Energy from Fossil Fuels: Challenges and Opportunities for Technology Innovation

Laura Díaz Anadón

Harvard University

John F. Kennedy School of Government

Science, Technology, and Public Policy program

Energy is critical through its effect on the economic, environmental, and socio-economical dimensions of human well-being. In the United States over 86% of primary energy consumed comes from fossil fuels (with the total number for the world being close to 80%). Fossil fuels are expected to continue to dominate in the decades to come given the capital intensity, longevity, and incumbent advantages of fossil-based energy systems. However, neither the United States nor the world can afford to depend upon an energy system that is so heavily reliant on fossil fuels. This paper discusses in turn: the main energy challenges; the role of technology innovation; the drivers of previous energy transitions; the implications for research; and the U.S. policy needs to incentivize innovation.

Major U.S. Energy Challenges in Numbers

Environmentally, with 86% of total U.S. greenhouse gas emissions (5.7 Gt of CO_2 Eq. in 2011), the energy sector is the largest contributor to what is increasingly recognized as the most intractable and dangerous environmental challenge posed by human activity: global climate change.[1] The largest components of U.S. energy GHG emissions stem from the use of coal for power and of oil for transportation: 38% of the emissions come in the form of CO_2 from the power sector—three quarters of those emissions come from coal; and 30% of the emissions come from the combustion of oil in the transportation sector (EPA, 2013). As shown in Figure 1, coal fuels 46% of the electric sector and oil 93% of the transportation sector. The consequences for human well-being of the GHG emissions

[1] In 2005 the United States contributed one-sixth of global GHG emissions (global GHG data for later years are not available) and in 2012 it contributed one-sixth of energy-related CO_2 emissions). The U.S. energy sector is also a major contributor to climate change globally, accounting for over two-thirds of total greenhouse gas emissions in 2012.

stemming from the fossil-fuel based U.S. energy system are already being felt and at a faster rate than expected.[2]

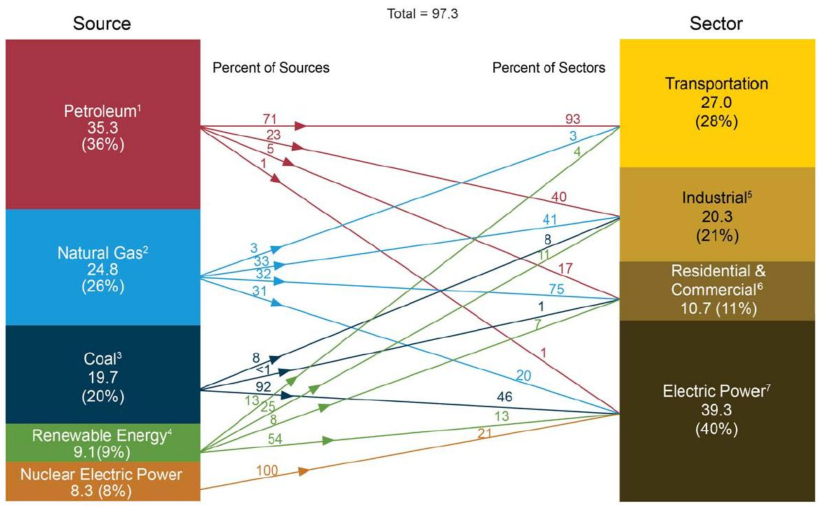

Figure 1: 2011 U.S. Primary energy consumption by source and sector in Quadrillion Btu, Quads (total consumption = 97.3 Quads) (Source: EIA, 2012).

Fossil fuel-based energy systems also emit substantial amounts of other pollutants such as SO_2, NO_x, and particulate matter, which result in large health, ecosystem, and economic damages. A National Academies' study estimated that in 2005 energy-related U.S. health costs were large: $62 billion from coal power, $0.7 billion from gas power, and $56 billion from oil used in transportation (NRC, 2010).

Economically, the fraction of GDP devoted to oil imports has been rising in the U.S., oscillating between 1.5% and 2.5% between 2005 and 2012 (a level that has not been as large since 1983) even though crude oil imports have decreased by 16% since 2005. The high U.S. dependence on foreign oil connects the economic and international security dimensions of the U.S. energy predicament through the U.S. economic vulnerability to oil supply disruptions and price shocks.[3]

[2] The IPCC 2007 report (IPCC, 2007) states that it is more than 50% likely that humans have contributed to more heat waves, floods, droughts, and wildfires; hurricanes and typhoons of greater power; and coastal property increasingly at risk from the surging seas, etc.

