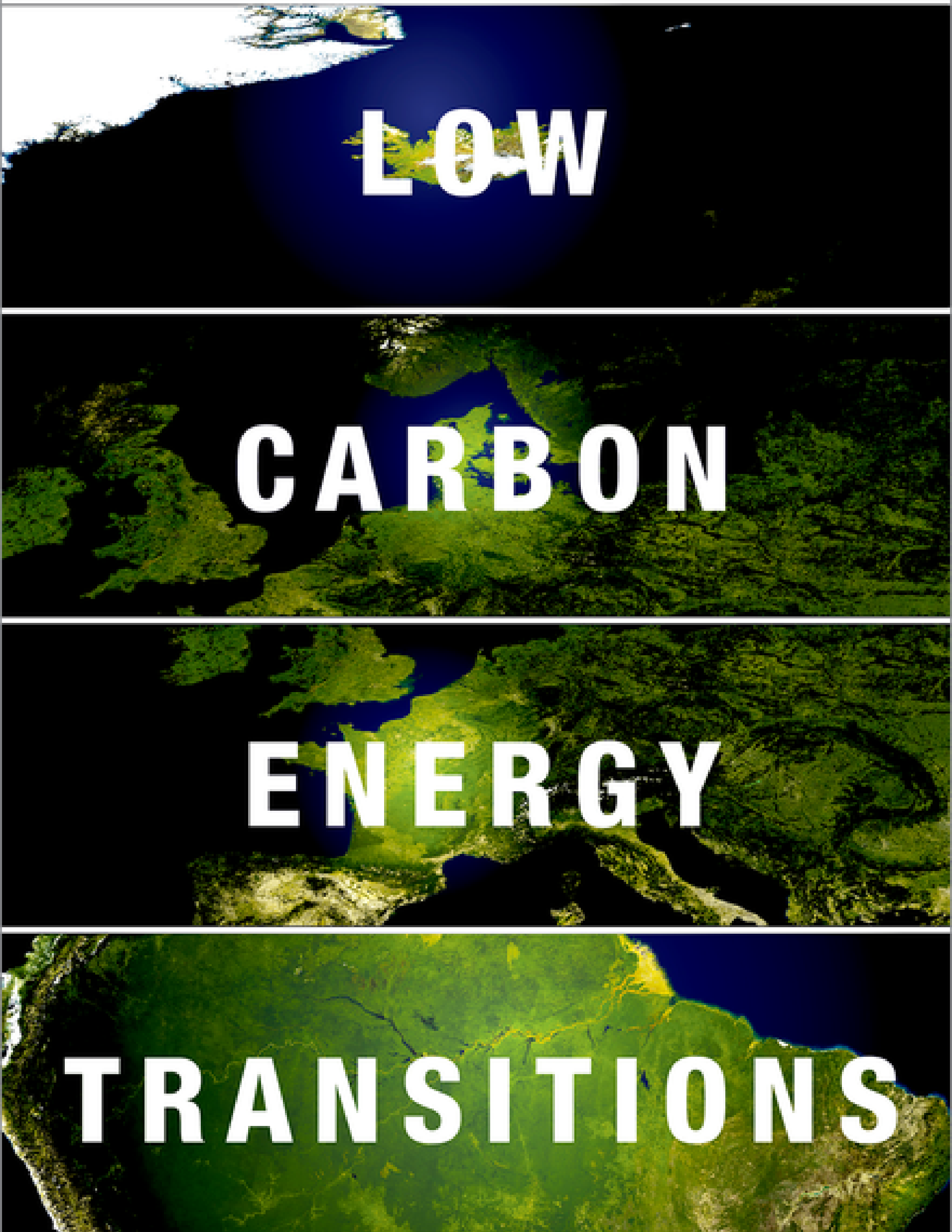
Turning Points in National Policy and Innovation



LOW CARBON ENERGY TRANSITIONS

KATHLEEN M. ARAÚJO

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INTRODUCTION

> If we don't change direction soon, we'll end up where we're heading . . . .
>
> —Chinese proverb cited by the International Energy Agency, *2011a*

The world at large is wrestling with important energy choices. There is a strong sense today that we need to manage energy differently. Priorities in resilience, security, jobs, and access emphasize a need to substitute low carbon energy for traditional fossil fuels. Nevertheless, no one is entirely clear about how to carry out such a shift at the national or international levels. A widely-held view is that national energy transitions of any significance take several decades, if not longer, and entail least-cost economics as a principal driver. Based on this line of thinking, only energy sources that are low-cost have a chance to take hold. Although this appears reasonable, it can miss opportunities for wider gains. Some say that change will require an acceleration of innovation. Yet what assures innovation is also not entirely certain.

A century ago, a person observing the energy playing field would have found substantially less fossil fuels being used and a limited niche industry in electricity. At that time, biomass and coal supplied the majority of the global energy mix, with technologies like automobiles, gas turbines, and airplanes still emerging.

Today, more than 85% of the world's energy is derived from fossil fuels (BP, 2017). The environment is also showing signs of stress as air quality reaches dangerous levels in some regions (particularly those with heavy coal use) and change in the climate redraws our maps and ecosystems. Security of the energy supply is also brought into question, particularly when geopolitics flare up or prices spike. As all of this occurs, the world's population continues along a path in which projected growth by mid-century may represent an increase from 7 to

Table I-1. Market Shares of Low Carbon Energy Studied

Country and Low Carbon Energy	1970	2015
• Icelandic geothermal energy in power	Negligible	29%[a]
• Brazilian ethanol in primary automotive fuels	~1%	34%[a]
• Danish wind power in electricity	Negligible	42%
• French nuclear power in electricity	4%	76%
• Icelandic geothermal energy in space heating	43%	~90%

[a] Reflects data for 2014.

SOURCE: Compiled with data from various sources: Brazil (Ministry of Mines and Energy/MME, 2016); Denmark (Energinet, n.d.); France (IEA, n.d.); Icelandic power and space heating (Orkustofnun, 2016; Ragnarsson, 2015).

9 billion inhabitants. Importantly, regions where growth is expected to be the highest are also ones where energy access is currently challenged.

Low carbon priorities now regularly feature in public discussions.[1] One need only look at calls for decarbonizing change made by the United Nations, World Bank, and World Economic Forum. In line with such priorities, this book considers low carbon energy transitions in prime mover countries. For the purposes here, *transitions* reflect the displacement of at least 15% of traditional energy sources with a low carbon alternative in a given energy mix (relative change), and increased utilization of the same, low carbon alternative in absolute terms by 100% or more. *Prime mover countries* are ones that accomplished this feat. Histories of Brazilian biofuels, Danish wind power, French nuclear power, and Icelandic geothermal energy are examined in depth, here, for the period principally since 1970 (Table I-1).

This book highlights the interplay of technology, natural systems, and society with underlying logic that is rooted in planning and management, policy and applied history, and broader, sociotechnical systems. The research recognizes history as a valuable and often missed tool for decision-making and planning (Neustadt and May, 1986; Schaeffer, 2007; Diamond and Robinson, 2010; Sinclair et al., 2016), and puts forward tools for theoretical and practical scoping of transitions. Models of national readiness will integrate material and human aspects of change in a way that can be applied to structural shifts in energy as well as other sectors, including information or biomedicine. Complementing the models of readiness is a framework based on sectoral intervention that

1. *Low carbon* is used widely to refer to activity that produces much less carbon. The concept is discussed in Chapters 1 and 2.

provides ways to consider induced and emergent change. In doing so, this book emphasizes turning points, while linking theory and practice.

What lies behind national shifts may surprise some. Quick explanations of costs serve a purpose, but the influences behind such costs are much less understood. There is also a tendency to dismiss energy choices as being driven by an abundance of the "right" resources. Such ideas and others are considered, highlighting how government can play a role but not always lead the change. Broadly, this book is designed to challenge how we think about national energy objectives, and how strategies can evolve in energy transitions.

Given the aims and coverage, this book will be of interest to policymakers and practitioners, as well as to students and citizens who think about energy options. For policymakers and practitioners, the book provides ways to consider energy system change and course corrections with perspective from contemporary examples. For members of industry and funding agencies, as well as for think tanks and inter- or nongovernmental organizations, this book provides in depth insight into pivotal junctures that can emerge with energy path realignments. For students and interested citizens who want to better understand energy paths, these histories shed light on theory and better practices in technology diffusion and learning.

Overall, my aim is to show how challenges and opportunities arise in connection with energy, as well as how choices in this regard are made. Chapter 1 provides an overview of the current, energy playing field, outlining the rationale for low carbon change. Chapter 2 examines ideas in theory and practice relating to systems change, innovation, and policy. Chapter 3 outlines new, conceptual tools and the research design. It then turns to relevant developments in the global context and provides a preview of the four countries' transitions. Chapters 4 through 7 provide in depth histories of national energy system change, with a special emphasis on policy and innovations. Chapter 8 comparatively evaluates findings in the context of overarching themes and explores limits for the research. Chapters 8 and 9 then draw inferences for policymakers and scholars. Chapter 9 concludes with promising directions for future research. Those wishing to learn more about specifics of the energy technologies will find a technology primer on geothermal energy, nuclear energy, biofuels, and wind power in the Appendix. Timelines of each country's sociotechnical history are also available there.

