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ENERGY

Department of Energy
Quadrennial Technology Review-2015
Framing Document

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The United States faces serious energy-linked challenges as well as substantial energy opportunities. Disruptions, both natural and man-made, threaten our aging energy infrastructure; global patterns of energy use are changing our climate; and our nation's dependence on foreign sources of energy comes at a significant cost to our economy. We need clean, reliable, secure, affordable energy services, and we need to be at the forefront of the global clean energy economy. This is our energy challenge and our opportunity.

To better understand and evaluate these challenges and opportunities, the United States Department of Energy (DOE) has begun its second review of energy technology Research, Development, Demonstration, and Deployment (RD^3) activities, opportunities, and pathways forward—the Quadrennial Technology Review-2015 (QTR-2015). This study will describe the nation's energy technology landscape; it will build on the first QTR written in 2011 (QTR-2011) and identify what has changed; and it will identify important RD^3 activities, opportunities, and pathways forward to help address our national energy-linked challenges. It will complement the work of the Quadrennial Energy Review (QER), which is currently focused on energy infrastructure and policy (http://energy.gov/epsa/initiatives/quadrennial-energy-review-qer).

This framing document is a principal means of facilitating subject matter expert (SME) and stakeholder engagement in the QTR-2015 process, including by industry, academia, and the public. DOE seeks input on the questions posed in this document, which correspond to those in the Request for Information to be published in the Federal Register. Instructions on submitting comments can be found at http://energy.gov/qtr.

Contents

FRAMING THE DOE QUADRENNIAL TECHNOLOGY REVIEW-2015

1. Introduction

The United States faces significant energy-linked challenges as well as substantial energy opportunities. Our current patterns of energy use are changing our climate, traditional and emerging disruptions threaten our energy systems, and our nation's dependence on foreign sources of energy supplies and energy technologies comes at a serious cost to our economy. We need clean, reliable, secure, affordable energy services, and we need to be at the forefront of the global clean energy economy. This is our energy challenge and our opportunity.

To better understand and evaluate these challenges and opportunities, the United States Department of Energy (DOE) has begun its second Quadrennial Technology Review of energy technology R&D activities, opportunities, and pathways forward—QTR-2015. This study will describe the nation's energy landscape; it will build on the first QTR written in 2011 (QTR-2011)[1,2] and identify what has changed since then; and it will identify important research, development, demonstration, and deployment (RDD&D or RD^3) activities, opportunities, and pathways forward to help address our nation's energy-linked challenges. The issues identified in the first QTR Framing Document[3] largely remain the same, so this QTR framing document will primarily focus on changes since then and the science and energy technology RD^3 opportunities going forward. This review is being undertaken by the Office of the Under Secretary for Science and Energy at the request of the Secretary of Energy. Included in this review are the Offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Indian Energy Policy and Programs (IE), Nuclear Energy (NE), Electricity Delivery and Energy Reliability (OE), and Science (SC), which are within the Office of the Under Secretary for Science and Energy, as well as linkages ARPA-E, Energy Policy and Systems Analysis, and other DOE offices.

Advancing scientific discoveries from the laboratory to the marketplace requires a multi-year science and engineering effort, coordinated with targeted policies and other actions. The QTR-2015 will identify and examine priority RD^3 areas and the relative roles of the public and private sectors in advancing key technologies at various stages of their development. It will begin with an examination of the characteristics of the various energy systems—fuels, electric power, buildings, industry, transport—and the corresponding RD^3 that is needed to transform these energy systems into ones that better address our economic, environmental, and energy security challenges. This Review will also link to more detailed technology roadmaps and other key documents in DOE energy technology research programs and related activities. Further, the QTR-2015 will examine approaches for evaluating energy technology RD^3 activities and use these to help inform DOE portfolio decisions. Finally, this Review will assess progress on the recommendations made in the QTR-2011 study.

A cross-agency Quadrennial Energy Review (QER) is also currently underway.[4] The QER is currently[5] focused on infrastructure and policy issues across the public sector, whereas the QTR is primarily focused on DOE supported RD^3 to meet national energy challenges and goals. These studies are parallel to and complementary with each other.

The 2014-2018 DOE Strategic Plan[6] establishes a framework for all of the Department's activities, including nuclear security, environmental management, basic science, and energy technology. The QTR-2015 begins with this Strategic Plan and examines key RD^3 that can help realize its goals and address national energy challenges, recognizing the critical roles of other government entities in key areas ranging from RD^3 to regulation; the central role of the private sector in developing, building, owning, and operating energy technologies across the economy; and the roles of industry, academia, and others for identifying new energy RD^3 opportunities. Addressing these issues require broad engagement and full transparency of inputs.

This framing document and its accompanying Request for Information (RFI) contribute to this process that the DOE believes will help lead to a more robust technology RD^3 portfolio that can help meet our nation's energy challenges. Written comments responding to the questions raised in this framing document and RFI are encouraged throughout the public comment period, until February 6, 2015.

In addition to this framing document and the comments received on it, DOE will make use of past and ongoing DOE program workshops and other activities, and other inputs from the private sector, academia, national labs, other subject matter experts (SMEs), and the broad stakeholder community. The DOE QTR technology assessment teams will also hold webinars to reach out to the broad communities of SMEs and stakeholders. Notices of these workshops and webinars and the materials discussed will be posted on the QTR website at http://energy.gov/qtr, with the opportunity to provide further input to the QTR process.

This framing document continues with the following. Section 2 describes the changing landscape of U.S. energy supplies and use; Section 3 describes key energy-linked challenges facing the U.S. that drive the need to transform the U.S. energy system; Section 4 describes RD^3 opportunities; and Section 5 raises questions for how to allocate resources and to accelerate DOE RD^3 activities to meet these challenges.

2. U.S. Energy Supply and Use

A complex array of technologies supply, deliver, and convert energy resources into valuable products and services, such as manufactured goods, thermal comfort, lighting, and mobility. The goal of the QTR is to identify energy technology RD^3 that will enable desired energy-linked products and services to be delivered at lower cost, with fewer environmental impacts, and with greater security.

Overall U.S. primary energy supply by source and energy use by sector are shown in Figure 2-1. Fossil fuels provide about 82% of all primary energy supplied and currently result in about 5.3 billion metric tonnes (GT) of CO$_2$ emitted to the atmosphere each year for energy, non-energy, and related use such as iron and steel or cement production.[7] Figure 2-2 illustrates how U.S. energy use has changed over time. Over the past 200+ years, the predominant source of U.S. primary energy supply has changed several times, with typical transition times of 50-100 years. These shifts in primary energy supplies include moving from wood to coal to oil and now towards natural gas. Similar transformations have occurred on the end-use side; for example, for space heating, homes have moved from fireplaces, to gas furnaces, and now increasingly to heat pumps. Over the past 15 years the energy consumption of the U.S. economy has been virtually unchanged, even though the population increased by 13% and real GDP increased by nearly 30%.[8] This improvement in energy efficiency is important progress, with economic, environmental, and security benefits. We now need to accelerate this progress and transition to clean energy systems that minimize environmental and economic costs.

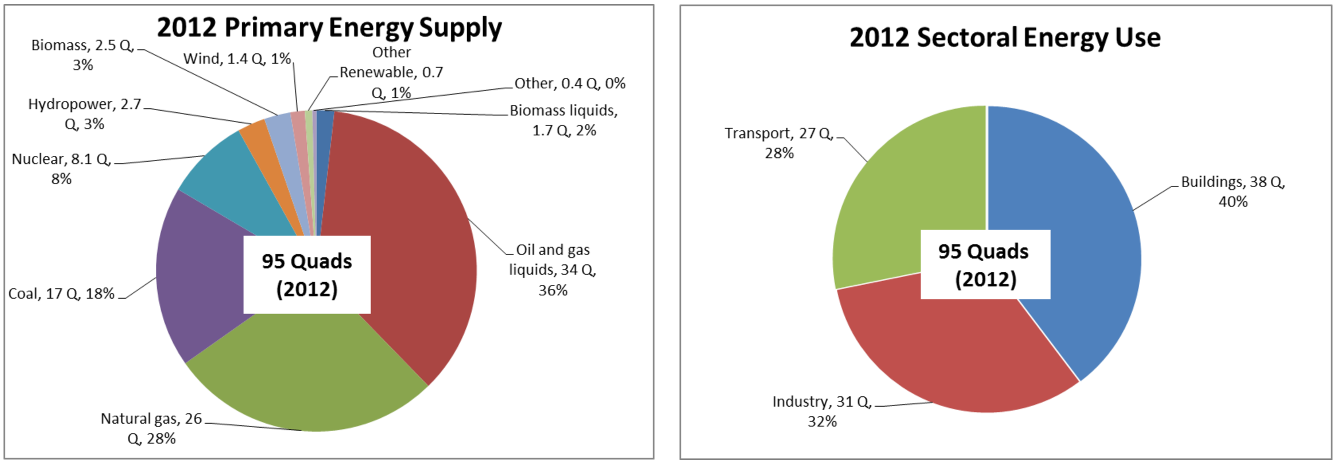

Figure 2-1: U.S. Energy Use by (a) Primary Energy Source in Quads and as a percent of total U.S. energy supply; and (b) Energy Sector supplied in Quads and in percent of total U.S. energy use.[9]

Sector End Use Energy Supply and Consumption. U.S. primary energy supply going to each sector and the principal energy end-uses are shown for the Buildings (Figure 2-3), Industry (Figure 2-4), Transportation (Figure 2-5), and Electric Power (Figure 2-6) sectors. The conversion losses in producing electricity are included in these figures to show the full share of primary energy devoted to each sector and end use.

