ext=.pdf
- National Oceanic and Atmospheric Administration, National Centers for Environmental Information, "Billion-Dollar Weather and Climate Disasters: Overview", http://www.ncdc.noaa.gov/billions/

[138] See, for example:

- Peter U. Clark, et al., "Consequences of twenty-first-century policy for multi-millennial climate and sea-level change", Nature Climate Change, V.6, April 2016, pp.360-369
- Susan Solomon, Gian-Kasper Plattneer, Reto Knutti, Pierre Friedlingstein, "Irreversible climate change due to carbon dioxide emissions", PNAS, V.106, N.6, February 10, 2009, pp.1704-1709

[139] Drew T. Shindell, Yunha Lee, Greg Faluvegi, "Climate and health impacts of U.S. emissions reductions consistent with 2 C", Nature Climate Change, 22 Feb. 2016, V.6, pp.503-507.

[140] J. Jason West, et al., "Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health", Nature Climate Change, V.3, October 2013, pp.885-889

[141] See, for example:

- Karen C. Rice, Janet S. Herman, "Acidification of Earth: An assessment across mechanisms and scales", Applied Geochemistry 27 (2012) pp.1-14.
- Garth T. Llewellyn, et al., "Evaluating a groundwater supply contamination incident attributed to Marcelus Shale gas development", Proc. Nat. Acad. Sci., Early edition online April 2015, V.112, N.20, pp.6325-6630, doi: 10.1073/pnas.1420279112.

[142] See, for example:

- "The Water-Energy Nexus: Challenges and Opportunities", U.S. Department of Energy, June 2014. http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities
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[143] Karen C. Rice, Janet S. Herman, "Acidification of Earth: An assessment across mechanisms and scales", Applied Geochemistry 27 (2012) pp.1-14.

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[146] See, for example: M.M. Hand, S. Baldwin, E.DeMeo, J.M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, and D. Sandor, eds Renewable Electricity Futures Study. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory. 2012. http://www.nrel.gov/analysis/re_futures/

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- M.J. Hornbach, et al., "Causal factors for seismicity near Azle, Texas." Nature Communications (6:6728), 21 April 2015.
- A.Witze, "Artificial Quakes Shake Oklahoma." Nature V520, 23 April 2015, pp. 418-419.
- M.D Petersen, et al, "Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Model—Results of 2014 Workshop and Sensitivity Studies." Report 2015-1070. Reston, VA: U.S. Geological Survey, 2015.
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[148] Quadrennial Technology Review 2015, op. cit, http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

[149] See, for example:

- U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure", 2015. http://www.energy.gov/epsa/quadrennial-energy-review-qer
- U.S. Department of Energy, "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather", 2013. http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather

[150] Stephen J. Davis, Ken Caldeira, H. Damon Matthews, "Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure", Science v.329, 10 Sept. 2009, pp.1330-1333. Stephen J. David, Robert H. Socolow, "Commitment accounting of CO_2 emissions", Environmental Research Letters 9 (2014) 084018

[151] Steven J. Davis, Robert H. Socolow, "Commitment accounting of CO_2 emissions", Environmental Research Letters V.9 (2014) doi: 10.1088/1748-9326/9/8/084018.

[152] The "wedge" framework is examined in QTR Chapter 10 (see Figure 10.6) and the Chapter 10 Supplemental. See:

- S. Pacala, R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 years with Current Technologies", Science, V.305, 13 August 2004, p.968-972.
- Steven J. Davis, Long Cao, Ken Caldeira, Martin I. Hoffert, "Rethinking Wedges", Environ. Res. Let. V.8 (2013)
- Eli Kintisch, "Climate Study Highlights Wedge Issue", Science, V.339, 11 Jan. 2013, pp.128-129

[153] See, for example:

- Steve Hatfield Dodds, "All in the timing", Nature V.493, 3 January 2013, pp.35-36.
- Joerl Rogelj, David L. McCollum, Andy Reisinger, Malte Meinshausen, Keywan Riahi, "Probabilistic cost estimates for climate change mitigation", Nature, V.493, 3 January 2013, pp.79-83.

[154] EIA AEO 2014, Table A9, for 2012. http://www.eia.gov/forecasts/archive/aeo14/

[155] U.S. Energy Information Administration, "Petroleum & Other Liquids", "Number and Capacity of Petroleum Refineries", http://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm ; Energy Information Administration, U.S. Fuel Ethanol Plant Production Capacity, http://www.eia.gov/petroleum/ethanolcapacity/

[156] U.S. energy infrastructure is examined in the Quadrennial Energy Review, 2015, op cit.

