Consortium for Science,
Policy & Outcomes
at Arizona State University

Energy-Climate Innovation: Simple as One, Two, Three

John A. Alic
Independent Consultant

Daniel Sarewitz
Professor of Science and Society at Arizona State University
Co-Director, Consortium for Science, Policy & Outcomes at ASU

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Abstract

Technological innovation is an implicit element of any plausible strategy for responding to climate change, yet the complexity of innovation processes has not been adequately accounted for in such strategies. We explain such complexity in terms of a simple three-level depiction of technological and social change. Our picture differs from other such schemas since our objective is not theory development but arriving at useful heuristics for addressing a specific set of policy problems: those of innovation in energy technologies and energy systems with the goal of reducing greenhouse gas emissions. This goal requires innovations in multiple technologies and systems in countries worldwide having widely varying patterns of economic output and energy consumption. The problem is thus one of complex socio-technical systems interacting at the scale of global societies and indeed the Earth system itself (the third level in our scheme). Policymakers have few tools suited to addressing problems of such complexity. For such reasons, efforts to steer the global energy system, in its entirety, in a new direction, as attempted by the Kyoto Protocol, will with high probability be defeated by unintended and unforeseeable consequences. Illustrations drawn from a considerable range of technologies and industries point to the reasons. Policymakers should instead focus directly on innovation at the lower level of technological artifacts (the first level in our scheme) or relatively simple networks of artifacts (the second level). Doing so will be facilitated by treating mitigation of climate change as a public good, and technology as an instrument for advancing that good, much as governments have treated provision of clean water and military security.

Keywords: innovation, climate change, public policy, energy systems.

Technological innovation since the time of the first Industrial Revolution is the proximate cause of global warming. Further innovation in technical and social systems is the necessary route to mitigation. Always and everywhere, innovation is messy, complicated, and contingent. Major questions for mitigation of climate change begin with choice of technological pathways and choice of policy tools for guiding the world energy system along desirable pathways. And while prospective technologies have been reasonably well mapped, policy choices—dependent on political coalitions that solidify and dissolve unpredictably—cannot be similarly mapped. With hindsight, the societal and technological aspects of innovation can be uncoupled; foresight necessarily remains conjectural because of system-level complexity.

Even if restricted to technological change alone—ignoring all of the policy, social, and institutional change that must also occur—and given that ongoing incremental innovation is the primary mechanism of performance improvement in all forms of technological change, energy restructuring and climate mitigation would require an uncountably enormous number of innovations, only some of which will discernibly move things in the right direction. Private firms will develop the needed innovations, drawing on a knowledge base supported in part by governments as a public good. Governments also influence energy-climate innovation through policies including regulations and subsidies, and innovation will be needed here too. Governments must find ways to reduce emissions of greenhouse gases (GHGs) while at the same time providing ample supplies of low-cost energy for those who cannot afford high-cost energy, a difficult task in poor parts of the world and impoverished enclaves even in the wealthiest countries. They will have to devise political arrangements that foster innovation while dampening and diffusing opposition by interests that see their freedom of action and profits threatened. Firms in affected industries, for example, will lobby for policies and regulatory rules that give them advantages over rivals in their own industry as well as for policies that favor their industry as a whole.

In this essay we emphasize the systemic nature of the problem and the unpredictable ways in which innovations and families of innovations interact. We do so in part by examining technological change in non-energy contexts. Policy proposals have sometimes been misconceived because they draw inappropriate lessons from such precedents. Calls for an energy-climate Manhattan Project or Apollo program, for example, fail to acknowledge the extent to which the tightly focused goals of both these undertakings enabled effective management. Energy-climate innovation, with multiple technological families and multiple goals that change over time, is inherently unmanageable in any analogous sense. And innovation on the scale needed to address GHG emissions and climate change is bound to have unexpected consequences, some of which may subvert the intended goals of policy.

1. Energy in Context

The basic dilemma for policy and politics has commonly been viewed in terms of externalities and the conflict between energy prices and presumptive climate change mitigation costs. While narrowly true, the issues run deeper. In wealthy countries, economic, political, and cultural forces have locked in place systems (for electric power, for transportation) based predominately on fossil fuels. These represent complex political and social arrangements and enormous sunk costs. At the same time, world energy markets function reasonably well—at least as well as many other markets, and better than, say, world markets for delivery of health services—and fossil fuels remain relatively abundant and relatively inexpensive. No one can know what level of energy prices might be necessary to offset the costs of environmental damages or drive to completion, within a few decades, the social and technical changes necessary to move away from fossil fuels. Prices might have to rise by an order of magnitude, which would bring its own set of highly unpredictable consequences for society and the environment.

Rising energy prices, for example, stimulate innovations that reduce consumption, through conservation and greater efficiency in energy conversion. At the same time, innovators respond on the supply side not only by introducing new low-carbon energy sources but by seeking newly profitable fossil fuel supplies. Thus rapidly rising prices on the global oil market after about 2005 stimulated production of unconventional oil and natural gas in the United States and Canada, and exploitation of oil sands, in particular, resulting in substantial increases in emissions of carbon dioxide (CO_2) and other GHGs, along with its other environmental impacts. At the same time, low-cost natural gas encouraged fuel-switching by North American utilities, with emissions declining as natural gas replaced coal (and also because of the economic slump that began in 2008). Falling US coal consumption then spurred rising exports of coal. Supply-side and demand-side innovations, in other words, tend to emerge in parallel and may have the unintended result of reducing impetus for decarbonization and slowing its overall pace.

Still more complex dynamics operate in other parts of the world. Populations will continue to increase over coming decades in many countries, if more slowly than in the past, and per capita incomes will continue to rise, if unevenly. Industrialized economies are energy-intensive now and developing countries becoming more so. Billions of people in poorer countries need reliable supplies of low-cost energy to support increases in living standards.[1] Development simply cannot proceed otherwise. Although development will mean wrenching changes for billions of people, an absence of development would bring, as a predictable outcome, growing poverty, misery, conflict, and environmental despoliation.

As development proceeds, wage labor in cities will replace agricultural employment, casual labor, and self-employment. Since 1990, for example, Nigeria's population has tripled and the proportion of people living in urban areas has increased from 30 percent to about 50 percent; even so, agriculture still accounts for around 70 percent of employment.[2] Agricultural productivity is notoriously low in developing countries; so is productivity in informal, off-the-books enterprises.[3] As farms consolidate, mechanize, and shift to cash crops, rural jobs disappear, factory-made goods displace household production, and people move to cities in search of work. Over time, per capital incomes rise and so does energy consumption. South Korea was still a poor country in 1980, with per capita income around $1800. Over the next decade, per capita income more than tripled, and South Korea's energy consumption doubled in the 1980s and redoubled over the next decade; per-capita energy consumption today is more than five times that in North Korea.[4] Change will come, one way or another, even to North Korea, and energy consumption will continue to rise in Nigeria and a hundred other countries as farms mechanize, households and businesses install air conditioning, personal vehicle fleets swell, and

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[1] Mark Caine, et al., *Our High-Energy Planet* (Oakland, CA: Breakthrough Institute, and Washington, DC and Tempe, AZ: Consortium for Science, Policy and Outcomes, April 2014).