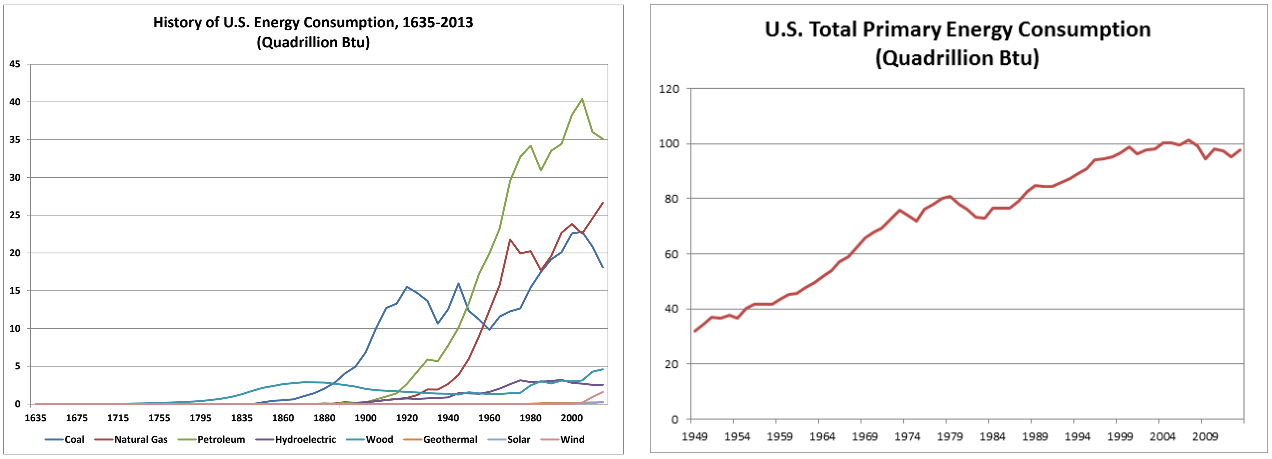

Figure 2-2: U.S. Primary Energy Use over time in Quads: (a) from 1800 to the present by source,[10] and (b) total primary energy consumption from 1949 to the present.[11]

For energy supplies, Figure 2-1a shows that fossil fuels supply the majority of primary energy in the U.S.; Figures 2-3 through 2-6 show where these primary energy sources are used. Coal is used primarily in the power generation sector (91%, Figure 2-6) and the remainder is used for steel, cement, and a few other applications in the industrial sector (9%, Figure 2-4). Petroleum is used largely in the transportation sector (69%, Figure 2-5), refining and off-road mobile applications such as agriculture, construction, and mining in the industrial sector (22%, Figure 2-4), and for some heating applications in the buildings sector (3%, Figure 2-3). Electricity has a wide range of sources beyond fossil fuels, particularly nuclear power (21%) and renewables (12%)—including hydropower (7%), biomass (1%), and wind power (4%).[12] Use of natural gas and renewables are growing rapidly in the electricity sector.

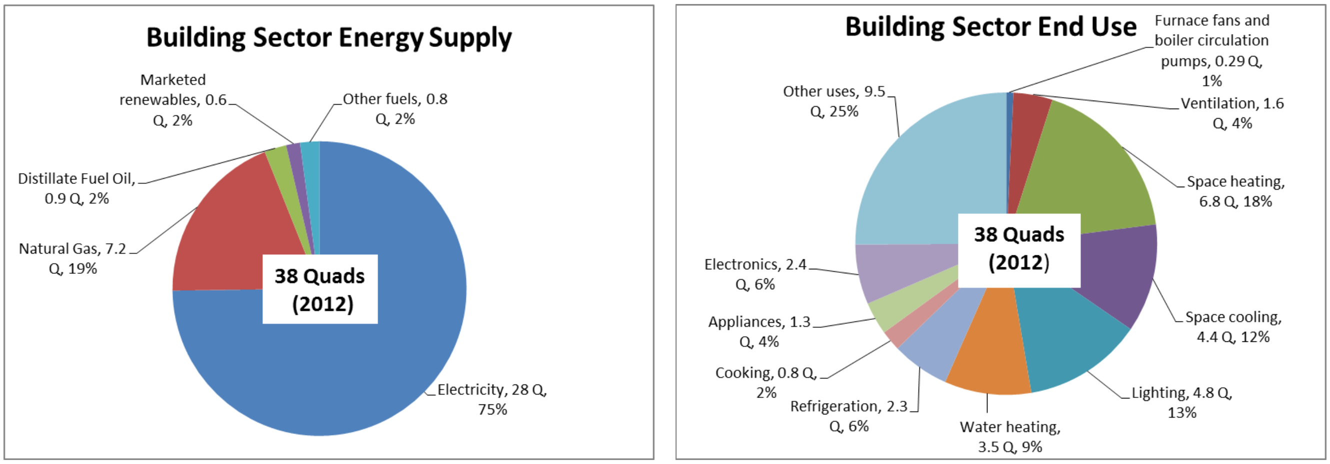

Figure 2-3: U.S. Building Energy Use by (a) Primary Energy Supply in Quads and as a percent of total U.S. building energy supply, and (b) Building Energy End-Uses in Quads and in percent of total U.S. building energy use. [13,14,15,16,17,18]

For energy end-uses, nearly two-thirds of buildings energy use goes to space heating, cooling, and ventilation, water heating, lighting, and refrigeration (Figure 2-3b). For industry, the major energy consumers are the energy-intensive manufacturing sectors such as primary metals manufacturing (e.g., steel), chemicals, paper, and petroleum refining, and electric motor drive and process heat, particularly steam (Figure 2-4b). For transport, almost all the energy is used by light-duty passenger vehicles and heavy freight trucks, followed by aircraft (Figure 2-5b). The electricity consumed by transportation represents an almost invisible slice of current consumption.

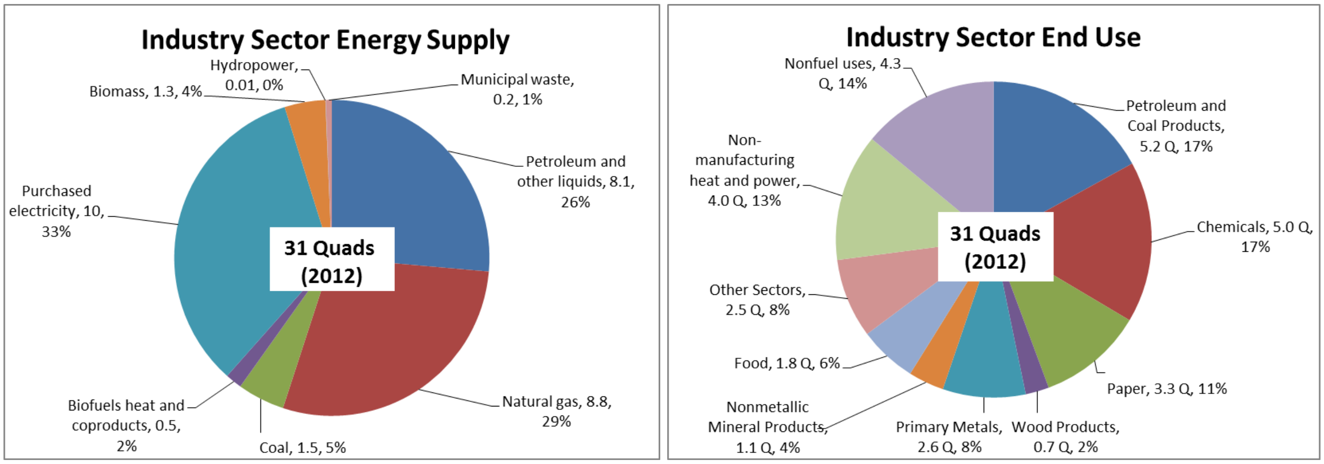

Figure 2-4: U.S. Industry Energy Use by (a) Primary Energy Supply in Quads and as a percent of total U.S. industry energy supply, and (b) Industry Energy End-Uses in Quads and in percent of total U.S. industry energy use.[19,20,21,22,23,24,25,26]