[157] Energy Information Administration, Commercial Buildings Energy Consumption Survey (CBECS) 2012 : http://www.eia.gov/consumption/commercial/reports/2012/preliminary/index.cfm downloaded 8/20/14.

[158] EIA, AEO 2014, Table A4. http://www.eia.gov/forecasts/archive/aeo14/

[159] Energy Information Administration "2010 Manufacturing Energy Consumption Survey (MECS)." Table 9-1: Enclosed Floorspace and Number of Establishment Buildings, 2010." 19 March 2015. Approximate Number of All Buildings Onsite (Total) = 346,914, https://www.energystar.gov/buildings/about-us/facts-and-stats

[160] ORNL, Transportation Energy Data Book, Edition 33, page 2. http://cta.ornl.gov/data/index.shtml

[161] Daniel Sperling, Deborah Gordon, "Two Billion Cars: Transforming a Culture", Transportation Research News 259, November-December 2008, Transportation Research Board, National Academy of Sciences. http://onlinepubs.trb.org/onlinepubs/trnews/trnews259billioncars.pdf

[162] See, for example: Abdul Rauf, Robert H. Crawford, "Building service life and its effect on the life cycle embodied energy of buildings", Energy V.79 (2015), pp.140-148.

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[164] James D. Lutz, Asa Hopkins, Virginie Letschert, Victor H. Franko, Andy Sturges, "Using National Survey Data to Estimate Lifetimes of Residential Appliances", Lawrence Berkeley National Laboratory, October 2011, LBNL- Report 81616. http://eetd.lbl.gov/publications/using-national-survey-data-to-estimat

See also, for example:

- ATD Home Inspection, "Average Life Span of Homes, Appliances, and Mechanicals", http://www.atdhomeinspection.com/advice/average-product-life/

[165] Energy Information Administration, "Age of Electric Power Generators Varies Widely", June 16, 2011, http://www.eia.gov/todayinenergy/detail.cfm?id=1830

[166] Jennifer O'Connor, "Survey on actual service lives for North American buildings", Woodframe Housing Durability and Disaster Issues conference, Las Vegas, October 2004, http://cwc.ca/wp-content/uploads/2013/12/DurabilityService_Life_E.pdf

[167] See, for example, the special issue of Nature, 23 March 2016, V.531:

- Walter R. Stahel, "Circular economy", Nature, 24 March 2016, V.531, pp.435-438
- Bruce Hood, "Make recycled goods covetable", Nature, 24 March 2016, V.531, pp.438-440
- John A. Mathews, Hao Tan, "Lessons from China", Nature, 24 March 2016, V.531, pp.440-442
- "Getting the circulation going", Nature, 24 March 2016, V.531, pp.443-446

[168] The weight of the CO_2 generated from gasoline or diesel is about 3 times the weight of the input fuel, assuming the average carbon in gasoline or diesel is linked to two hydrogen atoms (i.e., comparing the atomic weight of CO_2 at 12+16+16=44 to that of C+H+H at 12+1+1=14), not including the weight of the on-board CO_2 storage system and associated compressors and other equipment. This would pose a substantial weight (and storage volume) penalty for an on-board CO_2 capture and storage system.

[169] National Academy of Sciences, "Overcoming Barriers to Deployment of Plug-In Electric Vehicles", Committee on Overcoming Barriers to Electric-Vehicle Deployment, Board on Energy and Environmental systems, Division on Engineering and Physical Sciences, and Transportation Research Board, National Research Council, National Academies Press, Washington, D.C. 2015, http://www.nap.edu/catalog/21725/overcoming-barriers-to-deployment-of-plug-in-electric-vehicles

[170] U.S. Census Bureau Statistics of US Businesses (2011): http://www2.census.gov/econ/susb/data/2011/us_6digitnaics_2011.xls (retrieved on 2014-11-03)

[171] See, for example:

- Steve Hatfield Dodds, "All in the timing", Nature V.493, 3 January 2013, pp.35-36.
- Joerl Rogelj, David L. McCollum, Andy Reisinger, Malte Meinshausen, Keywan Riahi, "Probabilistic cost estimates for climate change mitigation", Nature, V.493, 3 January 2013, pp.79-83.