[3] The challenge of providing access to modern energy sources to billions of people to enable economic development is another (and perhaps even greater) challenge. An estimated 2.7 billion people still rely on traditional biomass for cooking, and 1.4 billion still have no access to electricity. Limited access to modern sources of energy is an important contributor to poverty levels worldwide, and is a major cause of the 3.5 premature deaths per year from indoor air pollution, but it is not covered in this paper due to its U.S. focus.

The Need for and Complexity of Energy Technology Innovation

Virtually all studies agree that innovation in energy-supply *and* end-use technologies will be necessary to overcome the major energy challenges associated with the U.S. dependence on coal for power and oil for transportation.[4] Partly as a result of the inherent uncertainty and complexity of the technology innovation process, there is more disagreement regarding the specific role that different technologies will play. Innovation starts (but does not end) with invention/discovery (Narayanamurti et al., 2013)—what we engineers refer to as RD&D (research, development and demonstration). To impact society, inventions and discoveries need to progress through other "stages": demonstration, market formation, and widespread deployment. Of course, technologies do not move through these stages in a linear fashion; often stages take place in parallel and there are feedbacks between them. And also the pace and direction of technology innovation is shaped by a multiplicity of actors (governmental, private, non-for-profit, consumers, etc.) and of institutions (norms, policies, culture, etc.). This complexity and the enormous size, ubiquity, interconnectedness, and commodity nature of most of the energy system, make this transition away from fossil fuels difficult. The experience of previous energy transformations offers some insights about what may be required.

History of Energy Transitions

Since the industrial revolution two main energy transitions have taken place. The first was the emergence of steam power from coal between the late 18th century and the 1920s that replaced ovens, boilers, furnaces, horses, and water power, and overcame the limited availability of mechanical power, low energy densities, and lack of ubiquitous and cheap transport systems. The second was the replacement of coal steam by electricity and petroleum-based technologies, which started in the late 19th century and is still taking place (see Figure 2). Stationary steam engines were first introduced to dewater coal mines and then spread (spilled over) to mechanize textile manufacturing facilities and agriculture and also to mobile applications in railways and ships (Grübler, 2012). The diffusion of gasoline engines (e.g.,

[4] In the electricity sector different studies see more prominent roles for nuclear power, fossil power with carbon capture and storage, renewable electricity, and increased end-use efficiency. In the transportation sector, vehicle electrification, different types of biofuels, compressed natural gas, and increased efficiency could all contribute to reducing oil consumption. Some of these technologies can work as complements, while others work as substitutes

automobiles) and electric appliances (e.g., lightbulbs) was the driving force behind the second transition. It took about100 years for steam engines and electric drives to reach 50% of market penetration. [5]

In both cases, the transition was not driven by either resource scarcity or lower prices, but rather, it was driven by the existence of *niche* end-use markets that were willing to pay a premium for performance that drove the initial (and crucial) technology improvements. These markets drove costs down through economies of scale, standardization, and learning-by-doing, and provided time for complementary technologies to emerge and for parallel RD&D to be conducted to further improve the technologies. Thus, the historical transitions suggest that a single technology cannot transform the energy system. Transformations often require the formation of technology clusters (end-use technologies, distribution systems, etc.) and new applications of the original technology, both of which take time. Conversely, existing technology clusters and organizations supporting the *status quo* create a path-dependency (Arthur, 1989), meaning that there is a lack of the institutional (e.g., regulatory, social) and physical infrastructures needed to enable the deployment of new technologies.