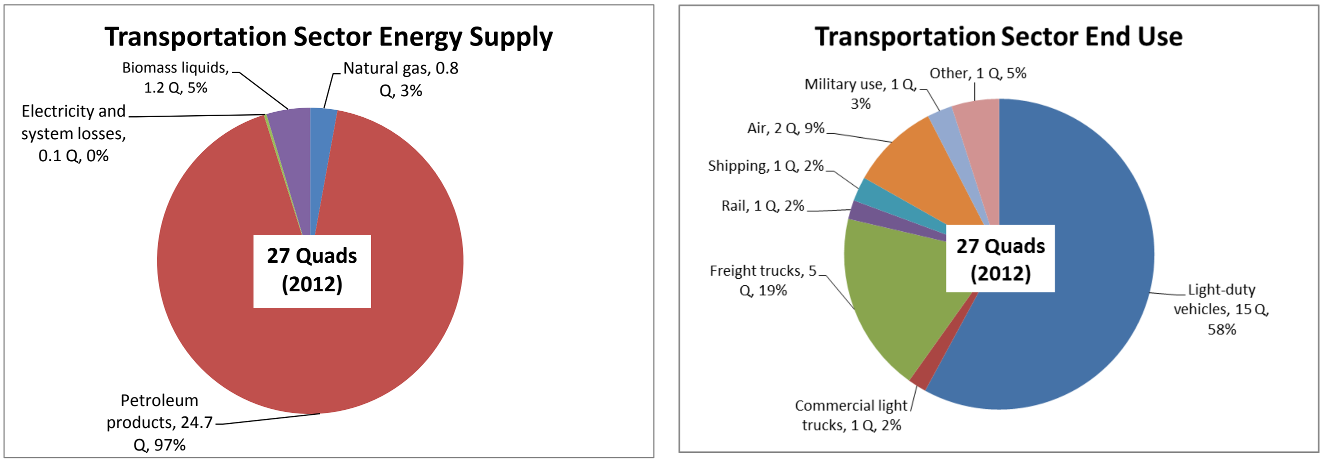

Figure 2-5: U.S. Transportation Energy Use by (a) Primary Energy Supply in Quads and as a percent of total U.S. transportation energy supply, and (b) Transportation Energy End Use in Quads and in percent of total U.S. transportation energy use. [27,28,29,30,31,32]

Changes in U.S. Energy Supply and Demand. Substantial changes in U.S. energy supply and end-use demand have taken place just in the last four years since the first QTR was written. These include rapid increases in the production of unconventional natural gas and oil, rapidly increasing use of natural gas and renewables in the electricity sector, initiation of new nuclear reactor construction, slowing demand growth for energy, implementation of new fuel economy standards for light-duty passenger vehicles, and new appliance standards. Increasing use of digital technologies in the electric power system and other sectors is driving a variety of new capabilities, and new risks. These many changes offer benefits, but the slow growth of energy technology markets in the U.S. (noted above in Figure 2-2b) limits market opportunities for new technology adoption, making it difficult to quickly implement these new technologies and capture economies of scale and learning.

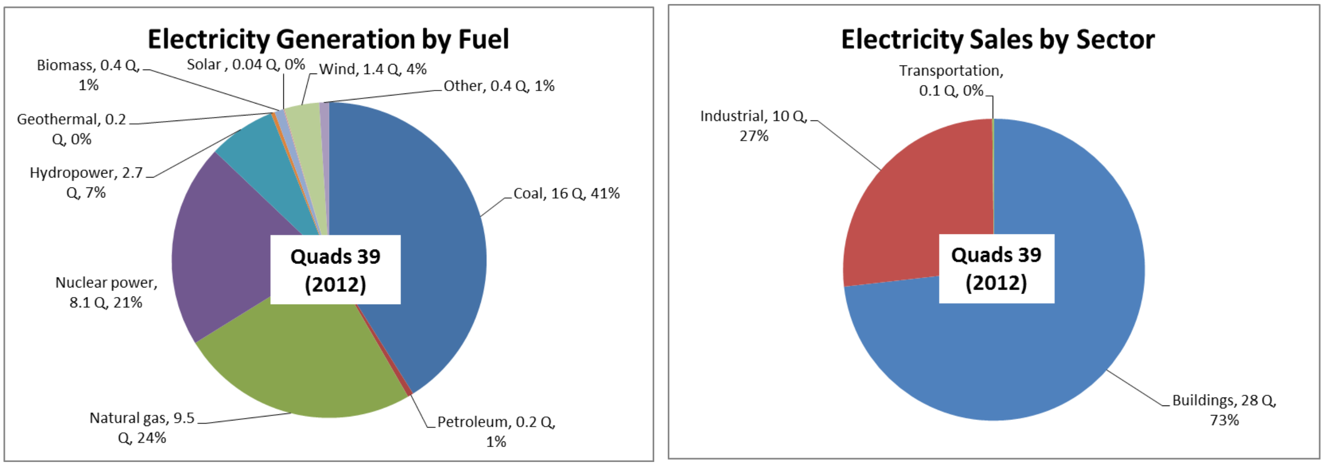

Figure 2-6: U.S. Power by (a) Primary Energy Supplies in Quads and as a percent of total U.S. electricity generation, and (b) Electricity End Use. [33,34,35,36,37]

3. Challenges to the Nation's Energy Systems

The U.S. faces significant energy-linked economic, environmental, security, and competitiveness challenges; these are detailed below.

Economic Challenges. Energy plays a central role in the U.S. economy, enabling all other activities—manufacturing, transport, services, quality of life. The total cost of energy supplies to end users in the U.S. was roughly $1.2 trillion in 2010,[38] or about 8% of our total GDP;[39] this does not include many of the large expenditures on the equipment and systems—in the buildings, industry, and transportation sectors[40]—that use this energy. Net petroleum imports cost the U.S. some $230 billion in 2013, roughly half of our total trade deficit.[41] Our aging electric power system also exacts substantial costs due to outages. Studies have estimated that disruptions to the U.S. electric power system cost, very roughly, $80 billion per year due to normal weather events, trees falling, equipment failing, and other such events, not considering the damage from extreme weather events such as superstorm Sandy.[42] These costs could rise if climate change drives increased frequency of such severe weather events, if maintenance further lags infrastructure aging, and if modernization does not keep up with the changing generation and end-use technologies and systems. As noted above, the QER is currently examining U.S. energy infrastructure issues and related policy in detail and will report findings in early 2015.

Demand for energy is relatively inelastic; that is, the quantity of energy consumed is not very sensitive to changes in the price of energy. This is true particularly in the short term across multiple demand sectors (buildings, industry, transportation) and across multiple energy carriers (electricity, fuels). When energy is produced domestically, price increases raise producer incomes at the expense of higher consumer expenditures; for energy imports, such price increases are a drag on our national trade balance.

Although U.S. oil production has increased sharply in recent years, with the unconventional oil production boom now supplanting four decades of generally declining conventional oil production in the U.S., the cost of imports remains a large fraction of our trade deficit due to the general global increase in oil prices over the past decade, although there is, presently, a decline in global oil prices. EIA projections for shale oil production indicate a peak around 2021 in the reference case.[43] The magnitude and timing of this peak depends on global market conditions, the quality and quantity of the resource (which is still subject to uncertainty) as well as the ability of RD^3 to develop technologies to access a broader range of unconventional resources and stay ahead of changing resource quality at competitive prices.

Technology advances can reduce costs. One recent example noted above is the set of technologies that enable extraction of oil and gas from previously unrecoverable (shale and tight) reserves, thereby increasing domestic supplies of gas and oil—resulting in the highest domestic oil production since 1970. Another example includes advances in automotive engines which maintain or improve automotive performance while increasing vehicle mileage, resulting in lower overall ownership costs.

Structural and behavioral factors, however, may inhibit the adoption of some technologies. For example, the costs of inefficient energy technologies are sometimes shouldered by consumers who do not participate in the purchase of those technologies. Consider residential appliances, where low-cost but inefficient appliances may be purchased by a landlord or builder but the energy costs are paid by the tenant or owner. While the QTR will not address policies that shape markets for energy technologies—these are the focus of the Quadrennial Energy Review—the QTR will seek to identify RD^3 opportunities that can succeed in both current and potential future markets.

In the transportation sector, the U.S. has the opportunity to develop and put into place a transition to clean sustainable domestic transportation fuels and systems. Sources—such as electricity, hydrogen, and natural gas—that reduce U.S. dependence on global transport fuel markets would be particularly useful as the costs for these sources are set domestically, in contrast to current petroleum-based fuels and liquid alternatives which are traded on global markets and their prices are thus tied to world market prices.[44]

The U.S. also has the opportunity to develop and export advanced clean energy technologies for the international market, which will be worth many billions of dollars over the next several decades. For example, just the solar, wind, and biofuels markets are estimated to currently be worth $250 billion per year globally, and are growing rapidly.[45] These markets may also be important for companies to achieve the economies of scale and learning for continued competitiveness both domestically and globally.

Environmental Challenges. Energy production, delivery, and end use all impact our environment. Impacts vary according to lifecycle stage, energy resource, and technologies implemented in energy supply, delivery, and use, and can include emission of air pollutants such as SO_x, NO_x, particulates, mercury, and CO_2; release of water pollutants; and impacts on the land from radioactive or toxic wastes or physical disruption due to fuel extraction, energy plant, or infrastructure siting. Depending on the magnitude and severity, these impacts may have serious consequences for human health, the health of local ecosystems, land and water availability for productive uses, and the global climate. Over the last several decades, significant progress has been made in reducing both air and water pollution from energy-related activities that affect the local environment, but many issues remain to be resolved.