1

Rethinking Energy at the Crossroads

> We can't solve problems by using the same kind of thinking we used when we created them.
>
> —Albert Einstein

The discovery of oil in Pennsylvania in 1859 was a relatively inconspicuous precursor to what would become an epic shift into the modern age of energy.[1] At the time, the search for "rock oil" was driven by a perception that lighting fuel was running out. Advances in petrochemical refining and internal combustion engines had yet to occur, and oil was more expensive than coal. In less than 100 years, oil gained worldwide prominence as an energy source and traded commodity.[2]

Along similar lines, electricity in the early 1900s powered less than 10% of the homes in the United States. Yet, in under a half a century, billions of homes around the world were equipped to utilize the refined form of energy. Estimates

1. The term "discovery" of oil or petroleum is used loosely here. Prior to 3000 BC, recorded history indicates that oil was used as asphaltic bitumen in Mesopotamia (Giebelhaus, 2004). Later adaptations included its use in waterproofing of ships and in construction, in addition to applications in medicine, illumination, and incendiary devices. At the time of the Titusville discovery, other developments relating to petroleum were already under way in Azerbaijan and France (Smil, 2010).

2. As of 2015, global primary energy (i.e., the raw supply of energy) totaled 13,276 million tonnes of oil equivalent (Mtoe), with oil representing 33% (BP, 2017). Additional primary energy sources included: coal (28%), natural gas (24%), hydropower (7%), nuclear power (5%), and other renewables (3%) (BP, 2017). Sources of energy are discussed more fully later in the chapter.

indicate that roughly 85% of the world's population had access to electricity in 2014 (World Bank, n.d.*b*). For both petroleum and electricity, significant changes in energy use and associated technologies were closely linked to evolutions in infrastructure, institutions, investment, and practices.

Today, countless decision-makers are focusing on transforming energy systems from fossil fuels to low carbon energy which is widely deemed to be a cleaner, more sustainable form of energy.[3] As of 2016, 176 countries have renewable energy targets in place, compared to 43 in 2005 (Renewable Energy Policy Network for the 21st Century [REN21], 2017). Many jurisdictions are also setting increasingly ambitious targets for 100% renewable energy or electricity (Bloomberg New Energy Finance [BNEF], 2016). In 2015, the G7 and G20 committed to accelerate the provision of access to renewables and efficiency (REN21, 2016). In conjunction with all of the above priorities, clean energy investment surged in 2015 to a new record of $329 billion, despite low, fossil fuel prices. A significant "decoupling" of economic and carbon dioxide (CO_2) growth was also evident, due in part to China's increased use of renewable energy and efforts by member countries of the Organization for Economic Cooperation and Development (OECD) to foster greater use of renewables and efficiency (REN21, 2016).[4] In April 2016, 175 countries signed the Paris Agreement, which aims to slow the growth of greenhouse gases (GHGs), including CO_2, in the atmosphere in order to limit global warming to "well below" a 2°C or 3.6°F increase, relative to pre-industrial levels.[5] Despite an announcement in 2017 that the US would withdraw, the general global focus appears to be in tact.

Importantly, it is not just governments that are currently focused on low carbon change. Traditional energy companies also have carbon-based priorities in energy. Oil and gas companies and power utilities are being asked to include stress tests in their portfolio assessments to reflect carbon or climate impacts (Hulac, 2016). In June 2015, heads of some of the largest European

3. *Energy systems* provide services like heating, cooling, power, and transport. They consist of infrastructure, fuels, people, institutions (including markets), practices, and the ecosystems that enable the provision of such services. *Low carbon* refers to a path that utilizes notably less carbon. This differs from (but can overlap with) renewable energy, which is "any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use" (Moomaw, et al, 2011). For more detailed discussion, see Chapter 2 and Section 1.2.1 of the *Special Report on Renewable Energy Sources and Climate Change Mitigation* (SRREN) (Moomaw et al., 2011).

4. OECD country groupings are based on a classification system that was set up in 1961. Loosely defined, OECD states are industrialized countries and non-OECD states are developing countries. For a discussion of country classifications, see OECD (n.d.), UN (2008, 2014), Nielsen (2011), and Araújo (2014).

5. Greenhouse gases are discussed in the following section.

oil companies published an open letter calling for a carbon pricing system to be instituted worldwide (Geeman, 2015). Ten CEOs of major energy companies also pledged in 2015 to collectively strengthen actions and investments to contribute to the reduction of GHG intensity, including carbon, in the global energy mix (Rascouet and Chmaytelli, 2015; Reed, 2015; World Economic Forum, 2015).

Private-sector banks, such as Citigroup, and the insurance industry are also scrutinizing low carbon pathways. Citigroup analyzed the cost difference of global energy investment pathways by considering the status quo and a path that reduces carbon through less fossil fuel plus greater utilization of renewables and nuclear energy. In doing so, it found “we can afford to act.” Specifically, there are marginal cost differences between the two paths through 2040, if fuller consequences are considered. A low carbon approach could be expected to equal $190.2 trillion, whereas a business-as-usual path would be $192 trillion (Channell et al., 2015). In addition, a path of inaction is associated by 2060 with an estimated $44 trillion in lost gross domestic product (GDP) on an undiscounted basis, not accounting for savings.[6]

RATIONALE FOR LOW CARBON CHANGE

Arguments for low carbon change are often based on rationales ranging from the need for safeguarding the environment and health to price flux and security. The following discusses aspects of these arguments.

Environment and Health

Fossil fuels are known for their links to the degradation of air, water, and land quality through emissions, spills, contamination, and extraction practices. At a global scale, energy (principally from fossil fuels) contributes a reported 68% of total GHGs, the accumulation of which is changing the composition of the atmosphere and the climate system (International Energy Agency [IEA], 2015*a*; see also Box 1-1). Among the GHGs emitted by the energy sector—namely CO_2, nitrous oxide (N_2O), and methane (CH_4)—CO_2 accounts for roughly two-thirds of all GHG emissions (IEA, 2015*b*).[7]

6. For a discussion of costs in energy system change, see Araújo (2016).

7. Life cycle assessments of energy systems also point to CO_2 emissions from cement usage in the construction of power plants.

Box 1-1

Greenhouse Gas Emissions

Greenhouse gas (GHG) emissions are increasingly recognized as primary determinants behind the radiative forcing of the atmosphere that is producing climate change (Intergovernmental Panel on Climate Change [IPCC], 2013, 2014). Atmospheric concentrations of CO_2, a principal indicator of GHGs, have risen from roughly 280 parts per million (ppm) in 1800 to 409 ppm in June 2017 (International Energy Agency [IEA], 2015*a* and 2015*b*; NOAA, 2017.).

Should trends continue, the CO_2 level is expected to rise substantially, producing more extreme weather events and an increase of 2–4°C in the average global surface temperature. A reference point of 450 ppm of CO_2 in the atmosphere is a working guideline for avoiding the more uncertain, and assumed to be the most disruptive, aspects of global warming. Table 1-1 indicates GHG emission intensities for various fuels on a per kilowatt hour (kWh) basis. Here, renewables and nuclear power have the lowest intensities, and fossil fuels have the highest, differing in many cases by multiple orders of magnitude.

Table 1-1. Life Cycle Analysis of Greenhouse Gas Emissions for Select Fuels (gCO_2 equiv per kWh)

Coal	Oil	Gas	Nuclear	Wind	Hydropower	Geothermal	Solar	Biomass
675–1,689	510–1,170	290–930	1–220	2–81	0–43	6–79	5–217	(633)–75

source: Based on a literature review of life cycle analyses for GHG emissions of power generation technologies (Moomaw et al., 2011).

Regionally, fossil fuel emissions can introduce precursors of acid deposition that disperse over thousands of kilometers to damage harvests, natural systems, and anthropogenic structures (Goldemberg, 2006*b*). Oil spills and gas flaring can also lead to the collapse of local fishing and farming, as well as the loss of habitat and biodiversity (Baumuller, Donnelly, Vines, and Weimar, 2011). Moreover, leakage and runoff of pollutants from coal mining or hydraulic fracturing of natural gas or oil can compromise soil and water aquifers (Environmental Protection Agency [EPA], n.d. and 2011*a*; Osbourne, Vengosh, Warner, and Jackson, 2011).[8]

8. The extent to which hydraulic fracturing pollutes water aquifers remains under debate and study (Bambrick, 2012; Macalister, 2011; Massachusetts Institute of Technology, 2011; Stevens, 2010; Urbina, 2011*a*, 2011*b*; Vaidyanathan, 2016; Yost, Stanek, DeWoskin, and Burgoon, 2016).