[2] "2014 World Development Indicators," World Bank, Table 3.12, wdi.worldbank.org/tables; "World Fact Book," Central Intelligence Agency, www.cia.gov/library/publications/the-world-factbook/geos/ni.html.

[3] Rafael La Porta and Andrei Shleifer, "Informality and Development," *Journal of Economic Perspectives*, Vol. 28, No. 3, 2014, pp. 109-126.

[4] "2014 World Development Indicators," Table 3.6.

energy-intensive industries such as steel and cement expand to meet demand for homes, schools, hospitals, office buildings and factories, and for roads, highways, and other public infrastructure.

Although many developing countries have opportunities to build out their energy systems with heavy emphasis on renewables, the poorer among them will justifiably gravitate towards low-cost sources of energy—which, at least for electrical power, will in many parts of the world continue to be coal. Many governments will also continue to subsidize energy, in part to mollify restive populations.[5] Even if low-income countries follow wealthy economies such as the United States and Germany in turning increasingly to renewables, fossil fuels—not only coal but oil, for which no broadly practical substitutes of demonstrated sustainability as a transportation fuel have been found—will continue to be extracted and burned. Emissions of CO_2 and other GHGs will continue to rise. So will global average temperatures.

2. Innovation in Context

Invention, commercialization of innovations, and diffusion proceed differently in different parts of the world, depending on "innovation systems" that reflect each nation's institutional structures, politics, and culture. Nicholas Bloom, an economist who has conducted extensive cross-national comparisons of firm-level performance, may overstate, or maybe not, in saying "If Sam Walton had been based in Italy or in India, he would have five stores by now, probably called 'Sam Walton's Family Market.' Each one would have been managed by one of his sons or sons-in-law."[6]

The common feature of innovation, whether technological, political, or behavioral (individual and societal), is this: Whatever is considered new is not just an idea but a change of some sort that has diffused and found acceptance, with observable consequences. Energy subsidies were an innovation in US politics and policy a century ago, when Washington first extended tax preferences for oil exploration. From 1916 drillers were permitted to write off costs rather than capitalizing them, reducing their tax bills; oil depletion allowances followed a decade

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[5] An IMF study estimates the value of energy subsidies worldwide at around 0.7 percent of world economic output, weighted heavily toward fossil fuel production by exporting nations; in more than a few of these countries, energy subsidies exceed public spending on education and health care combined. *Energy Subsidy Reform: Lessons and Implications* (N.p.: International Monetary Fund, January 28, 2013).

[6] "Interview: Nicholas Bloom," *Econ Focus* [Federal Reserve Bank of Richmond], Second Quarter 2014, pp. 22-26; quotation from p. 25.

later.[7] Policy innovation continues, taking forms that include new types of subsidies, such as feed-in tariffs in some US states and European countries that require electrical utilities to take and pay for power generated by solar panels installed on residential and commercial buildings.

In the pioneering analyses of Joseph Schumpeter during the first half of the 20th century, which continue to underpin our understanding of innovation, business entrepreneurs devise and bring to market new products (automobiles, telephones), learn to produce familiar goods or services in new ways (catalog retailing in the 1920s, Internet retailing today), and introduce new forms of organization (joint stock corporations, lean production in manufacturing).[8] New product concepts do not count as innovations until commercialization; that is, marketplace introduction, after which some new products (and processes) survive and flourish while others later fail, as battery-electric automobiles did in the early years of the auto industry—in 1915 over 40 US firms still manufactured battery-electric vehicles—and again in the 1990s.

As Schumpeter understood, the immensely productive dynamism of the US economy stems in considerable measure from the entry of new firms and the exit of old. George Westinghouse made his fortune during the electrification of America early in the 20th century. The company that bears his name went on to innovate in nuclear reactors for the Navy and then sold similar reactors to utilities. Toshiba now owns the Westinghouse brand name. Studebaker built buggies, then automobiles, then disappeared, unable to defend the niche it had established in the then-US, now global, auto industry. Pratt & Whitney, but not Curtiss Wright, learned to design and manufacture jet engines in place of piston engines to meet the demands of military and civilian customers, and American Airlines, but not Eastern, survived deregulation and the shift to discount air travel. As Schumpeter's influence grew, evolutionary analogies became common, with "the appearance, growth and disappearance of firms … likened to the processes of birth, growth, and death of biological organisms."[9]

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[7] Salvatore Lazzari, *Energy Tax Policy: History and Current Issues*, RL33578 (Washington, DC: Congressional Research Service, June 10, 2008), pp. 2-3.

[8] Schumpeter's hugely influential 1942 book *Capitalism, Socialism and Democracy* (5th edition, London: Allen and Unwin, 1976) is the most closely associated of his works with images of creative destruction as the driving force of capitalism.

[9] Edith Tilton Penrose, "Biological Analogies in the Theory of the Firm," *American Economic Review*, Vol. 42, No. 5, 1952, pp. 804-819; quotation from p. 804.

In views current today, the overall process reflects some combination of the forces of technology push—the result of inventors and entrepreneurs developing new goods and services in search of new and profitable markets—and market pull—the result of customers (individuals, households, businesses) seeking goods and services with attributes they value. Governments both push, as through R&D programs, and exert pull, through procurement. Indeed, the high costs common for infant technologies may leave governments as the only customers initially. US military and space agencies bought the first integrated circuit (IC) chips and solar photovoltaic (PV) cells, and after General Electric and Westinghouse developed nuclear propulsion reactors under contract for the US Navy's submarines, government subsidized design and construction of the first commercial nuclear power plant, based on a similar (Westinghouse) design, at Shippingport, Pennsylvania.

In the 1940s, to give a more extended example, jet engines were far more costly to purchase and operate than piston engines; they were also unreliable and prodigious guzzlers of fuel. No matter to militaries that adopted them, since jet fighters offered speeds and rates-of-climb far superior to propeller-drive planes, which could not hope to survive in aerial combat against the new jets. Subsequent technical improvements came quickly and continued for decades. Defense agencies paid many of the bills, through contracts for procurement and for R&D itself, and, less directly, through accumulation of operating experience, an aspect of innovation that economists call learning-by-using.[10] With evidence in hand of improvements in reliability and reductions in fuel consumption, airframe manufacturers began to design commercial aircraft around jet engines, and airline experience soon began making its own contributions to further technical gains. Starting in the 1950s, several firms also explored gas turbines as power units for cars and trucks, some built prototypes, and Chrysler, in the 1960s placed 50 turbine cars in the hands of selected motorists in a kind of beta test. No company attempted commercialization. In road vehicle applications, operating efficiency could not be raised to satisfactory levels, unlike larger units designed for aircraft. For fundamental technical reasons, gas turbines scale down poorly, and even in large sizes they deliver their best efficiency under steady high loads, the usual operating conditions for planes during cruise but not in autos.

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[10] Nathan Rosenberg, "Learning by Using," in *Inside the Black Box: Technology in Economics* (New York: Cambridge University Press, 1982), pp. 120-140.

On the other hand, electric utilities, with duty cycles more like those in aviation, began in the 1980s to buy turbines based on aircraft designs for peak generating capacity.