The use of fossil fuels for energy has and continues to emit large quantities of CO_2 into our atmosphere. These and other greenhouse gases are already and will increasingly disrupt our climate, with impacts including higher sea levels and increased damage to coastal cities[46]—particularly during storms, increased climate extremes, increased mid-latitude droughts in many areas,[47] and ocean acidification with significant impacts on ocean ecosystems.[48] Recent major reports detailing climate impacts include the Intergovernmental Panel on Climate Change 5th Assessment Report and the 3rd National Climate Assessment.[49]

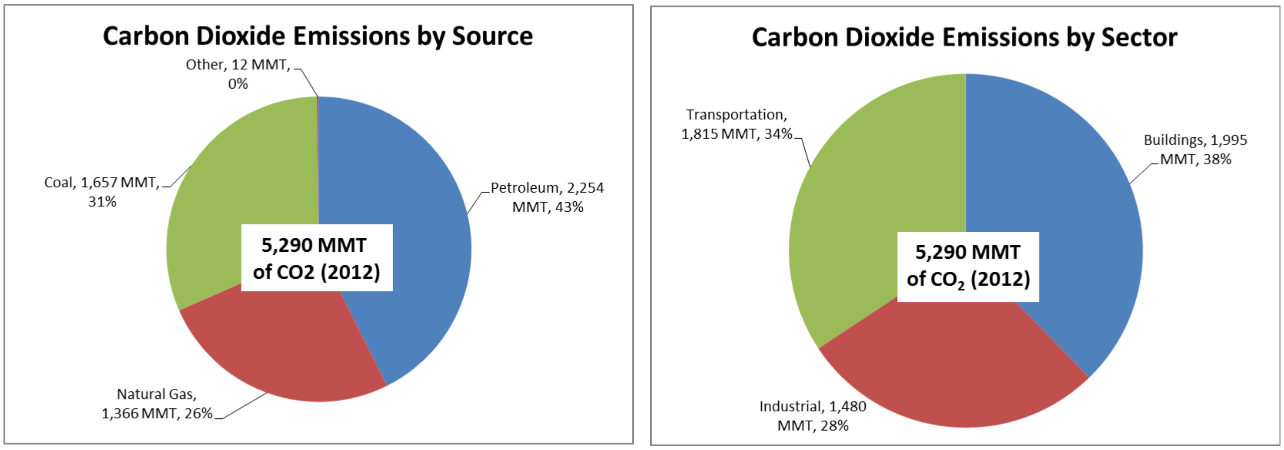

Figure 2-7: U.S. Carbon Dioxide (CO_2) Emissions by (a) Primary Energy Source in Million Metric Tons and as a percent of total U.S. Energy-Related CO_2 Emissions, and (b) End Use Sector.[50]

Energy supply and use can themselves be affected by changes to the environment. For example, limited water availability due to drought can constrain the operation of power plants and other energy production activities. Storms can stress the resiliency and robustness of energy systems.

Security Challenges. Energy-related threats to national security range from short-term and acute to long-term and pervasive. They can broadly be categorized into physical, cyber, economic, and conflict-related, though many of these threats are inter-related.

- **Physical** security threats are related to potential damage to supply and delivery infrastructure.[51] Such damage could be caused by malicious actors (domestic or foreign, state- or non-state-sponsored) carrying out destructive acts on physical hardware. Additionally, climate change, weather, and natural hazards pose increasing risk to critical assets in the energy system. Infrastructure systems of concern are electricity generation, electric transmission, distribution, and storage, natural gas and oil pipelines and storage, railroads—particularly as crude oil shipments grow, and water supply, treatment and distribution.
- **Cyber** security threats are related to the computer-based controls that operate and coordinate 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 and flow of energy and/or damage supply, transmission and distribution equipment.
- **Economic** security threats are related to price shocks, potential shortages of critical commodities and/or capital equipment, and long-term trade deficits (above). Commodity price shocks have led to significant economic disruptions in the past (e.g. oil shocks of 1970s). An emerging potential economic security threat is that critical energy system components (e.g., large transformers, large nuclear components) are made overseas where supply could be constricted unpredictably.
- **International** security threats are related to military/political unrest in foreign countries. Energy-related international security threats include unrest driven by energy prices and climate change-induced risks such as crop failure, water shortages, or extreme weather. These threats may increase the risk of state-sponsored or terrorist attack against the U.S.[52]

Competitiveness Challenges. As leaders in R&D on many energy technologies, the U.S. has the opportunity to lead the world in manufacturing clean energy technologies. Technology, manufacturing advances, and market deployment can move new energy technologies rapidly down the learning curve to lower costs. Those countries and companies that are able to drive these costs down first may capture a large first-mover advantage. Further, they develop the advantages of building strong supplier networks for the needed inputs, a skilled workforce, and the downstream companies that integrate the energy technology into systems for sale in markets around the world. Technology RD^3 can help the U.S. improve its competitiveness in key energy technology areas. Production and export of energy equipment represents a substantial market opportunity for the U.S. that would generate high-value jobs.

Timeframes. Time frames to change energy supply, delivery, and end-use equipment vary widely. Buildings typically last 60 years or more, whereas the equipment within them may be changed every 10-20 years. Industrial plants similarly last many decades, but the equipment within them is changed more rapidly. Vehicles typically last 10-15 years or more, depending on their use, but the highways and urban design around them will be in place for many decades. Central station power plants typically last 40-60 years or more, as can the infrastructure of railroads, pipelines, and power lines associated with them. Thus, substantial change in existing energy systems can require decades, raising important issues in the focus of RD^3 with respect to the balance of activity on new technologies versus retrofit technologies, the risk of stranded assets as national energy challenges force new technology directions, and the choice of technologies on which to conduct RD^3 if they are to be available in time to effectively meet national economic, environmental, and security challenges.

The energy sector is significantly impacted by the number of actors that must be engaged in changing energy supply, delivery, and end-use equipment. On the end-use side, in 2012 there were more than 5.6 million commercial buildings with a total of 87 billion square feet of floor space,[53] and currently there are about 120 million residential households. Similarly, there were a total of 230 million light-duty vehicles, which traveled a total of almost 2.7 trillion miles in 2011. All of these end-uses can benefit from improved efficiencies, with 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, to 17,000 firms across the supply chains for appliances and vehicles.[54] On the supply side the numbers are quite different, with just over 19,000 electric generation facilities providing power to the U.S. and many more small distributed facilities. The U.S. currently has about 142 refineries, with 139 operating.[55] Effecting change across these various actors impacts the choices of technology RD^3, including the development of public-private partnerships.

4. RD^3 Opportunities and Strategies

The QTR-2015 will explore key RD^3 opportunities to help meet the national energy-linked challenges listed above, and will use this analysis to help inform DOE budget planning over the next five years. This QTR will first examine the systems that component technologies support, and then it will examine the component technologies themselves. Key factors in considering which systems and technologies to examine include the following, which builds on the framework of the QTR-2011:

- **Time period**: Research should be undertaken within the next 10 years, with commercialization within 10-15 years.
- **Energy impacts**: The system/technology should have the potential to itself save or supply at least 1% (1 Quad) of U.S. primary energy by 2030 or to play a key enabling role in helping others do so.
- **Market potential**: The system or technology should, ultimately, have significant potential to succeed in the competitive market, recognizing that these markets are driven by economics and shaped by public policy. (Public policy will be separately examined in the QER.)
- **Environmental benefits**: The system or technology should have much lower emissions of CO_2 and other pollutants than what it replaces, or otherwise reduce the environmental impacts (e.g. impacts to land, water resources, ecosystems) and improve sustainability, recognizing that there frequently are tradeoffs across these.
- **Public role**: The system or technology should provide value to the public, and that the private sector is unlikely to undertake this research at sufficient scale alone.

In addition, key elements of strategy include the following:

- **Portfolio diversification**: The technology should not duplicate another, similar technology unless it offers significant differences in risk, return, time-of-impact, or other benefits.
- **Transition strategy**: As the R&D progresses, there should be a plan to increasingly transition efforts to the private sector, recognizing that a federal role may or may not remain in supporting development, standards or adoption policy.

Systems and technologies that have been identified as candidates for examination, considering these factors and strategies, include those described in the subsections below on: Fuels; Electric Power Systems; Electric Power Supply Technologies; Buildings; Industry; Transportation; Enabling Science; and Cross-cutting Analysis.

Advancing Systems and Technologies to Produce Cleaner Fuels. For the purposes of this discussion, a fuel is a gaseous, liquid, or solid carrier of chemical energy (nuclear fuels are addressed separately in the clean power section). Fuels are critical to our energy system because: they are dense, portable stores of energy; they degrade slowly (or not at all) over time; they can quickly and safely be transferred between devices and transported over long distances; and they are often manufactured from resources found in our environment. Fossil fuels currently account for about 82% of U.S. primary energy use (Figure 2-1a). Fossil fuel utilization in distributed applications results in significant GHG emissions and local and regional air pollution. Extraction of primary energy sources such as coal, natural gas, petroleum, and biomass can have significant local environmental consequences.