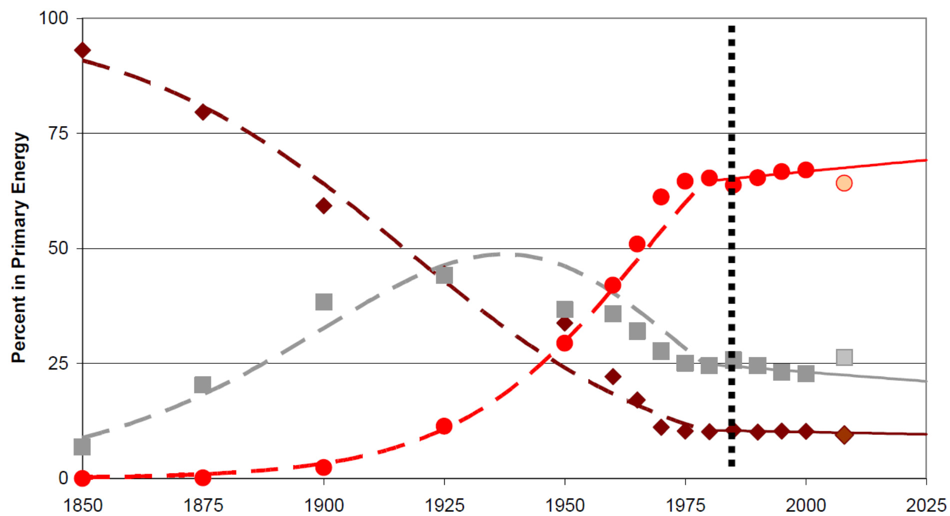

Figure 2: Two grand transitions in global energy systems measuring market shares in total primary energy use. Lines show traditional fuels (brown), coal (grey) and modern energy carriers (oil, gas, nuclear, and modern renewable, red). The market dynamics are approximated by a set of coupled logistic equations over the 1850 to 1975 period (dashed lines) (Source: Grübler, 2012).

[5] Steam engines largely displaced wind and water power. Technology improves during the diffusion process. For example, it took about 100 years for steam engine efficiency to increase from 1% to 20% and almost another century to increase from 20% to 40%.

Unlike in the previous transitions, most of the technologies with the potential to significantly displace coal in the power sector and/or oil in the transportation sector are not currently expected to offer significant comparative advantages in terms of services provided to consumers (with the exception of the environmental externalities that are still not priced in the United States). They are also not expected to offer reduced costs in the short-term. The commodification of energy, the path-dependency of large systems, the fact that the early versions of "hardware" energy technologies are usually risky and expensive, and the fact that the energy system is large, capital intensive, and long-lived, suggest that, if niche markets (e.g., using biofuels or biofuel co-products for the high-value chemicals sector, or CO_2 or other waste products as input to biofuels or other chemical synthesis, etc.) are insufficient to drive down costs quickly enough, government policies to encourage experimentation, scale-up, and learning may be required in the order of decades to enable this transition.[6] The cases of the sugarcane ethanol program started in 1975 in Brazil and the shale gas program in the United States are both illustrative. Without judging whether or not the Brazilian government's plan was cost-effective, its continuity and comprehensiveness (addressing yields, refineries, and vehicles—end-use technologies) contributed to ethanol becoming cost-competitive with gasoline in 27 years, replacing 40% of all the gasoline that would be consumed in Brazil.[7] It took shale gas production in the United States a similar amount of time, with stable R&D funding from the Gas Research Institute (an industry-government partnership) for 24 years, a tax credit for 12 years (MIT, 2011), and the persistence of a visionary entrepreneur, George Mitchell.[8]

[6] While some policies creating markets for some of these technologies are in place today—e.g., federal production tax credits for wind, investment tax credits for solar, a renewable fuel standard for biofuels, vehicle fuel economy standards, loan guarantees for nuclear power, and renewable portfolio standards in 29 states—both their cost-effectiveness and their ability to serve as a guide for long-term investments by firms have been questioned by many studies.

[7] Ethanol from sugar cane was already produced at small scales before WWI to stabilize sugar prices and later on to address oil scarcity during both World Wars, but 1975 marks the year of the start of the continued government push to develop the sugarcane ethanol industry. A recent study estimated the direct costs of the program between 1975 and 2000 to be $42.5 billion in 2013$in (Meyer et al., 2012), and the benefits in terms of foregone oil imports evaluated at international prices between 1975 and 2002 at $64.9 billion (Goldemberg et al., 2004) (note that these are just the two most prominent benefits and costs).The program is also using 2.9 million hectares of land, about 29,000 km^2 which is similar to the surface area of the state of Massachusetts. The complementary end-use technology—flex-fuel vehicles (FFV) capable of running on gasoline or on a blend of up to 85% ethanol—now dominate the automobile market, with 81% of light-duty vehicles in 2008.

[8] In the case of shale gas, the changes to the physical infrastructure required and end-use technologies were less significant.