As learning-by-using in aviation suggests, along with many other cases, the sources of performance gains go beyond the narrowly technical. Nuclear power plants also performed poorly in their early years. Capacity factors—the fraction of power theoretically available—averaged only 50-60 percent in utility service in the United States during the middle 1970s; by the early 2000s, the 100 or so plants then in operation were averaging 90 percent.[11] Nearly all these plants had been designed in the 1960s and 1970s, and most had been completed by the mid-1970s; their "technology," in other words, was largely fixed. Capacity factors rose as operators, technicians, engineers, and managers identified operating and maintenance practices that reduced the likelihood of unexpected outages and extended intervals between planned shutdowns. Only then did nuclear power become a reliable source of base-load generating capacity.

Based on a great many detailed accounts of innovation as it has occurred in different technological families and different industries, technical change can be visualized in terms of sporadic, unpredictable bursts of more-or-less radical innovation that interrupt and sometimes alter long-term trajectories of performance improvement. The overall process has been called punctuated equilibrium, a further analogy drawn from evolutionary biology.[12] Evocative as it is, the label can mislead, since "equilibrium" cannot be taken literally. Ongoing innovations may themselves be quite fundamental, yet lose visibility as they become submerged in the long-term trend of improvement. Over time, gains of the sort represented by Moore's Law for ICs (not of course a natural law but simply an observed and self-fulfilling regularity) and the equivalent PV "learning curve" bring reductions in costs and prices, gains in functional performance, and expanding application ranges. Moore's Law itself reflects a great many quite fundamental technical advances, including whole new families of ICs, such as complementary metal oxide semiconductor (CMOS) chips—inexpensive to fabricate and low in power consumption, hence ideal for consumer products such as digital watches and hand calculators, their first big markets

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[11] *Monthly Energy Review January 2015*, DOE/EIA-0035(2015/01) (Washington, DC: Energy Information Administration, January 28, 2015), Table 8.1, p. 117.

[12] See, e.g., Daniel A. Levinthal, "The Slow Pace of Rapid Technological Change: Gradualism and Punctuation in Technological Change," *Industrial and Corporate Change*, Vol. 7, No. 2, 1998, pp. 217-247.

(digital cameras are one of the more recent). Only the most detailed depictions of the Moore's Law trend reveal the consequent bumps and jerks.

Even though incremental innovation is ubiquitous, and central to technological advance, enthusiasts urging greater investments in radical and disruptive innovation sometimes downplay or dismiss these seemingly mundane portions of innovation ecosystems.[13] Yet truly radical innovations such as the jet engine, PV cell, and IC chip are rare and unpredictable; no one can know, with much certainty, where to look or how much money to spend in the search. Highly touted discoveries, moreover, sometimes languish indefinitely. In 1987 when President Ronald Reagan, flanked by three cabinet secretaries, introduced his administration's program for rapid commercialization of high-temperature superconductivity, he cast the new family of materials as heralding "a revolution of shattered paradigms." High-temperature superconductivity, he said, promised "a quantum leap in energy efficiency that would bring with it a host of benefits, not least among them a reduced dependence on foreign oil, a cleaner environment, and a stronger national economy."[14] Since that time, although scientists have produced a steady stream of research results, the promised innovations have not appeared.

To extend the parallel with biological evolution, technological innovation can be understood as driven by generation of variety, new ideas that survive at least to the point of commercialization (analogous to mutations), and selection, post-commercialization winnowing as customers pick and choose among products that reach the marketplace (analogous to survival in some sort of ecological niche). Technical advance engenders variety, whether through scientific discovery (lasers, synthetic fibers such as nylon) or early 20th century tinkering (automobiles, heavier-than-air flight) and its descendants (web apps). Entrepreneurial vision also generates variety (web apps), along with more routine sorts of business planning ("new and improved" cosmetics).

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[13] Nathan Rosenberg observed many years ago that "Schumpeter never quite over-came his preoccupation with the charismatic aspects of leadership and its role in instituting changes in the operation of the economic system. As a result, his own towering intellectual leadership in this area has led to an excessive concern with … the circumstances surrounding the initial 'breakthrough,' and to a neglect of …. the cumulative impact of relatively small innovations …." Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840-1910," *Journal of Economic History*, Vol. 23, No. 4, 1963, pp. 414-43; quotation on p. 424.

[14] One of us was present in the ballroom of the Washington Hilton when President Reagan, reading from a teleprompter, spoke of "shattered para-digims." "Remarks at the Federal Conference on Commercial Applications of Superconductivity, July 28, 1987," http://www.reagan.utexas.edu/archives/speeches/1987/072887a.htm.

Distinguishing between generation of variety and selection helps in structuring policy portfolios. Government R&D and demonstration projects showed nuclear power to be technically viable based on reactors originally designed for submarines. Given this new variety of energy source, utilities had to select—to decide whether or not to believe the promises of federal agencies proffering subsidies and suppliers such as General Electric and Westinghouse. Many utilities did invest, initial performance fell short of expectations, and the nuclear power boom flatlined. A few older plants have now been shut down and in the United States nuclear generating capacity seems to be in slow decline. The niche could continue to contract. Alternatively, proposals for a new generation of small, standardized, factory-fabricated reactor designs could attract private capital and government subsidies, although in countries such as the United States that bought into the 1960s vision of cheap and abundant non-polluting nuclear power, it seems at least as likely that memories of earlier overpromises and cost overruns will check their prospects.

3. Three Levels of Technological and Social Change

Our discussion of the complexity of innovation in general and for energy technology in particular is meant to illustrate a problem that is largely neglected in discussions and analysis of how best to catalyze a shift toward low-carbon energy systems: there are many different analytical perspectives for understanding and trying to intervene in energy innovation, and these perspectives are neither mutually commensurable nor cumulatively coherent. One result of this multidimensionality is a Tower-of-Babel-like public discourse and policy landscape that makes even sensible discussion, let alone policy analysis, challenging if not impossible. How should we think about the land-use demands of biomass for biofuels or for solar energy production? Solar versus wind? Of distributed versus concentrated solar? Of renewable energy storage versus natural gas backstopping? Of oil from fracking versus biofuels? What does innovation and technological change even mean given such multidimensional complexity? And how is action toward a single goal—decarbonization—possible amidst such complexity? As a nakedly empirical matter, on the global scale the answer to date is: it is not possible.

Our purpose in the remainder of this paper is to provide a framework for creating a clearer view of energy technology innovation, under the hypothesis that a clearer view might permit more sensible public discourse, and thus enable better democratic selection of options.

Without too much insult to analytical rigor, technological innovations can be separated from societal innovations which technology affects, which affect technology, and in which technology is embedded. This is possible because technological innovation, following a century of empirical and theoretical work, has become relatively well understood, certainly compared to social change. Yet if the two can be uncoupled analytically, any effort to do so must accept that prediction of social change will remain conjectural.