RD^3 opportunities that can help produce cleaner, more secure, and more diverse fuels are listed in Table 4-1.

Table 4-1. Opportunities to Advance Systems and Technologies for Cleaner Fuels.

• **SubSurface Technology and Engineering RD&D**	• Intelligent Wellbores: Materials; Data; Diagnostics; Drilling and Completion; Well Abandonment Analysis R&D • Subsurface Stress & Induced Seismicity: Stress State; Signal Acquisition and Processing; Local Manipulation of Stress; Risk Assessment • Permeability Manipulation: Physicochemical Rock Physics; Characterization and Manipulation; Novel Stimulation • New Subsurface Signals: Diagnostics; Acquisition; Integration • Note that these capabilities are cross-cutting and also apply to Carbon Capture and Storage (CCS), Advanced Geothermal Technologies, Nuclear Waste Disposal, and others (see below)
• **Alternative Hydrocarbon Fuels**	• Unconventional Oil and Gas (including minimizing environmental impacts) • Offshore Oil Spill Prevention • Advanced Coal Technologies • Gas Hydrates • Natural Gas Transportation, Storage, and Distribution; R&D on Midstream Issues • Conversion of Hydrocarbons to Intermediate Energy Carriers with No Carbon and CCS for Carbon from Feedstock
• **Biofuels and Bioproducts**	• Biofuels Feedstock Production: Short Rotation Woody Crops; Perennials; Algae; Polycultures; Microorganisms for Fuel; Synthetic Biology • Biofuel Collection and Transport • Advanced Pretreatment Processes • Biocatalysis • Feedstock Conversion: Biochemical Pathways • Lignin Processing • Feedstock Conversion: Thermochemical Pathways • BioProducts
• **Hydrogen**	• Hydrogen Production R&D: Reforming; Electrolysis; Direct Solar Thermal Chemical; Photoelectrochemical; Biochemical Hydrogen; Thermochemical Hydrogen; High-Temperature Thermochemical • Transport and Distribution R&D; Liquefaction; Compression; Pipeline distribution; Organic Liquid Carriers • Storage R&D; Compressed gas systems; Low Temperature or Liquid Storage; Sorbent or Hydride Storage • Storage R&D
• **Direct Renewable Energy-based Fuels**	• Direct Renewable Fuels Production • Solar Thermal Chemical Hydrogen • Photoelectrochemical Hydrogen
• **Enabling Science in Fuels Production**	• Computational R&D in Fuel Design and Production • Computational R&D in Subsurface Analysis
• **Energy-Water RD&D in Fuels Production**	• Produced Water Cleanup • CCS w/downhole CO2 pressure to produce clean H2O

Enabling Modernization of Electric Power Systems. The electric power sector is entering a period of profound change due to new technologies entering the sector and new requirements on the sector. These technologies include increased use of digital sensing and control technologies, the increased use of variable renewable technologies such as wind and solar photovoltaics, and the increased requirements on the electricity sector to be resilient to disruptions and to reduce emissions. Electricity is the only broadly deployed zero-carbon energy carrier. It is used extensively throughout the buildings and industrial sectors and may become increasingly important to the transportation sector. Broader use of electricity presents opportunities to improve efficiency and decrease GHG emissions in the end use sectors. Table 4-2a lists R&D opportunities that target modernization of the grid.

Table 4-2a. Opportunities for Enabling Modernization of the Electric Power Grid.

• **Grid Designs and Concepts**	• Planning Tools and Simulators • Grid Architectures and Interoperability (including nested microgrids) • Advanced Control Paradigms (including transactive controls) • Technical Analyses and Decision Tools
• **Measurements, Communications, and Controls**	• Low Cost Sensors • Communications and Data Management (including data processing, visualization, mining) • Models and Operations Planning • Grid Management Systems • Advanced Computing Platforms
• **Transmission and Distribution Components**	• Advanced Cables and Conductors • Next Generation Transformers • Power Flow Controllers • High Voltage Direct Current (HVDC) and Medium Voltage DC (MVDC) • Fault Current Limiters and Breakers
• **Electric Energy Storage**	• Pumped Storage Hydro • Compressed Air Energy Storage • Battery Storage • Flywheels and Other
• **Grid Cyber, Physical Security**	• Cybersecurity • Physical Security • Risk Management
• **Flexible and Distributed Energy Resources**	• Grid-Friendly Distributed Resources • Integrated and Aggregated Resources • Flexible Bulk Generation

Advancing Clean Electric Power Technologies. Forty-one percent of the U.S. primary energy supply is directed to electricity generation, which consumed 39 Quads in 2012 (Figure 2-6a). Table 4-2b lists R&D opportunities for advancing clean electric power technologies. This includes CO_2 management strategies for fossil energy and biopower, and advances in nuclear and renewable technologies. Other aspects of clean electric power technologies include advances in power electronics, distributed systems, and energy-water technologies.

Table 4-2b. Opportunities for Advancing Clean Electric Power Technologies.

• **Carbon Management for Fossil-Fueled Power, Industrial Plants, and other Large-Scale Site Sources**	• Advanced Energy Systems: Pulverized Coal (PC)-based technology; Gasification-based technology (e.g., air separation membranes, hydrogen turbines, gas cleanup, high temperature fuel cells); Alternative Combustion Processes (e.g., oxy-combustion, chemical looping); Advanced Materials • Carbon Capture: 2nd Gen Solvents; 2nd Gen sorbents; 2nd Gen Membranes; Transformational (e.g., electrochemical, phase change, hybrid systems, advanced cryogenic); Carbon Capture Simulation; Advanced Compression and Process Equipment • Carbon Storage: Demonstrate Safety/Permanence of CO_2 storage; Wellbore Integrity; Improved Tools to Identify Leakage; Advanced Models for Managing Fluid Flow; Geomechanical Processes that can Impact Seismicity; Geochemical Processes for Storage Formation; Caprock, Wellbore and Potential Release Pathways; Risk Analysis Tools; Development of Domestic Storage Infrastructure • Large-scale Integrated CCS Projects: CCS Integrated Systems at Commercial Scale while Maintaining Reliable, Predictable and Safe Plant Operations; Prove Carbon Utilization Options to Accelerate Commercial Deployment

Nuclear Power	Advanced Light Water Reactors (LWR) Small Modular Reactors (SMR) High Temperature Reactors: Generation 4 designs, including gas- and salt-cooled concepts Fast Reactors: Generation 4 Reactors Using a Fast-spectrum to Improve Fuel Cycle Management Fuel Cycle: Fuel Development and Back-end Management; Uranium from Seawater; Accident-tolerant Fuels; Minor-Actinide Bearing Fuel; Thorium Cycles; Storage/disposal and Associated Issues, including Sensors, Electronics, etc.
Nuclear-Renewable Hybrids	Nuclear-Renewable Hybrids Nuclear Electricity-Fuel Cycles (e.g. Hydrogen)
Geothermal Power	Resource Characterization: Undiscovered Hydrothermal; High Temperature Sedimentary Basins; Enhanced Geothermal Systems (EGS); Geothermal Characterization Tools Well-field Development Advanced Drilling Technology High Temperature Tools and Sensors Stimulation Technologies and Zonal Isolation CO_2 Downhole Cycles Advanced Power Cycles, such as Supercritical CO_2
BioPower-CCS	Biopower Advanced Cycles such as IGCC with Hot Gas Clean-up for Lowest Cost, Highest Performance, and Integration with CCS Biomass Feedstock Technologies Biomass Collection and Transport Technologies Waste to Energy (heat and power) for Solid, Liquid Wastes
Concentrating Solar Power	Tower Systems: Central Receiver Design for High Temperature (T); Thermal Storage for High T Trough Systems Solar Field Cost Reduction Advanced Power Cycles for Towers, such Supercritical-CO_2, Combined Cycles, etc.
Supercritical CO2	Supercritical CO_2 Brayton Cycle for Nuclear, Fossil, Geothermal, CSP Materials: Alloy characterization; Thermal Barriers; Coatings; Ceramics Component Testing and Development; Sensors; Systems Project Development and Engineering
Combined Heat and Power and Fuel Cells Distributed Generation **Tri-generation (power, heat, hydrogen)**	Combined Heat/Power Microturbines Fuel Cells for Distributed Generation, including Solid Oxide and Proton Exchange Membrane Systems
Solar Photovoltaic Power	Solar Photovoltaic (PV) Devices, High-Efficiency Low-Cost PV, etc. Balance of System (BOS) R&D Building Integrated PV in Architecturally Desirable Forms
Water/MHK Power	Water Power Marine and Hydrokinetic (MHK) Variable Speed Technologies
Wind Power	High Performance Computational Modeling from the Planetary Boundary Layer Down to Individual Turbine Components. Onshore Wind Technology: Direct Drive Systems, Power Electronics, Low-Mass High-Flex Blade Systems, Large Field-delivered Blades Off Shore Wind Technology: Direct Drive; Floating Platform
Power Electronics	Wide Band-Gap Semiconductors Circuit Topologies for Long Lifetime at High Performance
Energy-Water Technologies in grid applications	Advanced Cooling Technologies: Hybrid Wet-dry Cooling; Indirect Dry-Cooling; Steam Condensing Systems; Heat-Pipe Systems Water Clean-up Technologies for Power Applications
Hybrid Systems	Hybrid System Designs, such as Geo-CSP, NE-RE (above)

Increasing Efficiency of Buildings Systems and Technologies. Seventy-three percent of electric sales are directed to the buildings sector (see Figure 2-6b). About 25% of building energy now goes to “other uses”, a diverse collection of products including elevators, escalators, laboratory and medical equipment, pumps, and much more.[56] The extraordinary diversity of products complicates approaches to efficiency improvements but it also invites novel and cross-cutting solutions relying on enhanced sensors and controls, software to facilitate power management, and more efficient electronics.