[172] President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development, "Federal Energy Research and Development for the Challenges of the Twenty-First Century", Office of Science and Technology Policy, Executive Office of the President, November, 1997. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nov2007.pdf

[173] See, for example:

- Bela Nagy, J. Doyne Farmer, Quan M. Bui, Jessika E. Trancik, "Statistical Basis for Predicting Technological Progress", PLOS One, February 2013, V.8, N.2, e52669. See also the database at http://pcdb.santafe.edu/
- Edward S. Rubin, Inex M.L. Azevedo, Paulina Jaramillo, Sonia Yeh, "A review of learning rates for electricity supply technologies", Energy Policy 86, 2015, pp.198-218.

[174] Plotkin, S.; Stephens, T.; McManus, W. (March 2013). Vehicle Technology Deployment Pathways: An Examination of Timing and Investment Constraints. Transportation Energy Futures Report Series. Prepared for the U.S. Department of Energy by Argonne National Laboratory, Argonne, IL. DOE/GO-102013-3708. 56 pp. http://www.nrel.gov/docs/fy13osti/55638.pdf

[175] L.M. Murphy, P.L. Edwards, “Bridging the Valley of Death: Transitioning from Public to Private Sector Financing”, NREL/MP-720-34036, May 2003. http://www.nrel.gov/docs/gen/fy03/34036.pdf

See also:

- Bloomberg New Energy Finance, “Crossing the Valley of Death: Solutions to the next generation clean energy project financing gap”, 21 June 2010. http://www.cleanegroup.org/wp-content/uploads/Crossing-the-Valley-of-Death.pdf

[176] The process for appropriating funds for an established public RDD&D activity begins with an agency and the administration developing a proposed budget in the March to January period, the President’s budget submission to Congress in February, and Congress finalizing appropriations decisions in September for the new fiscal year beginning in October, a total of about 20 months. In practice, this process may take longer if funding is not appropriated by October 1, or due to other factors. For new areas of RDD&D for which there is not an established Congressional Authorization or Appropriation, the process may take much longer.

[177] Public supported R&D generally focuses on mid to longer term work and will typically require five years and often much more. For example, DOE supported R&D on solar PV and on wind turbines has been underway for over 30 years during which time the technologies have gone through many advances in order to achieve the results shown in Figure 2.

[178] The time required to meet regulatory requirements vary widely, but progress has been made in streamlining these processes in many cases. As examples, see:

- Nuclear Energy Institute, Fact Sheet, “Licensing New Nuclear Power Plants”, October 2014, http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Licensing-New-Nuclear-Power-Plants This identifies the development of a combined construction and operation license by the company of about two years, and the review by the Nuclear Regulatory Commission of about three years.
- Environmental Impact Statements under the National Energy Policy Act require a number of steps, as indicated by USDOE, “Environmental Impact Statement Explained”, http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Licensing-New-Nuclear-Power-Plants For active NEPA EIS activities, see: USDOE, Active NEPA Projects, http://energy.gov/nepa/active-nepa-projects

[179] As examples, consider the following:

- Buildings Sector. LED lighting went from cumulative sales of 400,000 in 2009 to about 80 million in 2014, see Figure 2, and are projected by Goldman Sachs Equity Research to account for about 2/3 of the market by 2020, or about ~10 years. See: Jaakko Kooroshy, et al, “The Low Carbon Economy”, Goldman Sachs Equity Research, Novenber 30, 2015, http://www.goldmansachs.com/our-thinking/pages/new-energy-landscape-folder/report-the-low-carbon-economy/report.pdf
- Transportation Sector. Market penetration times for major technology rollouts in the transportation sector required 23-33+ years after market entry. See: S. Plotkin, T. Stephens, W. McManus, (March 2013). Vehicle Technology Deployment Pathways: An Examination of Timing and Investment Constraints. Transportation Energy Futures Report Series. Prepared for the U.S. Department of Energy by Argonne National Laboratory, Argonne, IL. DOE/GO-102013-3708. 56 pp. http://www.nrel.gov/docs/fy13osti/55638.pdf

[180] IPCC, Assessment Report 4, Working Group 3, “Mitigation of Climate Change”, Box 13.7, https://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter13.pdf https://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

See also,

- Allen A. Fawcett, et al., “Can Paris pledges avert severe climate change?”, Science, 4 December 2015, V.350, N.6265, pp.1168-1169.