Twitter, a social innovation enabled by technology, succeeded, but no one could know initially whether users would accept and adapt to 140-character messaging. Indeed, market behavior routinely confounds predictions. Food and diet fashions come and go, defeating efforts at product design, prediction by market research groups, and persuasion through advertising.[15] In mobile telephony, Motorola, Nokia, and BlackBerry each rose and fell over a few short years. BlackBerry's stock market valuation increased from a few billion dollars in 1997 to over $80 billion in 2008, then fell to less than $5 billion; the main reason, according to a former executive: "People just didn't like it anymore."[16] Twitter spurred follow-on innovations, as many successful products do. New applications also emerge as "enabling" innovations, such as the Internet, spread. Other examples are less obvious. The (energy intensive) Hall-Héroult process for making aluminum led to cheap cookware as well as costly high-strength aircraft alloys. While cheap aluminum cookware might have been predicted, in the first few decades after all-aluminum DC-3s began carrying paying passengers no one could have foreseen firms such as People Express and Ryanair that pioneered low-cost vacation air travel. And while market-driven innovations such as mobile telephony spread swiftly in wealthy and poor countries alike, scarce resources—human and organizational capital especially—can hinder diffusion of both imported and indigenous innovations in developing economies. Thus widespread mobile telephone networks can be found in countries unable to supply electrical power from efficient generating plants on a dependable basis. Efforts to pick apart the reasons may end in suppositions, plausible but arguable, having to do, for instance, with entrepreneurial opportunity. For instance, mobile

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[15] Schumpeter: "It was not enough to produce satisfactory soap, it was also necessary to induce people to wash—a social function of advertisement that is often inadequately appreciated." Quoted on p. 258 in Thomas K. McCraw, *Prophet of Innovation: Joseph Schumpeter and Creative Destruction* (Cambridge, MA: Harvard University Press, 2007).

[16] Felix Gillette, Diane Brady, and Caroline Winter, "The Rise and Fall of BlackBerry: An Oral History," *Bloomberg Businessweek*, December 9-December 15, 2013, pp. 54-60; quotation on p. 58.

telephony may attract a country's more capable technicians and managers, people who see the chance to build an enterprise of their own in an emerging market without the burden of inbred practices, sunk investments, and established patterns of political payoff and patronage found in the electric power industries of so many countries.

Social scientists have learned a great deal about the diffusion of innovations such as Twitter: how advertising affects the spread of, say, margarine in place of butter; how word-of-mouth (and today its digital equivalents) sells popular music and pickup trucks (US automakers unveil new models in Texas for maximal impact); how birth control pills and other innovations in contraception influence individual behavior and collective phenomena such as household formation and family size; and how free public education leads young people to stay in school longer, learn more and earn more, with consequences including a greater likelihood that they will contribute to further innovation. At the same time, as such examples also suggest, the larger sets of social dynamics to which innovation contributes—changes in sexual behavior, cohabitation, and marriage, labor market participation (e.g., by women), social mobility, urbanization and globalization—may, while visible, resist agreed explanations, and will certainly resist conscious steering. Over decades of interaction, cause-effect relationships become submerged in large-scale social dynamics and difficult to tease out. Projections into the future are still more problematic.

In the following table, we consider technologies in terms of end products that perform valued functions, some of them vital, others more nearly matters of convenience.[17] Childhood vaccinations, for example, alter our immune system so we can expect to live to old age; electric toothbrushes, depending on how they are used, may help us avoid dentures. At the simplest level, then—Level 1—an Airbus flies us from New York to London with remarkable safety. Smartphones adjust automatically to London time and make it easy to reconfirm hotel reservations. At some point not too far in the future we may ride to the hotel in a driver-less, electrically-powered taxi.

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[17] Braden Allenby and Daniel Sarewitz, *The Techno-Human Condition* (Cambridge, MA: MIT Press, 2011), pp. 31-85.

Technologies, Networks, and Systems

Level 1: Complex Technologies

- Progressive incremental performance improvement over many decades (commercial aircraft).
- Increased technical complexity in a largely closed, engineered, manageable system with transparent performance metrics (fuel consumption, cost per seat mile, accident rate).
- Uncertainty reduced with accumulating technical knowledge and operating experience (mathematical models for prediction of aircraft performance).

Level 2: Complex Technological Networks[**]

- Core system reliability coexists with ancillary dysfunction (airport delays, noise).
- Continually increasing system complexity in a partly open, difficult-to-manage sociotechnical system (air traffic control, critical for accident prevention and at the same time a cause of delays and fuel-wasting routing patterns chosen for safety).
- Uncertainty managed through appropriate institutional and social arrangements (agreed rules for separation of aircraft in three dimensions; English as a standard language for pilots and air traffic controllers).

Level 3: Complex Sociotechnical and Earth Systems

- System boundaries disappear, system dynamics variably unpredictable (automation degrades piloting skills, a new cause of accidents; jet engine emissions affect stratospheric chemistry).
- Uncertainty grows with system complexity (long-term sustainability of mass air travel).

Note: This table uses aircraft/air travel as a familiar, easily comprehended example. At present aircraft are minor, not major, sources of greenhouse gas emissions, but their share is growing relative to other sources. Fuel, moreover, accounts for one-third or more of airline operating costs, so that energy pricing and fuel-saving innovations in airframe and engine design have been significant factors in competition.

At Level 1, technologies evolve through ongoing interactions between those who do the development and those who use new products and systems. Two modes of interaction predominate. For expensive, long-lived capital goods such as commercial aircraft, interactive dialog between suppliers and customers—manufacturers of airframes and engines on one side and airlines, lead customers especially, on the other—becomes part of the basis for design decisions; major attributes may emerge only after years of information exchange, informal discussion, and negotiation. Much the same is true—design decisions following from and based upon dialog and negotiation—for central-station electric generating plants, enterprise software systems, and highway bridges paid for by public agencies but designed and built by private firms. For consumer products such as smartphones and health insurance plans, on the other hand, latent demand is difficult to gauge. Potential customers may not be able to easily or accurately envision what an innovation will mean for them personally; they do not have "business plans" in their heads, unlike airlines shopping for next-generation planes from Boeing or Airbus. Market research may yield useful predictions for a new type of breakfast cereal, less often for take-up of innovations such as mobile telephony, which grew for years at rates far outstripping projections.

Technologies also function as parts of more complex networks—Level 2. The network label suggests the importance of linkages—working relationships, structured in some way—between actors that may include business firms and their customers, state agencies, intergovernmental organizations, and international regimes. An effective malaria vaccine would count as a scientific and medical breakthrough with profound effects in large parts of the world, and not just in preventing illness: economic output, for instance, depends ultimately on what individuals accomplish and healthy people are more productive. Gaining the benefits of malaria or other vaccines, in less developed countries especially, may require adjustments in health care delivery networks. For communicable diseases like measles, population-wide effectiveness depends on vaccination of a sufficiently large fractions of people to achieve community (or herd) immunity, at which point a kind of threshold effect kicks in and the likelihood of transmission to the unvaccinated minority falls to some very low level. Arresting and possibly eradicating such diseases then requires not only effective vaccines but effective means for reaching large numbers of people. This is a matter of organization and management: persuading skeptics of the benefits; negotiating arrangements with local political figures who may have their own agendas; developing standardized procedures; training workers, perhaps locally hired. Then too some vaccines must be refrigerated. The electrical power to accomplish this seemingly mundane task, or to make ice, may or may not be consistently available in low-income countries.