Implications for Research

It is important to consider that different technology pathways pose different challenges from a commercialization perspective. To take biofuels as an example, even though there are commercial biofuels available today,[9] their further expansion is not desirable due to the competition with food, limited environmental benefits, and their true cost given subsidies. Alternative processes are at different stages of development and rely on different types of cellulosic biomass, waste, and algae (Figure 3 shows major biofuel production routes). However, none of these new processes are demonstrated at scale, partly as a result of high costs and the uncertainties surrounding existing regulations and physical infrastructure. Developing biofuels that can more easily fit in with this infrastructure—the so called drop-in fuels—should be an important factor driving research without undermining the research on alternatives that would require significant infrastructure changes but with the potential in the longer-run to result in very significant cost reductions. This research should be underpinned by an analysis of the materials and energy embedded in that process to focus on areas with the potential to be cost-competitive in the long term. The materiality of the possible impact of different pathways is also contingent upon crucial improvements in crop productivity and waste availability to reduce feedstock costs, expand the supply, and minimize other impacts, making this a particularly important research area.

[9] Biofuels in the United States and abroad are largely produced from food crops. In 2012, 211 U.S. ethanol plants produced 13.3 billion gallons of ethanol from corn through hydrolysis and fermentation and sold it mainly as E10 (gasoline with 10% of ethanol in volume) to meet the requirements of the Renewable Fuel Standard. Also in 2012, 114 U.S. biodiesel plants produced almost 1 billion gallons of biodiesel, mainly from the transesterification of soybean oil, and sold mainly as B20 (diesel with 20% volume of biodiesel).