In buildings, a large fraction of energy is dedicated to providing low-temperature heat (27% for space and water heating, see Figure 2-3b). Opportunities to reduce this thermodynamically wasteful approach include development of high-efficiency heat pumps in addition to improved heat recovery. Beyond the potential innovations in individual technologies, buildings also present opportunities to better manage energy as entire systems. The quantity, quality and form of energy required by, and rejected from various components within and around the building system (including the surrounding environment) are often well-matched but not currently made use of. Sensors, actuators, equipment and small amounts of energy storage could be integrated with accurate, predictive, whole-building, grid-tied energy management systems that substantially reduce energy consumption while maintaining or improving the building energy services delivered. Table 4-3 presents identified opportunities to increase the efficiency of building technologies and systems.

Table 4-3. Opportunities to Increase the Efficiency of Buildings Systems and Technologies.

• **Building Energy Systems** ○ **Building Level** ○ **Building-Grid Integration** ○ **Linkages/tradeoffs Electricity/Gas**	• Building Retrofit Technologies Efficiency, Thermal Storage, Distributed Generation, • Technologies for Building Commissioning • Building Design Tools: Design Strategies and Design Tools; Computational Design, Commissioning, Operation, Retirement, Re-use; Design for Cradle-to-Cradle Materials Use • Design for Environment: Passive Design, etc.
• **Building Technologies**	• Buildings as Integrated Systems; Life Cycle of Building. Adapting Natural Design Elements.
	• Building Shell Technologies: Materials; Walls, Roofing, Especially Materials for Retrofits • Windows; Next Gen Electrochromics • Daylighting
	• Lighting: Solid State Lighting • Advanced Lighting Fixtures, Controls, Integration
	• Heat Pump Technologies • Refrigeration: Refrigerants for Low GWP and NearZero Ozone Impact; High Efficiency Insulants • Motors: High Efficiency Fractional Horsepower (hp) Motors and Small hp Motors, Adjustable Speed Drives
	• Solar Systems: Active and Passive Solar Thermal Systems for Space Heating/Cooling • Solar Thermal Systems for Water Heating, Pool Heating • Thermal Storage Materials, Phase Change Materials, Chemicals
	• Building/Grid Integration Technologies • Sensors and Controls—Technologies and also Demand Side Management (DSM), etc. • Electronics, including Grid-friendly Electronic Services Integrated into Appliances, Equipment • Building Distributed Power Integration, including Variable Sources such as Rooftop PV, Dispatchable Sources such as Gas-microturbine CHP and Fuel Cells (Solid Oxide, PEM, etc.), Controlled Charging of PHEVs/EVs, Distributed Storage, Demand Response, Smart Grid Systems, Efficiency, and Others; Transactive Controls
	• Appliances and Plug Loads: Appliances not Covered above, as well as other Plug Loads
	• Data Centers
• **Energy and Water in Buildings**	• Water Efficiency and Tradeoffs • Water Cleanup; Net Zero Water Buildings; Water Microsystems; Water Storage
• **Enabling Science**	• Computational Design • Advanced Materials, Materials by Design

Increasing Efficiency and Effectiveness of Industry and Manufacturing. The industrial sector currently consumes about 31 Quads of primary energy. Sixty percent of the energy supply to the industrial sector is directly provided by fossil resources (not including the fossil fuel contribution of the electricity purchased) and 34% of the energy supplied to the industrial sector is purchased electricity (including electricity losses). Opportunities for efficiency improvement include the development of new processes or technologies that require less energy to perform the same service, the use of high-efficiency motor drive systems, improved steam and other thermal systems, combined heat and power, and others. The industry and manufacturing sector can also play a key role in producing clean energy technologies at high quality and low cost. Table 4-4 identifies some of the opportunities for efficiency and effectiveness improvements in industry and manufacturing.

Table 4-4. Opportunities to Increase Efficiency and Effectiveness of Industry and Manufacturing.

• **Industrial Systems**	• Traditional Industrial Energy Savings Approaches • Waste-Heat Recovery Systems • Efficient Processes for High Energy Demand Sectors, and Alternative Materials (cement, steel) • Industrial System Integration—Distributed Energy Technologies, Motor Drive Systems, etc. • Efficient Thermal Energy Systems—High/Med/Low Temperature; Integration with Distributed Renewable, Nuclear, or Fossil-Carbon Capture Utilization Storage (CCUS) Systems • Materials Flows through Industry: Cradle-to-cradle Materials Flow; Design for Re-use • Computational Manufacturing Design, Operations • Critical Materials for Clean Energy • Manufacturing Clean Energy Products with Large Systems Implications • Low Carbon, Domestic Energy Fuels and Feedstocks • Manufacturing Next Gen Energy Conversion Technologies e.g., Natural Gas to Chemicals • Manufacturing Next Gen Infrastructural Products & Clean Energy Technologies • CCUS in Heavy Industry • Industry-Grid Integration through Distributed Industry-level Generation—Combined Heat and Power (CHP), Photovoltaics (PV), Demand Side Management (DSM); others • Industry Water-energy Systems; Water Cleanup; Integration • Industry Gas and Electric System Integration and tradeoffs: PV, Gas-microturbine CHP and Fuel Cells (Solid Oxide, PEM, etc.); Controlled Charging of Distributed Storage; Demand Response; Smart Grid Systems; efficiency; and Transactive Controls
• **Industry Technologies**	• Chemicals; Petroleum Refining; Iron & Steel; Pulp & Paper; others • Wide Band Gap Semiconductors, Power Electronics, Motor Drive; System Design • Additive Manufacturing; Digital Manufacturing • High Efficiency Separations Technologies (chemicals, refining, water) • Alternative Materials Development; Advanced Materials by Design • Industrial Process Heat: High/Med/Low Temp.; Electrothermal; Solar and other Renewables • Waste Heat Recovery Technologies; CHP/FC; ThermoElectric Generators (TEG); Thermo-Photovoltaics (TPV); etc. • Renewable Feedstocks and Bioproducts • Process Intensification • Water/Energy: Waste Water Delivery/Treatment Systems; Desalinization Technologies
• **Manufacturing technology**	• Metrology for Real-Time Process Control • Computational Manufacturing

Advancing Clean Transportation and Vehicle Systems and Technologies. The vast majority of the transportation sector's energy consumption is petroleum products (97%, Figure 2-5a). The primary energy users are light-duty passenger vehicles and heavy freight trucks, followed by aircraft, which together are responsible for 86% of the transportation sector's energy use (Figure 2-5b). Opportunities remain to improve vehicle efficiency and fuel economy and reduce oil consumption through advancements in internal combustion engines, light-weighting of vehicles, the use of alternative fuels, the electrification of the fleet, and other measures. R&D opportunities are presented in Table 4-5.

Table 4-5. Opportunities to Advance Clean Transportation and Vehicle Systems and Technologies.

• **Transportation Systems**	• Technologies for Interactions with Home and Business Infrastructure • Transportation Automation and Implications—VMT, Road Use, Parking Requirements, Vehicle and other Capital Stock • Automaker Innovation, Stock Turnover and the Pathways for Change • Fossil-CCS with Intermediate Energy Carriers to Fuel Vehicles: Electricity; Hydrogen; Bio Fuels; Others • Electric Vehicle Systems/Infrastructure Issues and R&D: Range, Performance, Integrated Design; Recharging and Requirements (especially fast charging on distribution networks), Dynamic Charging (wireless, contact, PV) • Hydrogen Fuel Cell Vehicle (HFCV) Systems/Infrastructure and R&D
• **Technologies** ○ **LDVs** ○ **HDVs** ○ **Off-Road** ○ **Aircraft**	• Transportation Fuels and Fuel Diversity: Flex Fuel; Renewable Super-premium; Natural Gas (NG) Engines/Storage, Ethanol 85% (E85); Electricity; H_2 Refueling Operations & Maintenance • Efficiency: Engine efficiency—Advanced Combustion Systems; Waste Heat Recovery • Lightweighting—Carbon Fiber/Magnesium/Titanium/others • Aerodynamics (e.g. HDVs)
	• Electrification: System Issues of Range, Performance, Integrated Design; Electronic Drive Train • Batter Performance; Battery Management and Protection • Power Electronics; Low-cost Wide Bandgap Technology • Motors; Advanced Materials for Motors
	• HFCVs: Fuel cells; Durability • Catalyst Reduction and Non-precious Metal Catalysts • Alkaline Anion Exchange Membrane Fuel Cells • H_2 Storage; H_2 Fuel Supply/Infrastructure
	• Heavy Duty Vehicles: Truck efficiency; NG in Trucks • Compressed Natural Gas (CNG)/Liquefied Natural Gas (LNG) Standards, Codes, Regulations for Operations and Maintenance • Zero-Emission Heavy Duty (short and long haul)
	• Off-road: Mining; Agriculture; Construction
	• Aircraft: Fuel Design for Aircraft • APU and Zero Emission Airport Operation
	• Other Modes / High-speed Rail / Low Emission Rail Transport
• **Enabling Science**	• Science – Combustion Modeling; Basic Materials R&D; Aerodynamics; Power Electronics; Insulators; Magnetics; Hydrogen Storage Materials and Interactions; Catalysts