Generally speaking, societies have learned to design, build, and operate these Level 2 networks. Learning is possible because the network goal is to deliver the Level 1 function that people depend on. Failure is therefore both conspicuous and clearly defined. When failures occur, the causes must be diagnosed and future failures of a similar sort prevented, in principle if not always in practice. Standard time zones came about in response to confusion that caused train wrecks. As railway networks grew and service became routine and reliable, firms such as Armour and Swift could take advantage of the new capabilities to revolutionize meatpacking and distribution. In practice, failures occur: trains and jetliners still crash, as do electrical grids, but they are pretty reliable, and when they become unreliable customers get very upset. Organizational competence—keeping refrigerated trains running on time—has always been a key to using technology effectively, and in principle the organizations that manage Level 2 networks must develop and exercise stewardship over the knowledge and skills needed to ensure that Level 1 technological components function reliably.

This is not true at Level 3. Here complexity becomes pervasive and outcomes difficult or impossible to predict.[18] As component parts in software-intensive digital systems, IC chips and the automation they catalyze, have contributed, inarguably if murkily, to jobless growth and wage inequality in the United States and elsewhere, which in turn feeds into political reactions that help determine national policies on a wide variety of issues with seemingly no connection to information technology, such as trade policies, education and training programs, and the social safety net. What we emphasize here is that intervening in the design and use of software-intensive digital systems is not one of the available tools for addressing the labor market and distributional consequences of those systems. This is in marked contrast to Level 2, where complexities may be very great indeed, but intervention is still focused on the technological system itself. For example, in 2003 an undetected software bug triggered a sequence of events leading to a major power blackout over the northeastern United States and Canada. All large software systems have such errors; with 10^{20} and more possible end-to-end execution paths, there is simply no way to test all possibilities. Technological system performance was restored by modifying the system itself (and while the 2003 fault will not recur, other bugs no doubt lurk).

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[18] As will be clear, our typology differs from others featuring three levels, as for example Frank W. Geels, "Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study," *Research Policy*, Vol. 31, 2002, pp. 1257-1274; and Frank W. Geels and Johan Schot, "Typology of Sociotechnical Transition Pathways," *Research Policy*, Vol. 36, 2007, pp. 399-417. Geels and others who have contributed to this literature adopt largely theoretical perspectives in seeking to explain relatively straightforward technological shifts: the case study alluded to in the title of the first paper cited above deals with the transition at sea from sail to steam, the history of which has been written. Further, and despite occasional protestations to the contrary, little of this work addresses policy. See, e.g., Adrian Smith, Jan-Peter Voß, and John Grin, "Innovation Studies and Sustainability Transitions: The Allure of the Multi-level Perspective and its Challenges," *Research Policy*, Vol. 39, 2010, pp. 435-448. Our concerns lie rather with practical policies and their implementation. We stress the political forces that affect system-level sociotechnical change and the fundamental uncertainty in outcomes that results, since political outcomes themselves are so difficult to predict. Who, after all, anticipated the demise of the Soviet Union (except in the most general terms)? More narrowly, the end of the Cold War led to shifts in some major US weapons programs, with possible effects on technological spinoffs that have had profound effects on commercial industry. Much of the literature associated with sociotechnical systems seems to us remarkably insensitive to raw political power (e.g., that wielded by large corporations), to bureaucratic politics (and agency effectiveness), and also to the constraints imposed on human systems by accepted laws of physical science. In this we share several concerns expressed in James Meadowcroft, "What About the Politics? Sustainable Development, Transition Management, and Long Term Energy Transitions," *Policy Sciences*, Vol. 42, No. 4, 2009, pp. 323-340.

In the early decades of the US auto industry, hundreds of firms competed to sell vehicles powered by gasoline engines, storage batteries, and steam—Level 1 innovations, products of the state of the evolving engineering arts. Purchasers eventually chose gasoline engines and the oil industry boomed. A steady stream of, again, Level 1 innovations in exploration, extraction, and refining kept fuel prices low. Cars and trucks needed hard-surfaced roads and highways, and governments (local, state, and federal) provided them (financed in part by the policy innovation of fuel taxes). This Level 2 network response brought increases in accidental injury and death arrested only in the 1960s by (federal) safety standards, regulations that addressed Level 2 dysfunction through Level 1 engineering, again by means of relatively standard engineering approaches. By this time, systemic or Level 3 complexity had long since emerged as well. Low-cost personal vehicles enabled families that could afford detached suburban homes to move outward from cities. Others moved inward from rural America, as Level 1 agricultural innovations, including mechanization (farmers sometimes adapted Model Ts as tractors or barnyard power sources) pushed up productivity and farm families that could not keep pace left the land for wage work in towns and cities. The trucking industry (Level 2) grew to supply wholesale distribution and retail sales outlets far from fixed railway lines; refrigerated tractor-trailers, for instance, took meat from terminals to supermarkets scattered through low-density suburbs. As agricultural employment fell, service-sector employment rose, along with white-collar jobs in goods-producing firms; veritable armies of clerical and administrative workers were needed to staff rapidly growing new enterprises with multiple divisions and many lines of business. Suburban sprawl, finally, brought seemingly unmanageable traffic congestion to some parts of the United States, contributing (in unmeasurable ways) to modest recent levels of counter-migration to cities, presumably accompanied by modest reductions in GHG emissions, at least from transport.

Climate change is a Level 3 phenomenon, the result of imperfectly understood mechanisms that encompass everything from wealth distribution and appetite for luxury goods to the politics of nuclear energy, not to mention the plate tectonic movements, unpredictable and immune to human influence, that led to the Fukushima disaster. And of course the nuclear reactors that provide dependable, CO_2-free electrical power were developed initially for making fissile material for bombs, which led to a Level 2 international regime that attempts to regulate proliferation of enriched uranium, plutonium, and bomb-making know-how. This regime functions imperfectly. While many analysts believe its failures have increased the risks of nuclear warheads again being used in anger, others argue, counterintuitively, that nuclear proliferation enhances deterrence. Theory is a woefully inadequate guide to such Level 3 matters. Fukushima, finally, had consequences far beyond Japan, for example in contributing to the political decision by Germany to switch from nuclear power to renewable sources, a risky attempt to break free of inertia and lock-in that, to date, has led to both rising energy costs and rising CO_2 emissions from the electrical power sector. Sweden made a similar choice, later reversed. If sustained and successful, Germany's approach will contribute to significant advances in renewable energy sources that can be integrated into an existing grid system. Yet the benefits lie well in the future and the transition costs will be forbidding and must be paid first.