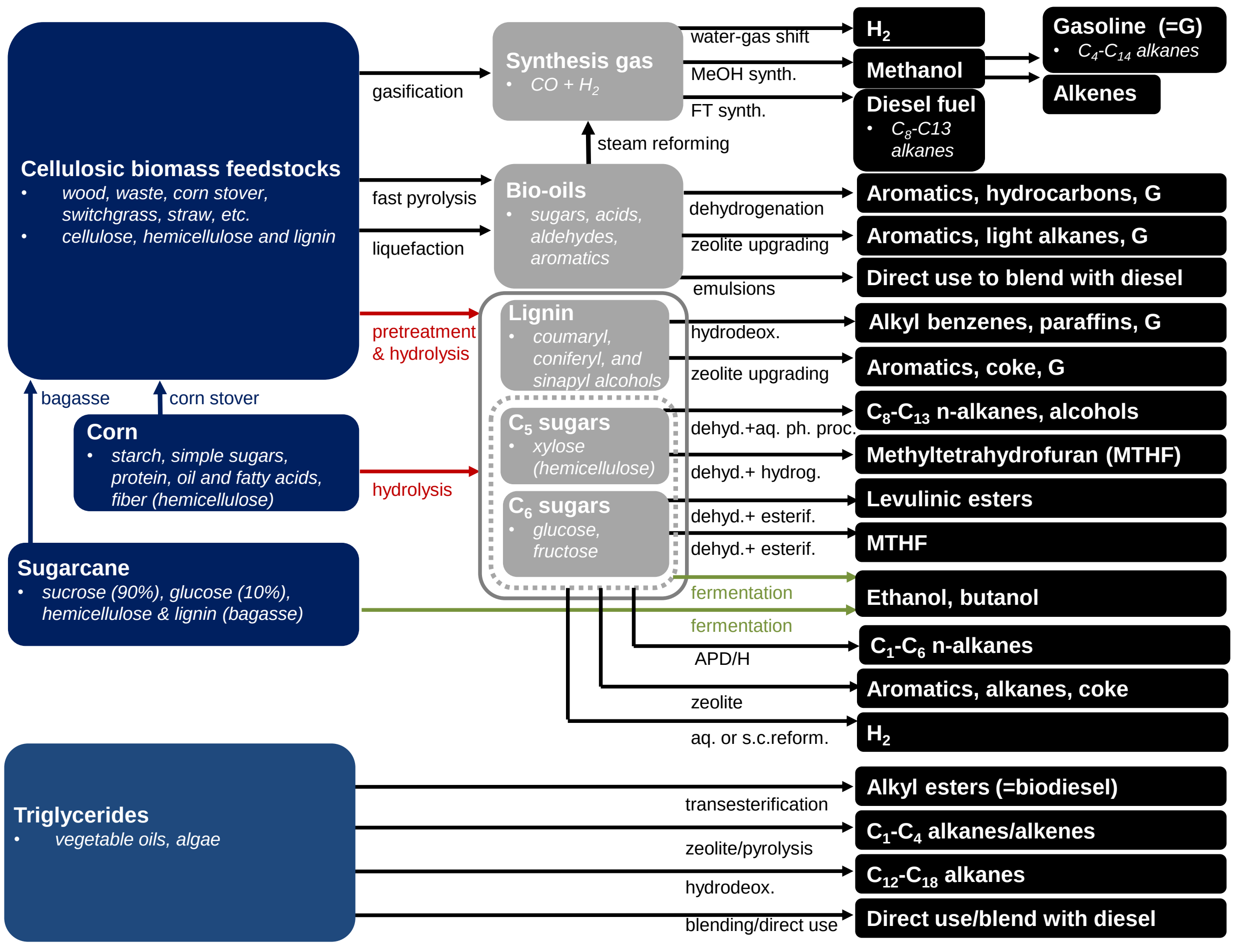

Figure 3: Routes to making different types of biofuels from different feedstocks (slightly adapted from Huber et al., 2006 and NSF, 2008). Arrows: black for chemical conversions, green for biological conversions, and red for both.

Policy Needs

Although there is growing government focus of support for energy RD&D (Anadon, 2012), research shows that even greater support for RD&D in these technology areas is necessary (Chan & Anadon, 2013). Research in solar power, biofuels, and utility scale energy-storage may result in the greatest returns on investment in terms of economic impact with a 2030 timeframe.[10] Previous experience also suggests that this RD&D needs a stable, long-term, and diverse set of research institutions working in close collaboration with industry (Anadon, Bunn & Narayanamurti, forthcoming in 2014). However, even if the U.S. government increased its federal RD&D investments in a wide range of technologies from about

[10] This research did not include all possible technologies, but instead covered 25 different technologies spanning solar photovoltaics, nuclear, bioenergy, carbon capture and storage, various vehicle technologies, and utility scale energy storage and focused on incorporating the uncertainty surrounding technical change.

\$2 billion a year to \$80 billion a year between 2010 and 2030, CO_2 emissions from the energy sector are likely to still be far away from CO_2 emissions targets consistent with the IPCC (about 1-2 Gt/year) (Figure 4). Additional demand-side policies are very likely to be necessary to catalyze the transition from a modeling and historical perspective. A sufficiently high price on carbon (either through a tax or a cap-and-trade) is likely to result in the most efficient outcome, particularly since there is uncertainty about the options that will be most successful (Anadon, Bunn & Narayanamurti, forthcoming in 2014).[11]

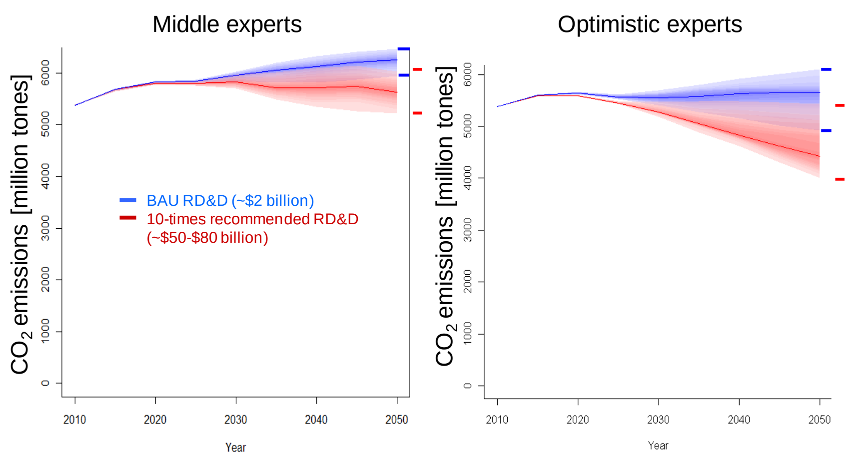

Figure 4: U.S. energy-related CO_2 emissions under business-as-usual federal energy RD&D investment with no additional demand-side policies (blue) and 10–times the experts' average recommended federal energy RD&D investments (somewhere between \$49 and \$82 billion per year) (red), with no additional demand-side policies, using middle-of-the-road and optimistic experts' technology cost projections (Anadon et al., 2011).

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[11] The aggressiveness and existence of waivers in the Renewable Fuel Standard reduce its ability to promote innovation and fail to encourage fuel efficiency, something that can be achieved by fuel or carbon taxes.

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