Specific to public health, an estimated 6.5 million deaths occur each year in connection to air pollution, with the total expected to rise absent change in the energy sector (IEA, 2016*b*). Fossil fuel emissions are singled out for their ties to respiratory disease, rheumatic disorders, cancers, and premature fatalities (Argo, 2001; Baumuller et al., 2011; Goldemberg and Lucon, 2010; United Nations Development Program [UNDP], UN Department of Economic and Social Affairs, World Energy Council [WEC], 2004). Such emissions include particulate matter, sulfur dioxides, nitrogen oxides, volatile organic compounds, carbon monoxide, and carbon dioxide, among pollutants.

In recent years, the ties between fossil fuel use and public health have assumed new importance. In China, for instance, where coal represents about two-thirds of the power mix (Energy Information Administration [EIA], 2015), air pollution episodes now occur regularly. In 2015, during the most severe episode, concentrations of primary pollutants in Beijing reached levels that were nearly 40 times greater than what the World Health Organization considers safe for 24-hour exposure (Finamore, 2016). This issue is leading to a restructuring in the country's energy sector toward less carbon-intensive gas and non-fossil power (Jianxiang, 2016).

A study by the U.S. National Academy of Science estimates that premature deaths linked to air pollution from fossil fuel in the United States equal $120 billion per year in health costs (National Academy of Science, 2010). Of the roughly 20,000 deaths per year cited in the study, the majority was attributed to fossil fuel emissions from power plants and vehicles. If the direct environmental costs of gasoline and diesel fuel were factored at the pump, gasoline and diesel fuel would be priced $0.23–0.38 per gallon higher.[9]

When comparing fossil fuel and renewable energy on a life cycle basis for power generation, the human health effects of renewable energy were found in a study for the United Nations Environment Program to be 10–30% of those from state-of-the-art fossil fuel–based power (UNEP, 2015). Environmental damage by pollutants such as particulate matter and toxic metals was also found to be 3 to 10 times less from renewables compared to fossil fuel systems (UNEP, 2015). In short, environmental and health effects of energy utilization are real and uneven.

9. This does not cover all effects, including those associated with climate change, pollution control devices, or oil combustion specific to travel by rail, sea, and air (National Academy of Science, 2010).

Table 1-2. Mineral Fuel Imports for Select Countries/Regions (2014)

	% National Imports (based on $)	Amount
China	16	$372 B
EU-28	27	$617 B
India	39	$177 B
Japan	32	$262 B
United States	15	$358 B

SOURCE: United Nations Comtrade [UN Comtrade], n.d.

Import Dependence, Wealth Transfer, and Local Economic Development

As a top-traded commodity, fossil fuel introduces dependence vulnerabilities. In 2014, oil, coal, and gas as well as their distillation products equaled roughly $3 trillion or 17% of total imports worldwide (UN Comtrade, n.d.).[10] For countries with considerable shares of these fuels in their overall imports, such as India at 39% or Japan at 32% in 2014 (Table 1-2), this reliance represents transferred wealth from domestic industries and provides points of leverage for exporter nations (Levi, 2010). If fossil fuel importer countries were to switch to locally-sourced renewable energy, the domestic community could benefit from favorable economic payback and innovation around a cleaner economy, in addition to the reduction of uncertainties associated with international trade.

Price Flux

Price fluctuations in fossil fuels present yet another area to watch for energy decision-makers, as links between economic activity and energy price volatility are fairly well recognized. A $10 per barrel increase in the price of oil, for instance, is estimated to slow the global economy by 0.5% per year (UNDP et al., 2004). In the past decade, price uncertainties for fossil fuels have reflected fairly substantial swings, with coal and oil representing a spread of more than a factor of three (Figure 1-1). With this kind of volatility, switching to locally-sourced energy, like renewables, can serve as a hedge against price flux, particularly for people who may not otherwise be able to secure energy at the higher prices.

10. This is based on reporting for mineral fuels in the UN Comtrade HS category, which also contains derivative elements like petroleum jelly and bituminous mixtures based on asphalt and the like (UN Comtrade, n.d.).

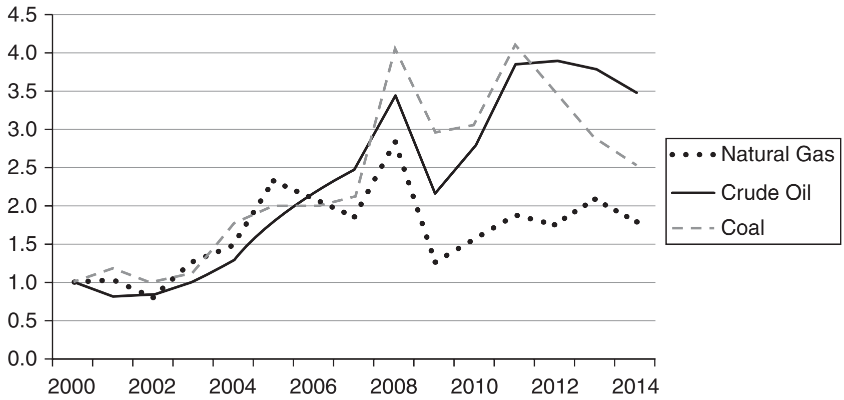

Figure 1-1 Change in fossil fuel prices (Base Year = 2000).
SOURCE: Adapted with data from BP (2015).

Looking strictly at oil, marker crude oil prices for Dubai, West Texas Intermediate (WTI), and North Sea more than doubled from a lower range at $24.04 to $28.60 to a higher range of $60 to $65.10 in the period between April 2015 and April 2016.[11] The currently low, yet dynamic prices are leading to a slowing of investment, with unprecedented cuts in upstream capital expenditure in addition to postponed or cancelled projects (Birol, 2016). For export nations like those in the Middle East, where oil revenues equaled roughly 30% of regional GDP in 2014, heavy reliance on such fuel revenues for public funds produces boom-and-bust cycles. This requires deep cuts in domestic expenditures in times of low prices, especially if special funds are not set aside. This can also trigger political instability, such as a strike in Kuwait to protest government cutbacks (Holodny, 2016). In such circumstances, the strategic use of locally-sourced, low carbon energy could serve as a hedge to minimize economic swings of uncertainty.

Subsidies

For many years, fossil fuels have been in a highly-favored position in terms of subsidies—a form of aid that is used to attain an economic or social goal (Carrington, 2015). In 2015, global subsidies for fossil fuel consumption were estimated at $325 billion, compared to that for renewables at $150 billion (IEA, 2016*f*). Through subsidization, prices are distorted, thus limiting consumers' capacity to judge scarcity and other considerations. Some may argue that the energy output per unit of subsidy makes fossil

11. Price highs occurred the week of May 4, 2015, and lows occurred the week of January 16, 2016 (IEA, 2016*e*).

fuels more attractive to support. Fossil fuels, however, are not new entrants to the energy landscape. This type of developmental aid could be used more effectively to enhance resilience or provide newer technologies a more even playing field.

Security

The security of an energy supply (i.e., the availability of sufficient and affordable energy) may be challenged by human error or attacks, political or cartel activity, natural disasters, or constraints of the delivery infrastructure. Although these issues could affect any energy system, a persistent form of energy insecurity that is associated with fossil fuels is instability of supplier regions. In recent years, for instance, political unrest, resource nationalism, and deliberate forms of supply disruption have been evident in some of the world's top oil and gas export nations.[12] Costs of safeguarding the international fuel supply, including routes and supplier stability, are often not factored into the calculus of energy options.[13]

Another aspect of energy security is the ownership of energy resources or reserves. Currently, national oil companies control roughly 90% of global oil reserves and 75% of production (Tordo, Tracy, and Arfaa, 2008, see also Figure 1-2), with a similar profile existing for natural gas. These state-owned energy companies (SOEs) have industrial aims that align more closely with the preferences of their respective national governments than do the aims of their private-sector counterparts (Marcel, 2005; McPherson, 2003; Stevens, 2003; United Nations Centre for Natural Resources, Energy and Transport

12. Resource nationalism or expropriation of oil and/or gas fields by the state has been evident in Venezuela, Bolivia, Ecuador, and Russia (British Broadcasting Company [BBC], 2006; Ingham, 2007; Johnson, 2007; Macalister, 2007). Some instances, particularly in Russia and Ecuador, may have occurred on the basis of contractual differences.

During the Arab Spring, revolutions and other major political uprisings occurred in countries of North and West Africa as well as in the Middle East, where fossil fuel exports are considerable (BP, 2017). Russia also has history of natural gas disputes with neighboring countries leading to delivery disruptions. A dispute in January 2009 with Ukraine, for instance, led to supply disruption in 18 other countries (R. Jones, 2009; Reuters, 2009).

13. When considering energy security and supply challenges, low carbon energy can also be affected, but in typically different ways. Bottlenecks as well as trade disputes associated with equipment have affected the adoption of wind and solar energy in recent years. The intermittency of supply also characterizes the availability of renewable energy resources like wind and solar power. However, this natural condition is increasingly being addressed with meteorological forecasting and balancing across fuels, geography, and time.