Level 3 problems cannot be fully analyzed and resolved on their own terms. Societies do not know how to intervene to achieve predictable outcomes: the variables are too many, their interconnections too uncertain for cause-effect relationships to be derived. Nobody can know what would follow from an attempt to end Iran's nuclear bomb program by force (or through treaty, for that matter—but the reasonable belief is that violence begets unintended consequences more quickly and unmanageably than diplomacy). Nor can anyone know how high a price on carbon would be needed to induce significant restructuring of the world energy system, much less how this restructuring would proceed. With strong price signals energy systems would certainly change, but not in predictable ways. In low-income countries, big increases in energy prices would be calamitous for billions of people. In principle, prices could be (further) subsidized, and richer countries might perhaps offset some of these expenditures. In practice, promises to compensate those disadvantaged by rising energy prices have little credibility within countries and interstate agreements have still less absent supranational authority, which does not exist.[19] Would Level 3 benefits outweigh the costs? The question is unanswerable, even incoherent. If the problem is CO_2 in the atmosphere, mitigation of climate change will have to be approached at Levels 1 and 2. Doing so effectively requires an appreciation of energy technologies and systems, how they differ from one another and from non-energy technologies, and of the characteristics of industries and markets that give rise to energy-technology innovations.

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[19] But see Robert O. Keohane and David G. Victor, "The Regime Complex for Climate Change," *Perspectives on Politics*, Vol. 9, No. 1, March 2011, pp. 7-23.

4. What's Special About Energy-Climate Innovation?

Two things. Energy is a commodity, like sweet corn or Muzak. Second, physical laws impose upper bounds on energy conversion processes. Both constraints operate chiefly at Level 1.

People do not care about energy in the ways they care about pickup trucks, much less birth control. They care about what energy provides: heat and light, horsepower, do-everything smartphones. Electricity and gasoline (within grades) sell on price alone, and residential solar systems will never diffuse like mobile telephones, which served a new function and so didn't have to displace an incumbent technology to proliferate. End products that consume energy can be differentiated through design features, giving business firms powerful incentives for innovation. Unless energy innovations make new products or new features possible, or promise meaningful end-product performance advantages—as by extending recharge intervals for battery-electric vehicles—private incentives for innovation extend little beyond cost reduction. The commodity nature of energy reinforces justifications for public policies to strengthen private incentives for innovation.

Physical laws tell us that energy systems cannot improve without apparent limit, as familiar digital technologies seem to. Smartphone apps multiply indefinitely, and although Moore's Law for ICs will at some point bump up against quantum effects, human ingenuity continues to push this point into the future. Ceilings on PV efficiency, on the other hand, were apparent from the beginning, and batteries, no matter how the design of lithium-ion cathodes might be tweaked, will always and necessarily give back less energy on discharge than put in during charging, just as air conditioners will always cause more heating than cooling.

At the same time, energy-system innovation goes on continuously. Architects and engineers learn to balance heating and air conditioning loads in buildings more effectively, minimizing spatial and temporal temperature variations to improve comfort levels while saving energy. PV firms fine-tune their manufacturing processes to raise production yields by fractions of a percentage point and automakers reduce engine friction and accessory losses to increase mileage ratings by a tenth of a mile per gallon. As these sorts of advances accumulate, they create moving targets for alternative technologies: battery-electric and fuel cell-electric powertrains must compete with increasingly efficient conventional engines incorporating innovations such as direct in-cylinder fuel injection that themselves represent considerable advances in the "state of the art."

Contrasts between the PV and auto industries illustrate some of the ways in which energy-related technologies and product markets interact. PV cells and systems are not quite commodities, but differences among them, in the eyes of most customers, tend to be minor. Without too much oversimplification, the several hundred companies worldwide that manufacture PV cells and systems can be said to follow one of two strategies: either they manufacture conventional single-crystal silicon devices, working to push down costs through process innovation and scale; or they seek to develop novel device structures and materials, such as compound or organic semiconductors, that promise a winning combination of manufacturing cost and efficiency (measured as the fraction of incident sunlight converted to electrical power). Competition in this industry, then, is closer to that for flat-screen televisions or energy-saving windows than for automobiles, which manufacturers differentiate with proliferating arrays of brand names, model designations, levels of performance, and comfort, convenience, and cosmetic features (heated leather seats, web connectivity, powered lift gates and running boards for SUVs and pickup trucks).

Entry barriers differ too, being much higher in the auto industry. While a new PV factory can be built and equipped for a few hundred million dollars, Tesla's "gigascale" battery plant, to be built in Nevada, is expected to cost \$5 billion.[20] Tesla, put together with Silicon Valley flair by Elon Musk, a classic Schumpeterian entrepreneur, seems to have ample financial resources, but several recent startups targeting similar niches—high-priced specialty vehicles differentiated by image as well as battery-electric (or hybrid) powertrains—ran through their capital quickly, could not arrange further financing, and closed their doors. Tesla, for its part, faces further barriers particular to its industry: legislation passed up to a century ago in many states bars automakers from direct selling, Tesla's preferred means of marketing and distribution. At a time when cars needed frequent service and customers wanted to kick a Model T's tires before putting down their money, these laws shielded independent dealerships from competition while allowing automakers to avoid the upfront costs of showrooms and repair facilities. Today they are an

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[20] Peter Elkind, "Inside Elon Musk's \$1.4 Billion Score," *Fortune*, December 1, 2014. The article's title refers to the financial package offered by Nevada, valued at "more than \$200,000 for each of the 6,500 direct jobs the gigafactory is supposed to create."

example of a phenomenon discussed by the historian Thomas Hughes and others: system-level inertia, or momentum, the tendency of large-scale sociotechnical systems to continue along established trajectories, sustained by interdependencies among technological systems and the institutions, interests, and practices that surround, contain, and constrain them.[21]

5. Breaking Systemic Momentum

Germany's Energiewende, or energy transition, provides an illustration, still unfolding, of complications following from a deliberate effort to steer large-scale systems in some new direction. With the last of Germany's nuclear plants scheduled to close in 2022, the Energiewende plan calls for renewables to supply half the country's electricity by 2030 and 80 percent by 2050, when primary energy consumption is to be half its 2008 level, and GHG emissions to decline by 80 percent or more relative to 1990.[22] Legislation passed in 2000 spurred heavy ongoing investments in wind energy and solar power, and Germany today has far more installed capacity today than any other European country. Even so, wind and solar produce power only when the wind blows and the sun shines, and in 2015 will generate no more than about 15 percent of Germany's electricity.[23] For the next decade or so, perhaps longer, the country must rely more heavily on fossil fuels or else change its policy. German utilities have been building new coal-fired plants and importing electricity from countries such as Poland that generate much of their power from coal; within Germany, entire towns are being moved to facilitate strip mining of lignite, a soft brown coal that, while abundant, is one of the most polluting of all fuels.[24]

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[21] "[C]haracteristics of technological momentum" include "acquired skill and knowledge, special-purpose machines and processes, enormous physical structures, and organizational bureaucracy." Thomas P. Hughes, "Technological Momentum," *Does Technology Drive History*, Merritt Roe Smith and Leo Marx, eds. (Cambridge, MA: MIT Press, 1994), pp. 102-113; quoted phrases from p. 108. Many others, historians and especially economists, also discuss technological lock-in. We adopt Hughes's language, less mechanical seeming, to keep the focus on institutions and politics rather than narrower economic phenomena.

[22] *Second Monitoring Report: "Energy of the Future"* (Berlin: Federal Ministry for Economic Affairs and Energy, March 2014), p. 4.

[23] *EU Energy, Transport, and GHG Emissions: Trends to 2050* (Luxembourg: European Union, 2014), p. 111.