Enabling Capabilities for Science and Energy. The DOE Office of Science is the lead Federal agency supporting fundamental scientific research for energy and the Nation's largest supporter of basic research in the physical sciences. The Office of Science portfolio has two primary components. The first supports basic science research across the diverse collection of energy-relevant fields, including biology, catalysis, chemistry, combustion, plasma science, materials, and mathematics. The second supports the suite of open-access scientific user facilities. These facilities—including supercomputers, high-intensity x-ray light sources, neutron scattering sources, and facilities for nanoscience, genomic sequencing, microbiology, and atmospheric monitoring—are among the most advanced tools of modern science, enabling researchers to explore a host of new scientific frontiers. While these facilities have been developed in support of discovery science, they continue to provide a unique value to applied RD^3, for both public and private sector participants. Table 4-6 provides a list of the facilities currently supported by the Office of Science.

Table 4-6. Office of Science User Facilities.

• **Analysis, Modeling, Simulation, and Prediction of Complex Phenomena**	• Advanced Scientific Computing Research • Argonne Leadership Computing Facility (ALCF) • Energy Sciences Network (ESnet) • Oak Ridge National Laboratory Leadership Computing Facility (OLCF) • National Energy Research Scientific Computing (NERSC) Center
• **Understanding and Controlling Matter at the Atomic and Molecular Scale**	• Basic Energy Science (Including Next Generation Technologies to be developed for) • X-ray Light Sources • National Synchrotron Light Source (NSLS), NSLS-II • Stanford Synchrotron Radiation Lightsource (SSRL) • Advanced Light Source (ALS) • Advanced Photon Source (APS) • Linac Coherent Light Source (LCLS) • Neutron Sources • Spallation Neutron Source (SNS) • High Flux Isotope Reactor (HFIR) • Nanoscience Centers (includes Electron Microscopy Facilities) • Center for Nanophase Materials Sciences (CNMS) • Molecular Foundry • Center for Integrated Nanotechnologies (CINT) • Center for Functional Nanomaterials (CFN) • Center for Nanoscale Materials (CNM) • Biological and Environmental Research • William R. Wiley Environmental Molecular Sciences Laboratory (EMSL) • Joint Genome Institute (JGI) • Atmospheric Radiation Measurement Climate Research Facility
• **Long Range Science and Technology Issues**	• Climate Modeling • Integrated Assessment Modeling • Fusion

Other Cross-cutting Analysis Capabilities. Other cross-cutting analysis capabilities include further development of system integration and complex system modeling, life cycle assessments, and energy return on investment. Improving understanding of the science of how decisions are made, and overall portfolio analysis capabilities to determine the best mix of investments in R&D are also critical. Further R&D in all these areas is needed.

Table 4-7: Other Cross-cutting Analysis Capabilities

• **Systems' Science**	• System Integration Modeling • Complex System Modeling
• **Integrated Analysis**	• Life Cycle Assessments • Energy Return on Investment
• **Decision Science and Behavioral R&D**	• Human Factors in Decision and Behavioral Science
• **Portfolio Analysis**	• Portfolio Analysis

Institutional Challenges. The QTR addresses technologies, not policies; the QER will address policies.

5. Key Questions

The goal of the QTR-2015 is to identify important RD^3 activities, opportunities, and pathways forward to help address our nation's energy-linked challenges. A brief summary of some of these opportunities was provided above for the energy supply and end use sectors. This leads to the following questions for which this request for information is seeking input:

- What energy-related mega-trends (domestic oil/gas supplies, renewable integration, increasing use of digital communications and control, reliability and resiliency requirements, environmental controls, demand growth in the developing world, etc.) will significantly impact the energy sector and the technology RD^3 agenda over the next 5-10 years, but are not currently receiving sufficient recognition?
- What are the big energy science and technology RD^3 opportunities that can help address our economic, environmental, and security challenges? What is missing from the current Tables (4-1 to 4-7) above? What are appropriate metrics to measure the potential impacts of these RD^3 activities, and what are their potential impacts?
- How can we identify, quantify, and address the risks and opportunities related to more interconnected, interdependent, and integrated energy systems?
- What basic science and research capabilities (e.g. computation, modeling, materials, user facilities, instrumentation) are most important to energy technology advancements? What opportunities are there to better integrate Science and Energy programs? What are the potential synergies across energy science and technology RD^3 activities?
- What data and analysis capabilities are needed to inform systems and technology understanding and promote sound RD^3 portfolio decision-making? What overall and specific balance across the spectrum of RD^3 activities should DOE set for its investments and why?
- What are the most effective means for technology transfer and how might these be used by DOE?
- What RD^3 should DOE support to help U.S. production be competitive in global clean energy markets?
- What RD^3 management practices of DOE programs should be replicated or avoided? What RD^3 management mechanisms have been most successful in the private sector and should be considered in the public sector? How can RD^3 activities be accelerated?
- What other key RD^3 questions and issues (not policy-related) should the QTR address?

DOE seeks input on these questions by February 21, 2015. Instructions on submitting comments can be found at http://energy.gov/qtr.

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[1] The QTR-2011 Framing Document, Report, and Tech Assessments are available at: http://energy.gov/downloads/first-quadrennial-technology-review-qtr-2011

[2] President's Council of Advisors on Science and Technology, "Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Energy Policy", 2010, Executive Office of the President: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf

[3] The QTR-2011 Framing Document is at: http://energy.gov/downloads/first-quadrennial-technology-review-qtr-2011

[4] The QER was established by the President at: http://www.whitehouse.gov/the-press-office/2014/01/09/presidential-memorandum-establishing-quadrennial-energy-review The work of the QER can be found at: http://energy.gov/epsa/initiatives/quadrennial-energy-review-qer

[5] In the future, QER studies will be done on policy issues related to energy supply, end use, and other energy issues.

[6] "U.S. Department of Energy Strategic Plan 2014-2018", http://energy.gov/downloads/2014-2018-strategic-plan

[7] See, for example: Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012", April 15, 2014, Table ES-2. Fossil Fuel combustion resulted in an estimated 5070 million metric tonnes (MMT) of CO_2 in 2012, Iron and Steel production generated 54 MMT; Non-energy use of Fuels generated 110 MMT, Natural Gas Systems 35 MMT, Cement and Lime production 70 MMT, etc.

[8] http://www.census.gov/popclock/ (comparison of 12/31/1999 to 12/31/2013); https://research.stlouisfed.org/fred2/series/GDPMCA1/downloaddata accessed 8/19/2014

[9] Data are from EIA's Annual Energy Outlook (AEO) 2014 Table A1, Total energy supply, disposition, and price summary, and Table A2, Energy consumption by sector and source (p. A-1 – A-3). Oil and gas liquids include crude oil, petroleum liquids, and natural gas liquids and imports of finished petroleum products, unfinished oils, alcohols, ethers, and other blending components. Biomass liquids include ethanol and biodiesel and were determined as a percent of petroleum and other liquids supply from Table A11 of EIA AEO 2014. Natural gas includes liquefied natural gas that is imported and re-exported. Nuclear values represent energy obtained from uranium when used in light water reactors. Biomass liquids include ethanol and biodiesel and were determined as a percent of petroleum and other liquids supply from Table A11 of EIA AEO 2014. Biomass includes grid-connected electricity from wood and wood waste, non-electric energy from wood, and biofuels heat and coproducts used in the production of liquid fuels, but excludes the energy content of the liquid fuels. Other renewable energy includes grid-connected electricity from landfill gas, biogenic municipal waste, photovoltaic and solar thermal sources, and non-electric energy from renewable sources such as active and passive solar systems.

[10] http://www.eia.gov/todayinenergy/detail.cfm?id=10

[11] Data from AER Table 1.1 http://www.eia.gov/beta/MER/index.cfm?tbl=T01.01#/?f=A&start=1949&end=2013&charted=4-6-14

[12] This may not include all the privately generated biopower used onsite or exported to the grid.

[13] Data are from Tables A4 and A5 of EIA's Annual Energy Outlook 2014 (p. A-9 – A-12).

[14] Marketed renewables includes wood used for primary and secondary heating in wood stoves or fireplaces for residential buildings and biomass for commercial buildings. It does not include nonmarketed renewables such as geothermal heat pumps, solar hot water heating, solar photovoltaic, or wind.