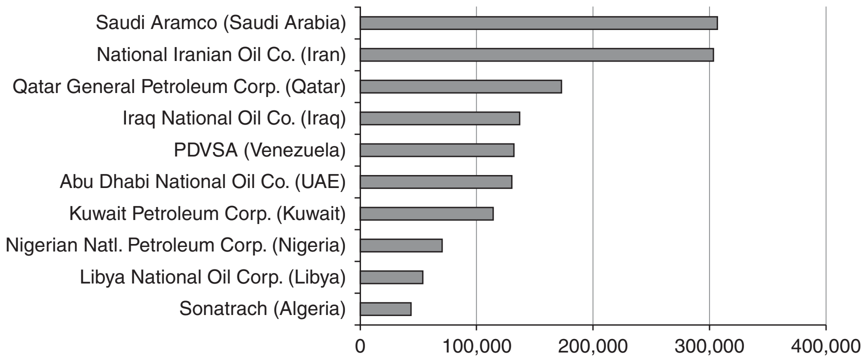

Figure 1-2 World's largest oil and gas companies based on oil equivalent reserves of liquids and natural gas (Million Barrels of Oil Equivalent/MBOE).
SOURCE: Adapted from Petrostrategies, as of July 18, 2012. All companies are at least partly, if not wholly, government-owned.

[UNCRET], 1980). This form of relationship between an energy supplier and a national government can produce societal benefits, such as support for affordable energy services for citizens. These ties can also be exploited, influencing the business plans of the SOEs, if the political agenda of a government or political unrest overshadows a company's aims. Although low carbon energy resources can also be controlled by the state, renewable energy forms are less prone to such security issues.

ENERGY SYSTEM CHANGE

When focusing on energy system change, it's important to expand on what is meant by an *energy system*. These systems are interconnected networks of people and institutions engaged in processes of energy exploration, production, transformation, delivery, and use within an enabling environment or ecosystem. Energy systems include inputs (i.e., fuel resources) and outputs or energy services that are linked by infrastructure and management systems, typically within a market (for a discussion of energy types, see Box 1-2).

Changes to such systems (i.e., energy transitions) can occur in the type, quality, or quantity of energy that is sourced, delivered, or utilized. These conversions can occur at any level, and typically entail co-evolutions in sociotechnical aspects such as user practices and market mechanisms. In recent decades, scholarly works on the subject of energy transitions have grown considerably. As new studies bridge disciplines and regions, annual publications have increased by more than a factor of 27 since 1970 (Figure 1-3).

Box 1-2

Sources of Energy

Primary energy is contained within natural resources including fossil fuels, uranium, and renewable energy. Unlike *final energy,* primary energy is mostly unrefined when it enters the energy system (Grubler et al., 2012). Final energy, such as electricity or gasoline, is available after processing, transformation, and distribution at the point of end use.

Primary energy includes a range of inputs. Feedstock for fossil fuels encompasses coal, natural gas, and oil—each of which is converted for use primarily through combustion. Elements such as uranium, plutonium, and thorium (and various isotopes, in some cases) generate nuclear energy through fission or fusion processes (Rogner et al., 2012). Renewable energy consists of sources such as hydro power, ocean and wave power, biomass, geothermal energy, wind power, and solar energy. Among the renewable sources (used interchangeably, here, with renewable energy technologies [RETs]), energy is derived essentially from solar radiation or the Earth's heat.

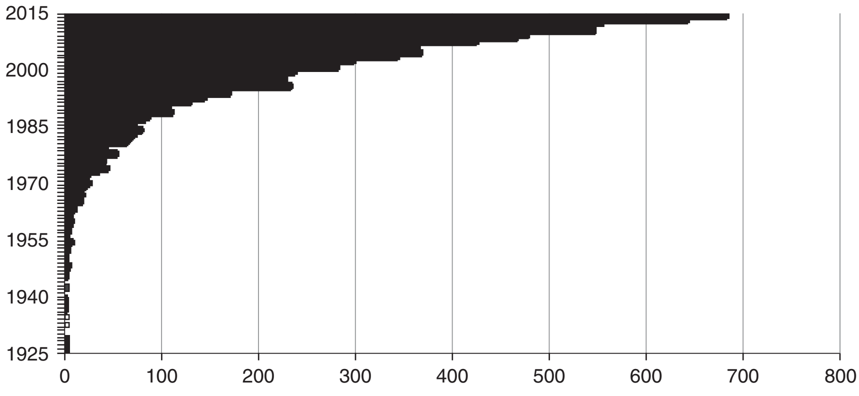

Figure 1-3 Scholarly writing on energy transitions, 1925–2015.
SOURCE: Compiled from Scopus, May 14, 2016, with "energy transition" and "energy system change" in the title, abstract, or keywords.

Contemporary thinking about energy transitions is deeply rooted in ideas from the 1970s and 1980s. During that period, writing began to increasingly address integrated conditions, emphasizing constraints in conventional resources that could be managed more strategically through alternative pathways like renewable energy, efficiency, and conservation (Anderer, McDonald, and Nakicenovic, 1981; Hafele, 1981; Lovins, 1976; Meadows, Meadows, Randers, and Behrens, 1972; Schumacher, 1973). At the time, there was a sense that deliberate change in energy systems was possible, but it would require that energy policies, corporate measures, and personal energy behavior be conceived in the context of broader energy challenges and not in terms of isolated aspects (Anderer et al, 1981).

A 1980 study by the Institute for Applied Ecology in Germany brought together these intellectual traditions with the concept of *Energiewende* or "energy transition" (Energy Transition, 2012; Krause et al., 1982). The study argued for a new energy path that would foster economic growth, yet be accomplished with efficiency. Looking at current efforts in Germany, the same change-oriented thinking of *Energiewende* continues today as the country produces more GDP with less energy (Morris and Pehnt, 2015). Further, Germany aims to reduce energy consumption to 50% of its 2008 usage by 2050, with 60% of the total comprising renewables. The country is doing so with new challenges and opportunities, as it leads in areas like highly-efficient building technologies that may become European Union (EU) standards.[14]

The above aims and ideas currently resonate with energy agendas in many regions of the world, including at the sub-national, national, and supra-national levels (REN21, 2017).

ALTERING THE ENERGY PLAYING FIELD

Adopting a plan to transform an energy system is no trivial undertaking. After all, energy infrastructure, practices, and industry are slow to change. Energy systems are traditionally characterized by limited competition and lengthy periods of research and development (R&D) investment (Flavin, 2008; Holdren, 2006*a*; Lund, 2006). Nonetheless, energy system change or transition is not new.

14. Germany's current efforts are linked to policy from September 2010 and fuller legislative measures from 2011 that represent a multi-pronged strategy to counter climate change, move away from nuclear power, reduce energy imports, strengthen energy security, stimulate a green economy and innovation, foster social justice, and support local economic development (Buchsbaum, 2016). The German power mix in 2015 consisted of 30% renewables (13% wind, 8% biomass, 6% solar photovoltaic, 3% hydropower), 14% nuclear, 52% fossil fuels, and 4% other (Appunn, 2016). Known for its initiatives in wind, solar, and biomass, among other areas, recent developments in Germany present research opportunities for the study of new transitions. For a discussion of aspects of the Germany transition, see Quitzow et al. (2016), Buchsbaum (2016), Pescia, Graichen, and Jacobs (2015).

At the country level, one can look at the transition from wood to coal that began in England in the 1500s and 1600s, when the growth of cities and deforestation practices produced conditions in which firewood had to be shipped greater distances (Brimblecombe, 1987; Fouquet, 2010; Landes, 1969; Rhodes, 2007). As the price of firewood increased, less wealthy citizens switched to coal while the nobility, including Queen Elizabeth I, maintained the practice of using wood because coal was considered to be less clean. When King James VI of Scotland assumed the throne of England and Ireland, he drew on knowledge about less sulfurous coal from Scottish practices to convert royal fuel from firewood to coal (Brimblecombe, 1987; Rhodes, 2007). This, in turn, influenced the nobility's view of coal, bringing their energy practices in line with other British citizens. Further developments in steam engines and canal systems extended the adoption of coal, with efficiency improvements in coal mining and steam-powered rail transport that enabled the creation of new markets (Brimblecombe, 1987; Rhodes, 2007; Fouquet, 2010).

Looking to more recent times, the British navy's shift from coal to petroleum highlights the significance of decision-makers co-evolving with changing conditions. In 1911, then British Home Secretary Winston Churchill opposed fuel switching for the British navy, seeing merit instead in a continued use of domestically-sourced coal. Yet as international tensions heightened with Germany, now First Admiral of the Navy Churchill changed his thinking, prioritizing naval tactical performance on the basis of power, efficiency, speed, and flexibility. This shift in strategic focus from domestic fuel sourcing to fleet performance meant that the British naval fleet would rely more heavily on oil imported from Persia (Churchill, 1928, 1968; Churchill and Heath, 1965; Yergin, 1991, 2011).

Considered at a global level, the primary energy mix has undergone fairly substantial inflections since 1850 (Figures 1-4 and 1-5). As energy use increased by roughly 20 times worldwide, the energy mix shifted from a reliance on biomass-based energy toward a mix of fossil fuels. Within this transformation came many, related shifts including catalytic cracking for refining oil, as well as the introduction of cars, electricity, and suburbanization, among factors.