[24] Stefan Nicola and Ladka Bauerova, "Dirtiest Coal's Rebirth in Europe Flattens Medieval Towns," *Bloomberg Businessweek,* January 6, 2014; Arne Jungjohann and Craig Morris, *The German Coal Conundrum: The Status of Coal Power in Germany's Energy Transition* (Washington, DC: Heinrich Böll Stiftung, June 2014).

Large-scale technological and institutional change brings risks and rewards, and German utilities worry about their profit-and-loss statements. While momentum is building in newly emerging systems, entrepreneurial opportunities loom large and losers may not be fully aware of their position. Once momentum has been built, sunk costs underpin systemic inertia.[25] And when a mature system is threatened, losers get plenty of warning and mobilize in opposition, fighting to block or at least to slow change. Because the benefits of environmental policies tend to be diffuse, perhaps imperceptible in the short term, innovators and entrepreneurs may face years of work in assembling and then holding together political coalitions that will back their plans, positions, and preferred policies without too much compromise.

Systems of governance matter too. Strong political currents underlie Energiewende. Germany's Green Party emerged in the early 1970s and became part of a coalition government as long ago as 1998. In the very different US political system, structured policies and plans such as Energiewende have no real legitimacy, and Congress has failed to pass a single major piece of environmental legislation since the Clean Air Act amendments of 1990, never mind a meaningful national energy "strategy," despite declarations of intent by US presidents going back to Richard Nixon.[26] The abdication by Congress has left a vacuum that the courts have perforce had to fill, through rulings, finalized after seemingly interminable delays, on increasingly strained interpretations of executive branch regulatory authority based on laws passed at a time when climate change had no visibility beyond the scientific community.[27] Movement away from coal-fired power plants has begun, yet the impetus has come mostly from economic forces (such as cheap natural gas from fracking) combined with anticipatory responses to tightening regulatory standards on pollutants including mercury and sulfur dioxide (SO_2). Utilities have decommissioned older, inefficient, and maintenance-intensive coal plants that they fear will be unable to meet future standards, at least without costly retrofits, and because some of these

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[25] Hughes, in "Technological Momentum in History: Hydrogenation in Germany 1898-1933," *Past & Present*, No. 44, 1969, pp. 106-132, emphasized the financial constraints of the firms he studied, along with the human and organizational capital represented by the knowledge and skill of their technical and managerial employees. Hughes was primarily concerned with how momentum was built, not how it could be altered; in his later work he stressed the system more than the enterprises that were part of it, and financial management receded in his analyses; as a historian of technology he perhaps also wanted to differentiate his approach from that of business history.

[26] http://www.cc.com/video-clips/n5dnf3/the-daily-show-with-jon-stewart-an-energy-independent-future.

[27] Jody Freeman and David B. Spence, "Old Statutes, New Problems," *University of Pennsylvania Law Review*, Vol. 163, No. 1, 2014, pp. 1-93.

plants, perhaps held in reserve for back-up and to provide peaking capacity, cost more to run than they bring in. By replacing them with high-efficiency gas turbines burning cheap natural gas, utilities expect increased profitability. CO_2 emissions also fall, but this is incidental. Although a number of technical approaches to carbon capture and storage (CCS) have been demonstrated, so that utilities could if required remove CO_2 from the flue gases of coal-burning plants—and those that run on natural gas or for that matter biomass—they have no reason to do so unless forced. In the United States, it would take a considerable feat of political architecture to force CCS on unwilling utilities and their customers. No other country has managed this, either.

Still, we can envision transformation of electric power generation, the largest source of global GHG emissions. Technical means exist, and further innovation will accompany concerted efforts to steer down new pathways. Energy conservation in buildings, too, seems reasonably straightforward, with a large inventory of proven Level 1 technologies available. Stronger incentives would speed implementation, again fostering, as a quite predictable consequence, ongoing incremental innovation. Much the same is true for many industrial processes. Transportation, by contrast, second to electric power generation as a source of GHGs globally, poses greater difficulties, technical and infrastructural; stated simply and despite four decades of predictions to the contrary,[28] there are no obvious Level 1 replacements for fossil fuels in transportation, leaving aside niches such as battery-electric vehicles in metropolitan areas.

Although incremental innovations sometimes culminate in radical technology change, as in the case of the Internet, no one should count on technological breakthroughs to alter the momentum of carbon-intensive energy systems. Genuine breakthroughs in energy technology have been rare. The most recent, nuclear power and solar PV, date from the middle of the last century. Most of today’s battery concepts, derived from well-known principles of electrochemisty, have been around for decades. Fuel cells, reduced to practice in the 1960s for the Gemini spacecraft, operate on principles known since the first half of the 19th century, and of course wind energy, hydropower, and biofuels go back still farther. The last energy technologies to spark waves of Schumpeterian transformation were steam power in the 18th century, central-station electric power generation in the 19th century, and oil and gas in the first half of the 20th century. Momentum will be shifted by means of large numbers of individually small innovations,

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[28] E.g., Amory B. Lovins, *Soft Energy Paths: Toward a Durable Peace* (New York: Penguin, 1977).

few of these with much visibility. To considerable extent, and depending on policy incentives, the pace will be set by life cycles for current Level 1 technologies: coal-fired power plants; residential and commercial buildings with leaky windows and poorly regulated heating and air conditioning systems; gas-guzzling light trucks bought as personal vehicles.

6. The Future of Energy-Climate Innovation

When policy goals cannot be adequately monetized, as for environmental impacts or national security, only government can drive innovation. Unsurprisingly, the World War II Manhattan project and Cold War Apollo program continue to be put forward as models for energy-climate innovation. They hold few positive lessons. Both were tightly managed within well-defined organizational hierarchies. For the Manhattan project, the goal was existentially compelling: to build an atomic bomb before the comparably skilled scientists and engineers of Hitler's Germany. As it happened, Germany put little effort into building a bomb, but no one in the United States could have known this with certainty. Likewise the Soviet Union did not seriously compete to land humans on the Moon, something few US officials realized until later, and the presumption of a space race helped keep the Apollo program on track. Although broad energy-system-wide goals for decarbonization may be articulated by activists, diplomats, and policymakers—as with Germany's Energiewende—the value of such goals is largely motivational; there can be no unitary goals for energy-climate technologies, comparable to building a bomb or a rocket, to which budgets and schedules can be keyed. The Manhattan project especially was run more like a "bet-the-company" undertaking in private sector than more typical government programs. The analogies advanced—most recently calling for a 10-year "Global Apollo Programme to Combat Climate Change"[29]—hold little beyond potentially misleading hortatory value.