[181] United Nations Framework Convention on Climate Change, The Paris Agreement, http://unfccc.int/paris_agreement/items/9485.php

[182] For analysis of the benefits of holding temperatures to 1.5°C rather than 2°C see, for example:

- Carl-Friedrich Schleussner, Joeri Rogelj, Michael Schaeffer, Tabea Lissner, Rachel Licker, Eric M. Fischer, Reto Knutti, Anders Levermann, Katja Frieler, William Hare, “Science and policy Characteristics of the Paris Agreement temperature goal”, Nature Climate Change, online 25 July 2016, V. 6, pp. 827-835, 2016.

[183] Steven J. Davis, Ken Caldeira, H. Damon Matthews, “Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure”, Science, V.329, 10 September 2010, pp.1330-1333.

[184] Note that new secure, clean technologies are often not cost competitive with conventional technologies when they enter the market because they have not yet captured economies of scale and learning that conventional technologies have already realized over the past decades, and because little or no market benefit is provided the new technology for its better energy security and lower environmental and health impacts. However, these new technologies often have the potential to be fully cost competitive when they realize economies of scale and learning, even without considering their energy security, environmental, health, and other benefits.

[185] A new Smart Manufacturing Institute and Manufacturing Hub have been established; see:

- Fact Sheet: “President Obama Announces Winner of New Smart Manufacturing Innovation Institute and New Manufacturing Hub,” June 20, 2016, https://www.whitehouse.gov/the-press-office/2016/06/20/fact-sheet-president-obama-announces-winner-new-smart-manufacturing
- “Smart Manufacturing Leadership Coalition”, https://smartmanufacturingcoalition.org

[186] The Department of Energy Advanced Manufacturing Office is currently exploring the development of an Institute on Process Intensification, which could include modular approaches. See:

- “Energy Department Requests Proposals for New Institute to Boost Efficiency in Manufacturing, May 5, 2016, http://energy.gov/technologytransitions/articles/energy-department-requests-proposals-new-institute-boost-efficiency

[187] In particular, see: Technology Assessment 6.B Advanced Materials Manufacturing.

[188] See, for example, the case study of the Consortium for the Advanced Simulation of Light Water Reactors (CASL) in Chapter 6 Supplemental Information Public-Private Consortia and Technology Transition Case Studies for system design, and see QTR Chapter 3 for grid integration.

[189] Donald E. Stokes, "Pasteur's Quadrant: Basic Science and Technological Innovation", Brooking's Institution Press, 1997.

[190] For example, a building owner may purchase equipment for the building, but does not pay the energy bills and has no incentive to purchase more expensive high-effiency equipment in order to benefit from the energy savings since the renter pays those bills. Conversely, the renter may pay the energy bills and would benefit from the installation of more efficient equipment, but does not have a role in purchasing more efficient equipment.

[191] American Energy Innovation Council, "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities", February 2015, see figure 22 and 23. http://americanenergyinnovation.org/ http://www.americanenergyinnovation.org/wp-content/uploads/2015/02/AEIC-Restoring-American-Energy-Innovation-Leadership-2015.pdf. See also: American Energy Innovation Council, "Catalyzing American Ingenuity: The Role of Government in Energy Innovation", 2011, Figure 3, http://www.americanenergyinnovation.org/wp-content/uploads/2012/04/AEIC_Catalyzing_Ingenuity_2011.pdf. The source data for the energy R&D portion of this figure is noted as coming from: Dooley, JJ. The Rise and Decline of U.S. Private Sector Investments in Energy R&D since the Arab Oil Embargo of 1973. Pacific Northwest National Laboratory, November 2010. http://www.pnl.gov/main/publications/external/technical_reports/PNNL -19958.pdf. In turn, Dooley notes difficulties with the survey methodology, which was conducted by the NSF across 20,000+ companies.

[192] Benjamin Gaddy, Varun Sivaram, Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong model for Clean Energy innovation" MIT Energy Initiative Workiing Paper, July 2016. http://energy.mit.edu/publication/venture-capital-cleantech/

[193] Robert Solow, "Technical change and the Aggregate Production function", Review of Economics and Statistics 39, pp.312-320, 1957.

See also, for example:

- Edward Denison, Trends in American Economic Growth 1929-1982, Brookings Institution, Washington, DC, 1985.
- Ishaq Nadiri, "Innovations and Technological Spillovers", NBER Working Paper #4423, National Bureau of Economic Research, Washington, DC, 1993, http://www.nber.org/papers/w4423.pdf

[194] As a very recent example, see: Klaus Prettner, Katharina Werner, "Why it pays off to pay us well: The impact of basic research on economic growth and welfare", Research Policy 45 (2016), 1075-1090.