Moving from historical examples of energy system change to forward-looking prospects, resource availability plays a key role when weighing energy options. Simple estimates of fossil fuels, for example, indicate a supply availability of roughly 50–115 years, based on reserve-to-production ratios of 50.6, 52.5, and 153.0 years for oil, gas and coal, respectively (BP, 2017).[15] Measured in somewhat different terms, estimates of low carbon energy potential indicate that the existing global

15. It is worth bearing in mind that changes in science, technology, and practice may extend the supply. See World Energy Council (2010*c*) for a discussion of reserves and resources, including proved, probable (indicated), possible (inferred), and undiscovered resources.

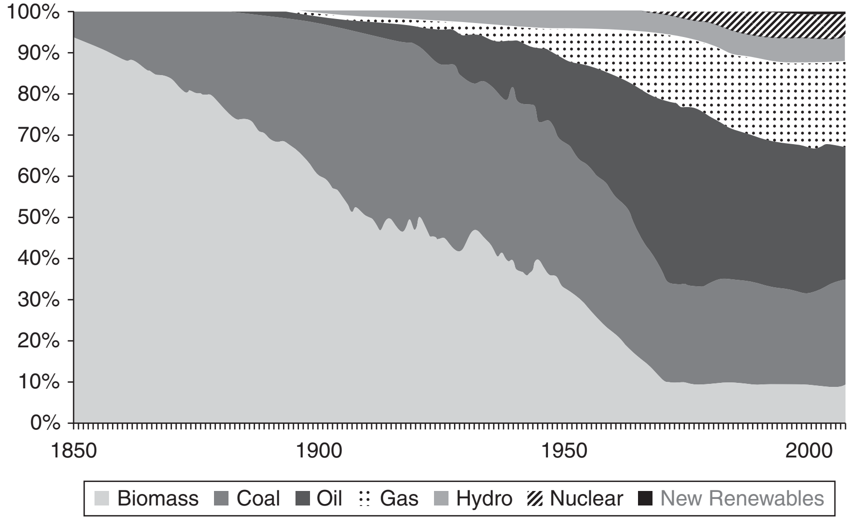

Figure 1-4 Global primary energy (share), 1850–2008.
From Araújo (2014). Adapted from Grubler, et al., (2012). NOTE: "New" renewables include technologies such as solar photovoltaic energy, geothermal power, and wind power. They do not include energy derived from traditional water or wind mills, wind-powered sea travel, solar water heating, and the like. The chart also does not reflect muscle power from animals and humans.

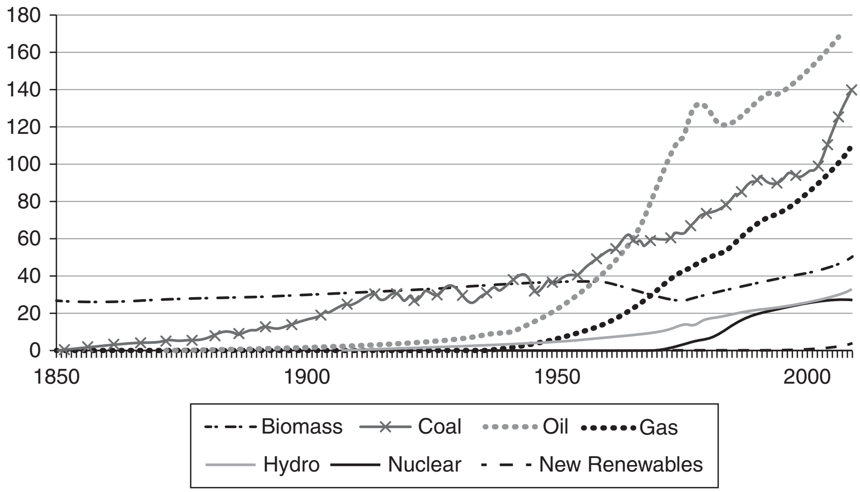

Figure 1-5 Global primary energy (exajoules/EJ), 1850–2008.
From Araújo (2014). Adapted from Grubler, et al., (2012). NOTE: "New" renewables include technologies such as solar photovoltaic energy, geothermal power, and wind power. They do not include energy derived from traditional water or wind mills, wind-powered sea travel, solar water heating, and the like. The chart also does not reflect muscle power from animals and humans.

Table 1-3. Global Resource Base for Select Low Carbon Energy (EJ/Year)

Resource	**2008 Use**[a]	**Technical Potential**	**Theoretical Potential**
Hydropower	11.6	50	147
Biomass	50.3	276	2,900
Solar energy	0.5	1,575–49,837	3,900,000
Wind energy	0.8	640	6,000
Geothermal energy	0.4	5,000	140,000,000
Ocean energy	0.00		7,400
Nuclear energy	9.85	1,890[b]	7,100[b]
Total	73.45		

[a] 2008 use is taken from Moomaw et al. (2011) and based on direct equivalent accounting.
[b] Technical and theoretical potentials for nuclear energy are in EJ not EJ per year. These nuclear energy potentials reflect open cycle processes. If closed cycle processes were used with fast reactors, technical and theoretical potentials would equal 113,000 EJ and 426,000 EJ, respectively. The range of solar technical potentials reflects different assumptions pertaining to annual clear sky irradiance, annual average sky clearance, and available land area.

SOURCE: Adapted from UNDP et al., 2000, unless otherwise noted.

NOTE: Estimates, such as those by the International Energy Agency, the *Global Energy Assessment*, and the *Special Report on Renewable Energy Sources and Climate Mitigation,* provide related and, at times, different numbers based on assumptions and scoping. See, for example, discussions of the theoretical potential for geothermal energy in IEA, 2011*b*; Goldstein et al., 2012; Rogner et al., 2012.

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utilization of energy is a small fraction of what could be effectively harnessed (Table 1-3).[16] The total amount of energy used worldwide in 2008, for instance, represented about 1% of the technical potential for geothermal energy and roughly 5% of the lower estimate for solar energy. Today's numbers remain similar.

What is often missed in energy discussions is the reality that renewable energy is widely available, essentially everywhere in varying combinations and potentials. By contrast, finite fuel sources like fossil fuels and uranium are not.

16. Precise definitions for technical and theoretical potential vary. *Technical potential* is frequently analogous to "resource," implying energy that can technically be extracted irrespective of economic feasibility. *Theoretical potential* refers to energy availability that is deduced as possible based on an understanding of the resource flows yet is not feasible to extract given prevailing technology and economic conditions. See United Nations Development Program [UNDP], UN Department of Economic and Social Affairs, World Energy Council [WEC] (2000) for a discussion of assumptions used for fuel potentials in Table 1-3 estimates. For a discussion of low carbon energy versus renewable energy and other forms, see Chapter 2.

Adopting a low carbon path that avoids an increase of 2°C would require on the order of $53 trillion in global, cumulative investment, according to one estimate (IEA, 2014). This includes costs for infrastructure and related expenditures associated with the energy supply and improved efficiencies by 2035. Although cost and benefit assessments have their limitations, it is reasonable to say that such a scale of investment will face challenges.[17] Financing can be seen as risky if the cost of capital is based on established returns of investment and newer technologies do not yet have a track record. Stranded assets can also complicate a shift if decision-makers limit their choice to legacy pathways due to unrecoverable, earlier investments. Going even further, players may choose to not engage because they see themselves as unable to capture all the benefits (Anex, 2000; Cowen, 2008; Dosi, Malerbra, Ramello, and Silva, 2006; Gravelle and Rees, 2004; Mitchell et al., 2011).

In such circumstances, *green financing* will be an important bridge.[18] Green bonds, for instance, offer ways to connect low-cost capital held by institutional investors with low carbon projects (World Economic Forum, 2013). Platforms for interaction between project developers and investors can also be developed as public financing agencies streamline risk mitigation (IRENA, 2016). Institutional investors, including pension funds, insurance companies, and sovereign wealth funds, also have opportunities to become critical players in the mobilization of such a wide-ranging initiative. In fact, efforts by groups like the United Nations Environmental Programme (UNEP), G20, International Monetary Fund/World Bank Group, and OECD are under way to align the global financial system with more sustainable aims (OECD, 2015*a* and 2015*b*, n.d.; UNEP, 2016; World Bank, 2015). Here, policy can play a critical role by focusing attention on prime areas where investments are needed, in addition to creating more stable and predictable investment environments.

Path dependence may be one of the strongest forces that impedes change. With this phenomenon, previous choices limit later options based on the inflexibility of sunk costs, the increased returns from continuing on the existing path, or the interrelatedness of technologies, among other factors (Arthur, 1989; David, 1985). Greg Unruh applied this idea in what he called *carbon lock-in*—conditions in which industrial economies have become entrenched in fossil fuel–intensive systems through the co-evolutionary development of technological and institutional processes driven by returns of scale that, in turn,

17. For a discussion of methods and scoping considerations in cost assessments of energy system change, see Araújo (2016). For more on barriers, see Organization for Economic Cooperation and Development (2015*a*); Brown, Chandler, Lapsa, and Sovacool (2008).