[15] Other fuels include propane, kerosene, residual fuel oil, coal, and motor gasoline.

[16] Appliances include clothes dryers, clothes washers, freezers, and dishwashers.

[17] Electronics include televisions and related equipment, specifically set-top boxes, home theater systems, DVD players, and video game consoles; computers and related equipment, specifically desktop and laptop computers, monitors, and networking equipment; office equipment (PC); and office equipment (non-PC).

[18] Other uses includes electric devices, heating elements, appliances such as outdoor grills, exterior lights, pool heaters, spa heaters, backup electricity generators, and motors not listed in residential buildings; transformers; medical imaging and other medical equipment; elevators; escalators; off-road electric vehicles; laboratory fume hoods; coffee brewers; water services; pumps; emergency generators; laundry equipment, combined heat and power, and manufacturing performed in commercial buildings; and cooking (distillate) plus residual fuel oil, propane, coal, motor gasoline, kerosene, and marketed renewable fuels (biomass).

[19] 2012 data are from Table A6 of EIA's Annual Energy Outlook 2014. 2010 data are from Table 1.1 of EIA's 2010 Manufacturing Energy Consumption Survey Data (http://www.eia.gov/consumption/manufacturing/data/2010/#r1).

[20] Petroleum and other liquids includes ethane, natural gasoline, refinery olefins, lubricants, miscellaneous petroleum products, motor gasoline, distillate fuel oil, residual fuel oil, petrochemical feedstocks, petroleum coke, asphalt and road oil, and still gas.

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[21] Natural gas total includes natural gas used in heat and power; feedstocks; natural-gas-to-liquids heat and power; well, field, and lease operations, in natural gas processing plant machinery; and for liquefaction in export facilities.
[22] Coal includes metallurgical coal and coke, other industrial coal, and coal-to-liquids heat and power.
[23] Municipal waste includes municipal waste, landfill gas, and municipal sewage sludge. A portion of the municipal waste stream contains petroleum-derived plastics and other non-renewable sources.
[24] Sector data is from 2010 Manufacturing Energy Consumption Survey. The sector percentage for 2010 and 2012 was assumed to be the same and has been adjusted to reflect 2012 total industry energy consumption. Electricity related losses are reported for 2012 and are allocated across sectors according to percent of total sector fuel consumption.
[25] Other sectors include fabricated metal products; transportation equipment; plastics and rubber products; machinery; computer and electronic products; textile mills; electrical equipment, appliances, and components; pharmaceuticals and medicines; beverage and tobacco products; printing and related support; furniture and related products; textile product mills; apparel; and leather and allied products.
[26] Non-manufacturing heat and power and nonfuel use estimates come from Table MT-18 of EIA's AEO 2014. Electricity related losses associated with transmission and distribution are not assumed for either category because the electricity is used on-site.
[27] Transportation sector end use data are from Table A7 of EIA's Annual Energy Outlook 2014 (p. A-16 – A-17). Energy consumption by fuel data are from Table 4-4 of the Bureau of Transportation Statistic's National Transportation Statistics (http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_04.html).
[28] Petroleum products include most nonutility use of fossil fuels to produce electricity and small amounts (about 0.1 quadrillion Btu per year since 1990) of renewable energy in the form of ethanol blended into motor gasoline.
[29] Natural gas is consumed in the operation of pipelines, primarily in compressors, and small amounts consumed as vehicle fuel.
[30] Estimate for biomass liquids determined from total transportation consumption report in 2012 as determined by the Bureau of Transportation Statistics, which states that total transportation consumption is the sum of biomass, natural gas, and petroleum categories.
[31] Electricity includes system losses incurred in the generation, transmission, and distribution of electricity plus plant use and unaccounted for electrical system energy losses.
[32] Commercial light trucks are assumed to be between 8,501 and 10,000 pounds gross vehicle weight rating.
[33] Data are from Table A8 of EIA's Annual Energy Outlook 2014 (p. A-19).
[34] Other fuel includes pumped storage, non-biogenic municipal waste, refinery gas, still gas, batteries, chemicals, hydrogen, pitch, purchased stream, sulfur, and miscellaneous technologies.
[35] Solar includes both solar thermal and solar photovoltaic.
[36] Biomass includes wood, wood waste, municipal waste, landfill gas, and municipal sewage sludge.
[37] Hydropower refers to conventional hydroelectric.
[38] http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0306
[39] http://www.data360.org/dsg.aspx?Data_Set_Group_Id=231
[40] Note that the figure is the cost to end-users. Thus, most of the costs for power plants are included in the cost of electricity to end-users, but the costs of fuel to end-users do not include the costs consumers pay for their vehicles, furnaces, or other such equipment.
[41] https://www.census.gov/foreign-trade/Press-Release/current_press_release/exh9.pdf. Downloaded 8/20/14.
[42] LaCommare, Kristina Hamachi, and Joseph H. Eto, "Cost of Power Interruptions to Electricity Consumers in the United States (U.S.)", Berkeley: LBNL, 2006. Download: PDF (93.38 KB)
[43] Energy Information Administration, Annual Energy Outlook, 2014, http://www.eia.gov/forecasts/aeo/pdf/0383%282014%29.pdf
[44] DOE Strategic Plan: http://energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf and QTR-2011.
[45] http://cleanedge.com/reports/Clean-Energy-Trends-2013
http://cleantechnica.com/2013/03/12/biofuel-wind-and-solar-global-market-values-set-to-double-by-2012/
[46] Thomas Sumner, "No stopping the collapse of West Antarctic Ice Sheet", Science V.344, 16 May 2014, pp.683. Ian Joughin, Benjamin E. Smith, Brooke Medley, "Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica,", Science V.344, 16 May 2014, pp.735-738.

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[47] See, for example: 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 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. Kevin E. Trenberth, et al., "Global warming and changes in drought", Nature Climate Change, V.4, pp.17-22, Jan. 2014

[48] See, for example: http://www.interacademies.net/File.aspx?id=9075 , The Royal Society, "Ocean acidification due to increasing atmospheric carbon dioxide", Policy document 12/05, June 2005; www.royalsoc.ac.uk O. Hoegh-Guldberg, et al., "Coral Reefs Under Rapid Climate Change and Ocean Acidification", Science V.318, 14 Dec. 2007, pp.1737-1742. Robert F. Service, "Rising Acidity Brings an Ocean of Trouble", Science V. 337, pp.146-148, 13 July 2012. 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. K.L. Ricke, J.C. Orr, K. Schneider, K. Caldeira, "Risks to coral reefs from ocean carbonate chemistry changes in recent earth system model projections", Environmental Research Letters, V.8, pp.1-6, 2013. Astrid C. Wittman, Hans-O. Portner, "Sensitivities of extant animal taxa to ocean acidification", Nature Climate Change, V.3, pp.995-1001, November 2013. Kristy J. Kroeker, Fiorenza Micheli, Maria Cristina Gambi, "Ocean acidification causes ecosystem shifts via altered competitive interactions", Nature Climate Change, V.3, pp.156-159, February 2013. 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. Eli Kintisch, "Sea Butterflies Are a Canary for Ocean Acidification", Science, V.344, 9 May 2014, pp.569. N. Bednarsek, R.A. Freely, J.C.P. Reum, B. Peterson, J. Menkel, S.R. Alin, B.Hales, "Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem", Proceedings of the Royal Society B, V.281, N.1785, pp. 2914. K.J.S. Meier, L. Beuafort, S. Heuussner, P. Ziveri, "The role of ocean acidification in Emiliania huxleyi coccolith thinning in the Mediterranean Sea", Biogeosciences, V.11, 2857-2869, 2014.

[49] IPCC: http://www.ipcc.ch/index.htm
National Climate Assessment: http://nca2014.globalchange.gov/

[50] Data are from AEO 2014 Table A18, Energy-related carbon dioxide emissions by sector and source (p. A-35). Industrial sector includes combined heat and power plants that have a non-regulatory status, and small on-site generating systems. Natural gas source includes lease and plant fuel. Petroleum source includes international bunker fuels, both civilian and military, which are excluded from the accounting of carbon dioxide emissions under the United Nations convention. From 1990 to 2012, international bunker fuels accounted for 90 to 126 million metric tons of CO2 annually. Other source includes emissions from geothermal power and nonbiogenic emissions from municipal waste.

[51] There is a large literature on grid vulnerabilities, including: 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.93, N.9, 27 August 2004. Peter Fairley, "The Unruly Power Grid", IEEE Spectrum, August 2004. 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. 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).

[52] DOD, Quadrennial Defense Review, http://www.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf Impact of climate disruption on developing country stability. CNA: https://www.cna.org/reports/accelerating-risks; https://www.cna.org/sites/default/files/MAB_2014.pdf 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.

[53] 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.

[54] 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)

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[55] http://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm

[56] Other uses include: heating elements, exterior lights, pool heaters, spa heaters, and motors not listed in residential buildings; transformers; medical imaging and other medical equipment; elevators; escalators; laboratory fume hoods; coffee brewers; water services; pumps; etc. that are not otherwise captured in EIA data sets.