[195] Board on Energy and Environmental Systems, "Was It Worth It: Energy Efficiency and Fossil Energy Research 1978-2000", National Research Council; National Academies of Science, Engineering, and Medicine; National Academy Press, Washington, DC, 2001. http://www.nap.edu/catalog/10165/energy-research-at-doe-was-it-worth-it-energy-efficiency

[196] See, for example, the retrospective benefits studies listed at: http://www.energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations and http://www.energy.gov/eere/analysis/policy-and-analysis-publications

[197] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Saving Energy and Money with Appliance and Equipment Standards in the United States", http://energy.gov/sites/prod/files/2015/02/f19/equipment_standards_factsheet_updated_Feb_11_2015.pdf

[198] Some pollution is controlled by technologies put into place to help meet regulatory requirements, and the costs for this equipment are taken into account. However, there are substantial public costs for the pollution and GHGs that are not controlled.

[199] Externalities are the costs or benefits that affect a third party without their choice, resulting in goods or services whose market prices do not accurately reflect the full cost that their provision incurs. Externalities can be positive or negative for the third party. An example of a positive externality is an individual's purchase of a solar panel, thus reducing CO_2 emissions that would otherwise contribute to global climate change that impacts everyone. An example of a negative externality is the health costs incurred by someone due to air pollution. Economic efficiency requires that all costs and benefits of a good or service should be internalized in its price.

[200] See:

- Charles T. Driscoll, et al, "U.S. power plant carbon standards and clean air and health co-benefits", Nature Climate Change, 4 May 2015, v.5, pp.535-540.
- Tammy M. Thompson, Sebastian Rausch, Rebecca K. Saari, Noelle E. Selin, "A Systems approach to evaluating the air quality co-benefits of US carbon policies", Nature Climate Change, 24 Aug 2014, V.4, pp.917-923.
- Neal Fann, Kirk R. Baker, Chalres M. Fulcher, "Characterizing the PM2.5-related health benefits of emission reductions for 17 industrial, area and mobile emissions sectors across the U.S.", Environment International 49 (2012) 141-151.
- Francesca Dominici, Michael Greenstone, Cass R. Sunstein, "Particulate Matter Matters", Science V.344, 18 April 2014, pp.257-258
- Julia Schmale, Drew Shindell, Erika von Schneidemmesser, Ilan Chabay, Mark Lawrence, "Clean up our skies", Nature V.515, 20 Nov, 2014, pp.335-337

[201] As another example, the Federal government is the largest single user of energy in the United States; RDD&D to reduce these costs can directly support the Federal mission.

[202] U.S. Department of Energy, "Science and Energy Plan: Fiscal Year 2016", September 2015. http://energy.gov/downloads/science-and-energy-plan

Acronyms

AEO	Annual Eneregy Outlook (of the U.S. Energy Information Administration)
AER	Annual Energy Review (of the U.S. Energy Information Administration)
BC	Black Carbon
BEV	Battery Electric Vehicle
°C	Centigrade Degrees
C3	A plant that uses a particular photosynthetic pathway to fix carbon atoms from CO_2.
CAFE	Corporate Automobile Fuel Economy
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EIA	U.S. Energy Information Administration
EV	Electric Vehicle
°F	Fahrenheit Degrees
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMSL	Global Mean Sea Level
GT	Gigatonnes (billion metric tonnes)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change (of the United Nations)
AR	Assessment Report (of the IPCC)
WG	Working Group (of the Assessment by the IPCC)
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
LPG	Liquefied Petroleum Gas
m	Meter
MMBbl/d	Million Barrels per day
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_x	Nitrogen Oxides

NRC	National Research Council (of the National Academies of Sciences, Engineering, and Medicine)
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
PAH	Polycyclic Aromatic Hydrocarbon
PEV	Plug-in Electric Vehicle
pH	A logarithmic scale used to measure the acidity or alkalinity of a solution: less than 7 is acidic, more than 7 is alkaline.
PM	Particulate Matter. $PM_{2.5}$ is particulate matter with a size range around 2.5 microns or less.
ppmv	Parts per million by volume
PV	Photovoltaic
DPV	Distributed photovoltaic, such as the solar panels used on residential rooftops
UPV	Utility photovoltaic
QER	Quadrennial Energy Review
QTR	Quadrennial Technology Review 2015
RDD&D	Research, Development, Demonstration, and Deployment
SO_x	Sulfur Oxide
UNEP	United Nations Environment Programme
VC	Venture Capital
VOC	Volatile Organic Compound