18. Definitions of green finance, like that of low carbon, are not fixed. See Lindenberg (2014).

create persistent market and policy failures (Unruh, 2000). This "vicious cycle" inhibits the diffusion of carbon-saving technologies despite cost-neutral or even cost-effective remedies that have apparent environmental and economic advantages (Unruh, 2000, citing Ksomo, 1987). Such self-reinforcing reliance on an incumbent carbon-dependent path is not necessarily permanent, but it can persist by creating systematic market and policy barriers to alternatives such as energy efficiency and renewable energy technologies (Unruh, 2000, 2002).

Today's newer entrants, like modern renewable energy, can encounter challenges in technological maturity that the fossil fuel industry overcame in previous eras.[19] In such cases, inherent advantages in the status quo may drive incumbent actors with vested interests to resist change. Resistance might then crystallize, with traditional players seeking to block structural change, technological progress, or the rise of industry challengers (Juma, 2016; Moe, 2015). This can be done by exerting pressure on governments to impose administrative procedures, taxes, trade barriers, or regulations in order to prevent new entrants from challenging the current power structures or undermining existing fee structures (Moe, 2015; Olson, 1982).

While resistance and organizational/institutional inertia will likely continue to impede some progress on low carbon adoption, rapid change is already evident in industries, such as banking, telephones, medicine, and computing, that have defeated similar odds. The underlying insight from such shifts is that agents of change are redefining the playing field rather than accepting lock-in as an ongoing status quo (Bardach, 1977; Garud and Karnoe, 2001, 2003; Garud, Kumaraswamy, and Kamoe, 2009; Kingdon, 1995; March and Olsen, 1989).

CENTRAL QUESTIONS

Given the convergence of low carbon priorities and the challenges facing wider utilization of low carbon energy, my aim in this book is to provide in depth perspective on how four, leading countries of advanced, low carbon energy technologies shifted their national energy systems in the period since 1970. I do so by examining the following, key questions:

19. The use of the term "modern renewables" recognizes that wind-, solar-, geothermal-, biomass-, and water-based energy sources have been used for centuries. Traditional uses include wind energy applications in sea power. This study focuses on more, contemporary applications.

- How can national energy transitions be explained in terms of inflection points; key interventions by government, industry and civil society; and structural change?
- To what extent do the patterns of change align and differ in the four, energy transitions that are examined?
- What role does policy play, particularly with innovations, in the cases that are considered?[20]

In answering these questions, I also explore elements of cost, societal acceptance and human development, industrial progress, carbon intensity, and natural resources.

Whatever the reason for switching to low carbon energy—to foster resilience, improve access, reduce import dependence, or address the business case for change—understanding underlying dynamics may provide timely insights.

20. *Policy* is considered here as explicit or implicit rules and (in)action of public entities. *Innovation* is seen as enhancements through novel or recombinatory ideas and applications in science, technology, and other areas, including societal practices.

2

Beyond Malthus

> Evolution is a sequence of replacements.
>
> —Elliott Montroll, *Physicist (1978)*

This chapter explores the evolving understanding of carbon and sustainability since the 18th and 19th centuries. Relevant applications of influential ideas are then identified with respect to knowledge, innovation, policy, and meta-level change.

CARBON AND THE GREENHOUSE GAS EFFECT

More than 100 years ago, Swedish scientist Svante Arrhenius hypothesized about the onset of ice ages and interglacial periods by considering high latitude temperature shifts (NASA Earth Observatory, n.d.). Applying an energy budget model and ideas of other scientists, like John Tyndall, Arrhenius argued that changes in trace atmospheric constituents, particularly carbon dioxide, could significantly alter the Earth's heat budget (Arrhenius, 1896, 1897; NASA Earth Observatory, n.d.).

Today, science indicates that the global, average surface temperature has continued to rise alongside the increase in greenhouse gases. Among global GHGs, CO_2 emissions have increased by more than a factor of 1,000 in absolute terms since 1800 (Figure 2-1 and Box 2-1). During that time, global carbon emissions found in the primary energy supply increased by roughly 6% per year (Grubler, 2008*a*). This growth in carbon emissions from energy is significant because CO_2 from fuel combustion dominates global GHG emissions (IEA, 2015*a* and 2015*b*; IPCC, 2013). As noted earlier, 68%

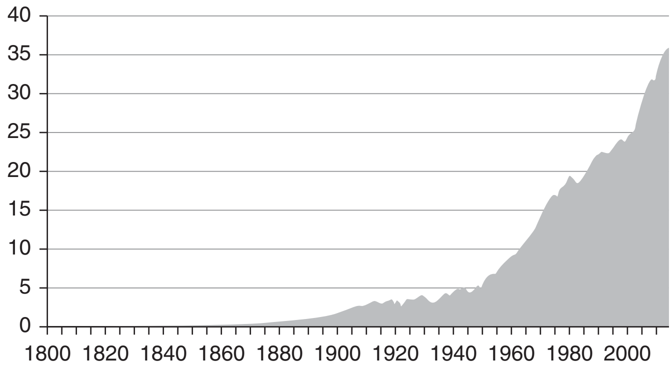

Figure 2-1 Global CO_2 emissions ($GtCO_2$), 1800–2013.
Adapted from Boden, T. A., Marland, G., and. Andres, R. J. (2016). *Global, Regional, and National Fossil-fuel CO_2 Emissions*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. Oak Ridge, TN: US Department of Energy. doi 10.3334/CDIAC/00001_V2016.

Box 2-1

The Kaya Identity

The *Kaya identity* expresses carbon dioxide emissions as the product of the carbon intensity of energy (CO_2/E), energy intensity of economic activity (E/GDP), economic output per capita (GDP/P), and population (P) (Kaya, 1990):

$$CO_2 = (CO_2/E) * (E/GDP) * (GDP/P) * P.$$

For further discussion of CO_2 in the context of systems change, see Kaya, Nakicenovic, Nordhuas, and Toth (1992) and Kaya and Yokobuchi (1993).

of the global GHGs that are attributed to human activity are linked to the energy sector; namely, fuel combustion and fugitive emissions (IEA, 2015*a*). Within this share, 90% consisted of CO_2 (IEA, 2015*a*).

In contrast to the rise in absolute numbers, carbon emissions per unit of output in the global primary energy supply has decreased 36% overall or by slightly less than 0.2% per year over the past two centuries (Grubler, 2008*a*).[1]

1. Other carbon intensity metrics include carbon per unit of gross domestic product and per person. The differences in metrics must be factored in discussions about carbon reductions.

This subtle decarbonizing pattern in the energy mix is explained by the faster growth rate of energy use in relation to the rate of carbon emissions from that use. The delinking of energy utilization and carbon emissions occurred in part with the introduction of less carbon-intensive fossil fuel sources, like natural gas, in which a higher hydrogen-to-carbon ratio is evident (Gibbons and Gwin, 2009; Grubler, 2004, citing Marchetti, 1985).[2] Delinking is also fostered by the introduction of nuclear energy and the increased utilization of renewables in the latter half of the 20th century. Because global energy demand is projected to rise approximately 32% by 2040, choices influencing relative shares of renewable energy technologies (RETs) and nuclear energy will be important for these trends (IEA, 2015*d*).

SUSTAINABILITY

Well before Svante Arrhenius developed calculations on CO_2, British writer Thomas Malthus laid the conceptual ground work for ideas on sustainability in *An Essay on the Principle of Population*, first published in 1798 (1999). In his now classic writing, Malthus emphasized limitations of natural resources on societal growth. Building on Malthus' ideas, the concept of sustainable development emphasizes interdependent priorities valuing the environment, economics, and society across generations (World Commission on Environment and Development [WCED], 1987). Driven in part by complexities of competing priorities, the concept of sustainable development is widely used, yet also subject to criticism for its looseness of definition and form of gauging (Bartlett, 1997/1998; Daly, 1996; Taylor, 1992).

In today's discussions about energy, it is not uncommon to hear *sustainable* used interchangeably with *renewable, clean*, and *low carbon*. Although overlap exists between the meanings, differences matter. *Sustainable* refers broadly to durability and in more rigorous definitions is described as enduring intergenerationally in a way that does not unduly undermine society, the economy, or the environment. *Renewable* energy, as mentioned in Chapter 1, typically refers to energy forms that naturally regenerate. A more nuanced definition would stipulate that regeneration occurs in a manner that exceeds or matches the draw-down of the energy source. *Clean* energy is widely used in the context of fuel use that does not pollute. By contrast, *low carbon* energy signifies an approach that emits less carbon, yet the term opens questions about scope. Does the term refer to the life cycle of a fuel or to one particular stage,

2. The hydrogen–carbon ratios or H/C for various fuels are coal (0.5–1:1), oil (2:1), natural gas (4:1).

such as production or consumption? A number of examples will help clarify these distinctions.