Related lessons follow from two unequivocal accomplishments in environmental policy, the Montreal Protocol on Substances that Deplete the Ozone Layer, an international treaty, and 1990 amendments to the US Clean Air Act that limited power plant SO_2 emissions. The Montreal Protocol, which took effect in 1989, established timetables for ending production of offending chlorofluorocarbons (CFCs) such as Freon (a DuPont trademark). It worked for three

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[29] Louise Downing, "Scientists Start $150 Billion Program to Cut Clean-Energy Costs," *BloombergBusiness*, June 1, 2015; online.

primary reasons. Ozone depletion was well understood scientifically and known to raise risks of skin cancer, among other effects. Second, while CFCs were widely used as both refrigerants and aerosol spray propellants, a handful of large companies supplied most of the world market and several, including DuPont, had replacements well along in development and could expect to profit from the forced introduction of CFC substitutes. Third, while the new chemicals would cost more, the increases could be largely hidden in end-item pricing; they would add only a little to the total cost of a refrigerator or an automobile air conditioning system and purchasers would never see the bill. In essence, a Level 1 solution was available and could be plugged into a Level 2 network via a regulatory hammer aligned with profit-making potential, the interests of environmentalists, and a straightforward scientific finding confirmed by direct observation.

Much the same was true for SO_2 emitted by coal-burning power plants, known to cause smog and acid rain. Smog was visible to all and the evidence that SO_2 caused acid rain hard to deny. Technical solutions in the form of stack-gas scrubbers were available. Congress held out carrots by awarding tradable permits at no cost to utilities based on past SO_2 emissions. While opponents warned that compliance costs would drive up household electrical bills, their figures proved grossly inflated; as regulatory mandates took effect, both capital costs and operating costs came down rapidly—another illustration of incremental innovation at work. Unexpectedly, railroad deregulation also helped, as freight bills for shipping coal from mine mouths to power plants fell—another example of Level 2 network complexity.

Both these cases represent Level 1 solutions to Level 2 dysfunction. With increasing scale—more CFCs and SO_2 entering the atmosphere—symptoms appeared. Science pointed unambiguously to the causes and available or prospective technologies promised remedies. Policy *output*, in the form of the Montreal Protocol and the Clean Air Act amendments, then led—quite directly—to the desired *outcomes*, but what made these outcomes both technologically and politically viable was the availability of Level 1 solutions.

Climate change differs on multiple dimensions from these two examples, and neither SO_2 control nor the Montreal Protocol seems an especially useful precedent. The scale of the energy-climate problem is far greater, the technical solutions will be manifold and far more expensive, and the dangers do not, at least as yet, have the immediacy of urban smog or lakes bereft of fish or skin cancers feared as much by elected officials and corporate chieftains as by environmental activists and ordinary citizens. While some Level 1 technology remedies are in sight or available, they are too few (e.g., for reducing CO_2 from transportation) and some at least promise to be too costly to gain widespread support.

How then to proceed? Here we focus on the United States, the country we know best and something of a bellwether in technology and science, if not in energy-climate policy. Political theory and policy history tells us that the United States exhibits a "strong structural bias within our existing lawmaking institutions in favor of government acting slowly and incrementally."[30] Given a weak and fragmented federal system designed in the 18th century to make any sort of big change in policy difficult first to enact and then to implement, neither energy taxes such as might be based on estimates of the social cost of carbon, nor a cap-and-trade approach such as embodied in the Waxman-Markey bill that failed to pass in 2009, have much chance of future approval, at least in strong enough form to make much of a difference for climate mitigation. And if theorists favor such nominally "clean" approaches on grounds of economic efficiency, opponents almost invariably find scope for creative reinterpretation of laws and regulations, if not simple evasion. While energy bills can get through Congress if linked with "energy security" (or "independence"), it has been decades since the House and Senate could agree on environmental legislation of any significance. Focusing on Level 1 technological innovation, which is inherently incremental, rather than hoping that political forces will somehow come together to generate transformative change, better suits US institutions and those of numerous other countries.

Yet our point is not to bemoan the design of existing institutions. On the contrary, our analysis seeks to highlight how the realities of democracy, innovation, and climate change must all be taken into account in searching for practicable technological pathways to reducing the risks from human interference in the climate system. If one understands climate change mitigation as a Level 3 problem of complex sociotechnical systems interacting at the scale of global societies and indeed the Earth system itself, then neither the history of policy, nor of innovation, offers any very convincing precedents for how to modify *system* performance, deliberately and with outcomes both desired and foreseeable. This situation feels unsatisfactory and paradoxical:

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[30] Richard J. Lazarus, "Super Wicked Problems and Climate Change: Restraining the Present to Liberate the Future," *Cornell Law Review*, Vol. 94, 2009, pp. 1153-1233; quotation from p. 1180.

climate change plays out due to the Level 3 complexities; surely the solutions must lie in modifying those complexities as well? Our understanding of innovation as a social process tells us otherwise. Taking the essence of mitigation to be a Level 1 technology problem—a problem of innovations, mostly incremental but in large numbers and widely implemented—the history of innovation teaches us that the most productive policy pathways for rapid advance and performance improvement are likely to be those that are pursued at that same level, Level 1, like SO_2 scrubbers or automobile fuel economy standards, rather than efforts to steer the complex global energy system, in its entirety, in a new direction, as attempted by the Kyoto Protocol. And while we admire the ambition and risk-taking embodied in Germany's Energiewende, we emphasize that the success of this nation-scale effort is far from settled. Even if enormous Level 1 challenges such as energy storage for backing up renewable energy sources are overcome, the Level 2 political, economic, and organizational obstacles remain formidable. Initial results, which include rising energy costs and rising carbon emissions, are not likely to be reversed soon.

For a strategic approach to climate mitigation that would suit the American experience, we point toward a history of major public investments justified in terms of their capacity to deliver public goods. This has been the case for large public investments in Level 1 technologies for national defense (nuclear submarines and spy satellites), public health (sewage systems, vaccines), transportation infrastructure (the Interstate Highway System), and also for energy supply (the Tennessee Valley Authority and electrification of the American West). The public-goods justification itself contrasts markedly with the main rationale that has driven climate politics for three decades—the meting out of punishment for the unintended consequences of locked-in Level 3 systems. A public-goods approach, in contrast, focuses on expanding opportunity and benefits for all, and it enfranchises rather than alienates the private sector, which is the source of the innovation and products that are the tangible, Level 1 manifestation of expanding public welfare. Americans do not oppose clean, cheap, universally available energy achieved through wealth-creating innovations driven, in turn, by public investment.

The essence of the energy-climate innovation challenge is in some ways summed up by President Barack Obama's decision late in 2015 to reject the Keystone pipeline, which was to transport oil from the tar sands of western Canada to the refineries of the American Gulf Coast. [31] The rejection marked the culmination of a bruising, years-long political battle, with environmentalists arguing that producing oil from the tar sands catastrophically accelerates global warming, and opponents (mostly conservative Republicans, but some Democrats as well) arguing that it would create needed jobs and economic opportunity. The president's rejection, in the end, was a political gesture made to signal to the world his environmental bona fides on the eve of another international climate conference. But the rejection was made politically and economically possible by the low cost of oil worldwide, and the rapid expansion of cheap natural gas due to fracking, which combined to render the pipeline unnecessary for America's energy future. Meanwhile, when oil prices begin to climb once more, as they assuredly will, the tar sands will find their way into energy markets through other means. Until the Level 1 problem of carbon emissions is solved through innovation, the Level 3 problems of climate change will remain intractably political.

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[31] Coral Davenport, "President Rejects Keystone Pipeline, Invoking Climate," *New York Times*, November 7, 2015, p. A1 and A12.