- Natural gas is sometimes classed among low carbon fuels to differentiate it from more carbon-intensive coal and petroleum-based fuels. With this rationale, natural gas constitutes a low carbon fuel that is not renewable.
- Nuclear energy is characterized by some as a form of clean energy, if one discounts nuclear waste and focuses on the limited emissions of its power generation (excluding construction, mining, etc). Following this line of thinking, nuclear energy might be described as clean energy that is not renewable.
- Perhaps surprising for some, renewable energy can be managed in ways that are not sustainable, low carbon, or clean. The extraction of geothermal energy, for example, can radically draw down heat or steam from its source. In such a case, the energy source might be renewable, but not sustainable in practice. Somewhat differently, the production and use of biomass can result in varying levels of pollution, including CO_2. Depending on how biomass is managed, it can be renewable, but not low carbon or clean.[3]

What affects many of the above distinctions is the way a specific type of energy is managed from end to end (not just its production). Here, the succinctness of definitions is also challenged by continuous changes in technology and management practices. If such terms are used in international conventions, attention is required in how the concepts are defined. For this study, low carbon energy includes non-fossil fuels, namely renewable and nuclear energy. The terms "sustainability" and "durability" of energy transitions are used interchangeably.

KNOWLEDGE, INNOVATION, AND POLICY THEORY

Knowledge, innovation, and policy are powerful forces of transformation. Certain ideas on these forms of change can guide studies of energy transitions.

3. Definitions in the *Special Report on Renewable Energy* (SRREN), Section 1.2.1 distinguish renewable from sustainable energy, and exclude some forms of slow-growing bioenergy. Bioenergy is renewable, but may or may not be sustainable in practice. It also is high in carbon relative to other renewable resources like solar and wind (and nuclear). Further distinctions could focus on carbon intensity (Communications with B. Moomaw, 2016).

Knowledge

Knowledge has a role to play in systems change. Economist and historian of technology change Joel Mokyr wrote that it was not inventors or socioeconomic factors that drove the Industrial Revolution, but rather people exchanging knowledge (2002). Such knowledge can be thought of in terms of its source or level of authority. What some may call "established knowledge," for example, is typically tested through mainstream, disciplinary investigation and accepted by scientific peers. By contrast, local knowledge "does not owe its origin, testing, degree of verification, truth, status, or currency to distinctive professional techniques, but rather to common sense, causal empiricism, or thoughtful speculation and analysis" (Lindblom and Cohen, 1979). The latter form aligns with ideas on learning and innovation that emphasize the importance of user insights in extending the knowledge frontier (Johnson, Lorenz, and Lundvall, 2002; Lundvall, 1985, 1988; Von Hippel and Tyre, 1995). The pivotal nature of knowledge is also reflected in the context of adaptive capacity and the agility of a country to evolve (Smil, 2010), all of which factor in energy systems.

Innovation

Innovation, defined broadly as adaptations to improve performance and/or quality, can also be instrumental for energy transitions. Classic views of innovation highlight a linear progression in which technological development occurs in three stages: (1) invention, when an idea first emerges; (2) innovation, the first practical application of the invention; and (3) diffusion, when the innovation is dispersed widely for use (Schumpeter, 1942/1975). More recent views of the innovation life cycle map the inception of an idea and its incubation through testing and prototyping to niche market development, through to widespread diffusion with feedback loops, links, and overlap throughout the cycle (Grubler et al., 2012; Kline and Rosenberg, 1986; Nakicenovic, Grubler, and Macdonald, 1998/1999). Both approaches envision processes that principally occur in traditional institutional settings, yet there is a growing awareness that innovation and the agents of such change can extend well beyond industrial laboratories and academic settings (Lundvall, 1988, 2010; von Hippel, 2005, 2010) and do not need to be rigidly sequenced (Sovacool and Sawin, 2012). This book recognizes innovation in energy systems as an improvement that can occur with conventional and unconventional paths, and which enhances the quantitative or qualitative utilization of energy, including the sourcing, conversion, application and use, distribution, and final disposal. Such scoping allows for shifts that improve the system in less obvious ways, such as through its governance and financing practices.

Theory-building on national innovation systems (NIS) emphasizes the interactions among institutions and other elements within a country that produce systemic feedbacks and constructive adaptations in the advance of a technology (Edquist, 2005; Freeman, 1987; Lundvall, 1992; Nelson, 1993; Ridley, Yee-Cheong, and Juma, 2006). This body of theory recognizes that shared language, culture, and institutions at the country level can serve to frame important conditions for innovation systems. Richard Nelson and Bengt-Åke Lundvall developed two primary lines within NIS literature. Richard Nelson's applied analysis highlighted the role of national research and development systems (Edquist, 2005, citing Nelson, 1993), whereas Lundvall's more theoretical approach emphasized the role of learning in user–producer interactions and the home market for economic specialization (Edquist, 2005; Lundvall, 1992). Given the national scoping of this study, a wide view of innovation is used, acknowledging that developments can arise from a change in technology, products, processes, or practices tied to learning and experimentation, serendipity, and breakthroughs from any sector for a given country.

Technology[4]

Technology change provides another lens for understanding energy transitions. In the most basic terms, the introduction of a new technology can influence how energy is sourced, delivered and used. The concept of technology change in neoclassical economics has centered on (1) the relationship between supply and demand, (2) performance in production for which technology is an input, and (3) research and development, however these do not account for the unplanned and less precise elements of development (Mokyr, 1990; Mytelka and Smith, 2001; Nelson and Winter, 1982).[5] Evolutionary economics provided a critical point of departure for this thinking by emphasizing how natural selection and competition can be critical drivers, rather than the profit maximization and market equilibrium emphasized in neoclassical economic theory (Nelson and Winter, 1982).

4. Technology often includes hardware and software, such as equipment and computer applications, but it can also mean products, processes, devices, and practices (Grubler et al., 1999*a*, 1999*b*). For our purposes here, technology is defined as hardware, software, and material inputs (i.e., energy and raw materials), using the term "system" to encompass the broader conceptualizations of technology. Related dimensions, such as knowledge and practices, are considered under separate labels.

5. According to the neoclassical economics schools of thought, technology is viewed as an intermediary factor in relation to the basic factors of production: labor and capital (Hadjilambrinos, 2000). Technology change, then, derives from the need to improve resource utilization (Hadjilambrinos, 2000, citing Cohendet et al., 1991, Gilbert, 1985, and Moroney and Trapani, 1981).

Today, change in technology is often viewed in the context of incremental or radical/disruptive shifts (Abernathy and Utterback, 1978; Dosi, 1982; Grubler, 1998; Grubler, Nakicenovic, and Victor, 1999*a*, 1999*b*). *Incremental change* implies slight modifications to existing technology, like the addition of a catalytic converter to an automobile, whereas *radical* or *disruptive change* refers to substantial adaptations in one technology or when one technology supplants another. An example of a more radical form of disruptive change was evident in the emergence of automobiles that replaced carriages. This change opened new directions for practices, access and infrastructure. Joel Mokyr argued that incremental and disruptive changes do not need to be mutually exclusive, but can overlap since most macro-level inventions build on the accumulation of micro-level ones (1990).

Greg Unruh differentiates transition stages with a taxonomy that includes end-of-pipe (incremental), continuous (nondisruptive), and discontinuous change (disruptive or radical) (2002). The addition of an intermediary stage allows for an enhancement or upgrade to the existing architecture that repositions the prevailing technology trajectory along a more sustainable pathway (Unruh, 2002; Berkhout, 2002). While bridging legacy and novel technologies, this middle type of shift maintains inherent limitations since nothing is fundamentally changed about the technology or the institutions themselves (Berkhout, 2002).

Frank Geels and Johan Schot have theorized about the structure of technology change (Geels and Schot, 2007). Unlike many, related models that focus on the intensity of systemic disruption, Geels and Schot's approach differentiates processes to include transformation, reconfiguration, substitution, and realignment/dealignment. These concepts will be useful to bear in mind as additional theory-building on energy systems change is proposed later in this book.

Frames and Policy

There is a saying that great opportunities are often disguised as unsolvable problems. How we perceive conditions matters for the way in which we respond, with perspective being influenced by experience, philosophy, and power, among other factors (Allison, 1969; Allison and Zelikow, 1999; Schoen and Rein, 1995). Thinking in terms of frames, the challenges of an energy shortage, for instance, can be viewed negatively. Yet those same conditions also present windows of opportunity to modernize and improve the overall system. In such cases, focusing events may serve as inflection points for broader change (Birkland, 1997, 1998; Birkland and Warnement, 2013; Kingdon, 1995; Zahariadis, 1999). For policymakers wanting to develop more resilient energy strategies, infrastructure replacement following storm damage, for example, can serve as a point for integrated assessment and course correction aligned with longer-term aims (Baumgarten and Jones, 1993; Jones and Baumgartner, 2005; Howlett, Ramesh, and Perl, 2009).

Whether one sees shifts in energy paths as an opportunity or challenge, policy design and implementation eventually come into play. Hood's taxonomy of policy instruments suggests that one could approach governmental action by focusing on governing resources, like information, authority, finance, and organization (Hood, 1968). Bemelsmans-Videc, Rist, and Vedung, by contrast, offer a more simplified way of envisioning policy in terms of regulations, incentives, and information (2005). Irrespective of the approach, national policy styles differ, based at least partly on domestic idiosyncrasies in institutions and culture (Howlett, 2002; Linder and Peters, 1989). Writing on policy mixes and interaction effects speaks to the importance of good alignment of policy tools with conditions, aims, governance approach, and resources (Guerozoni and Raiteri, 2015; Howlett and Raynor, 2013; Kern et al., 2017). There is a sense, however, in the context of sustainability transitions, that policy mixes must more fully account for the dynamic settings in which energy systems reside, including real-world complexities, explicit incorporation of process, and strategic dimensions (Rogge and Reichardt, 2016). Effective implementation of a feed-in type of market premium policy, for example, should include upper and lower price limits, and clear guidance on triggers for policy review to minimize disruption. Policies, such as these, will be discussed more in Chapter 7 and 8.

THEORIES ON META-LEVEL CHANGE

Structure, Function, and Connection Points

Theories on meta-level change provide another set of important foundations for theory-building on energy transitions. Large technical systems, techno-economic paradigms, and multilevel perspectives are among the more well-known contributions.

History of science writing on large technical systems (LTS) conceives of complex and seamless webs that include not only the physical infrastructure, but also economic, legal, and social elements that can manifest in organizations, rules, and other elements (1983, 1998, and 2012). According to Thomas Hughes, systems builders, like Thomas Edison with electricity, focus on fostering the coherence of their technical systems within the social environment. As the systems and the environment mutually influence the other, the system grows and advances with a momentum that includes re-enforcing contributions from actors and inventions (Hughes, 1983, 1989).[6] When the system matures, it becomes resistant to change. *Reverse salients* may develop, in which components of the system create lag or are out of step. An example of this can be seen in the use of floppy disks for nuclear weapons systems. The mostly obsolete storage files require costly measures to maintain (BBC, 2016). When such a reverse salient is not rectified within an incumbent system, the condition can become radical, bringing about a new and competing system (Hughes, 2012).

Ideas on *techno-economic paradigms* (TEP) build on long-wave theories of business cycles to offer complementary ideas about change. As outlined by scholars, including Chris Freeman, Carlota Perez, and Francisco Louca, TEPs are seen as configurations of interlocking technologies, processes, economic structures, and beliefs that endure based on gains from key factors (Freeman and Louca, 2002; Freeman and Perez, 1988; Perez, 2009*a*), but which can transition with a technological revolution (Freeman and Perez, 1988; Twomey and Gaziulusoy, 2014). This approach emphasizes how *new logic*, including research rationale and norms, replaces earlier thinking over the course of five or six decades to shape the modernization of existing industries alongside newer entrants (Freeman and Louca, 2002; Perez, 1985, 2004*a* and 2009*b*). Flux is seen as being minimized through links between political, business, and cultural trajectories. In the context of sustainability, a new TEP could emerge in line with this aim, through novel information and communications (Perez, 2009*b*).

Described as a "middle range theory," the *multilevel perspective* (MLP) draws on sociology, evolutionary economics, and science, technology, and society studies (STS) to explain sociotechnical transitions toward sustainability (Geels, 2005; 2006). In conjunction with the work of Frank Geels, Johan Schot, and others, the MLP approach focuses on a sociotechnical system of nested niche, regime, and landscape levels in which each level provides different kinds of coordination and structuration to activities in local practices (Geels, 2002; Geels and Schot, 2007; Grin et al., 2010).[7] Niches are seen as the locus for radical novelties where innovations can accumulate. Co-evolving interactions are critical among technology, user practices, markets and industrial networks, policy, scientific understanding, cultural meaning, and infrastructure (Geels, 2005, 2011). According to this line of thinking, major change is produced by the *realignment of trajectories within and between the various levels.*

6. See Hirsh and Sovacool (2006) for additional discussion.

7. *Niches* are incubation spaces that are shielded from mainstream market selection (Geels, 2006, citing Schot, 1998). *Regimes* include cognitive routines, patterned development, regulatory structure, lifestyles related to technology systems, and sunk investment in equipment, infrastructure, and competency (Geels and Schot, 2007; see also Nelson and Winters, 1982; Unruh, 2000). *Landscapes* refer to the broader, external environment and include macro-economic conditions, culture, and macro-political developments (Geels and Schot, 2007).

Closely aligned with the MLP is the study of *strategic niche management* (SNM) and *transitions management*. This body of work considers ways to nurture socially desired aims and technological innovation (Schot et al, 1994; Kemp and Loorbach, 2006; Raven et al, 2010; Raven, 2012; Smith and Raven, 2012). Experimentation in niches is an area of particular focus for SNM, overlapping with features of the next model to be considered: *technology innovation systems* (TIS).

TIS theory, as put forward by Marko Hekkert and others, brings a function-based approach to understanding how systems perform as innovations are generated, diffused, and used (Hekkert et al., 2007; Jacobsson and Bergek, 2004; Raven, 2012). Seven subfunctions are outlined: entrepreneurial steps, knowledge development and exchange, guidance of a search, market formation, resource mobilization, and the counteracting of resistance/establishing legitimacy (Hekkert et al., 2007). The caliber of subfunction attainment and the relationships among the subfunctions influence whether a transition occurs. This body of work has been extended with related analytical tools, namely a mapping tool for subfunctions (Grin et al., 2012; Negro, 2007; Negro et al., 2007) and a typology of interactions between the functions that enable a transition (Suurs and Hekkert, 2008). TIS is seen as a powerful way to evaluate the internal strengths and weaknesses of a specific sociotechnical system, yet some transition scholars note that more could be elaborated on the timescales. Recently, TIS theory began to focus on the system's external environment (Grin et al., 2010). Important, emergent work has also identified ways to bridge MLP and TIS (Markard and Truffer, 2008).

A more institutional alternative for scoping energy system change is found in the analytical studies of the Transitions Pathways for the Low Carbon Economy Research Consortium. With it, Timothy Foxon and Ronan Bolton described a conceptual framework that envisions three ways that a decarbonized future can be attained: (1) centralized government, (2) market rules, and (3) a "one thousand flowers" to enable change (Bolton and Foxon, 2015; Foxon, 2013; Foxon et al., 2010). The centralized government path is one in which the national government "exerts strong influence over the energy system in order to deal with the trilemma of security, costs, and emission reduction targets," where technology push occurs with a focus on large centralized technologies (Bolton and Fox, 2015). By contrast, the market rules path is one in which a liberalized market framework prevails, with large energy utilities as the dominant investors. The third path or "one thousand flowers" sees a decentralized approach in which nontraditional investors in the energy system play a leading role with more distributed technologies

(Bolton and Foxon, 2015). Naturally, these are guiding conceptual constructs. Reality is often more nuanced (see Chapter 3).

Related theory-building also considers technology life cycles within a broader system. For this, Arnulf Grubler and co-authors (2012) outline an *energy technology innovation system* (ETIS) by locating a transformative energy ecosystem in the context of knowledge, technology characteristics, and actors/institutions. This framework highlights interacting stages of nonlinear development, namely research, development, demonstration, market formation, and diffusion. As the name suggests, this approach is predicated on innovation, providing some means for tracking metrics and considering elements like the loss of knowledge (Grubler and Wilson, 2014).

Another, more recent framework looks specifically at *complex established legacy sectors* (CELS). Focusing on the legacy infrastructure, such as that in transport, power, and the like, William Bonvillian and Charles Weiss explain that technology, economic, political, and social paradigms create barriers to desirable technology innovations (2015; Weiss and Bonvillian, 2013). Observing that dynamic shifts often are stymied by a mismatch of broader social goals and incentives that reinforce existing pathways, Bonvillian and Weiss outline a framework of obstacles to the market launch of innovation. Such barriers encompass perverse subsidies, pricing and cost structures; established infrastructure and institutional architecture that impose regulatory hurdles or other disadvantages to new entrants; politically-powerful, vested interest backed by public support; a financing system that is not suited for the development timeline of capital-intensive legacy-sector innovations; public habits and perceptions attuned to current technology; knowledge and human resource structure that are oriented to legacy sectors; aversion to innovation; and market imperfections that go beyond those faced by other innovations (Weiss and Bonvillian, 2013; Bonvillian and Weiss, 2015). As with the preceding ETIS framing, this approach focuses on innovation. Much of the path dependence features of this framework are relevant to the deployment of nonincumbent forms of energy in such systems.

Looking across all the preceding frameworks, one finds different levels as well as dimensions of analysis. The social embeddedness of the system is a common feature, underscoring how disruptive change involves a range of actors and actions well beyond the lab or the field. Some of the models have an economy or market-centered orientation, like that of the TEP, CELS, and Transition Project paradigms. Others focus more on structure, alignment, or functions, in which outcomes are influenced by a larger set of a social inputs. As systems thinking evolves in conjunction with energy, innovation, and sustainability, many new interdisciplinary connection points will emerge for problem-solving and theory-building.