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

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

John Alic and Daniel Sarewitz

Technological innovation since the time of the first Industrial Revolution is the proximate cause of global warming.[1] Further innovation in technical and social systems is the necessary route to mitigation. Governments must find ways to supply low-cost energy to those who cannot afford high-cost energy, a difficult task in poor parts of the world and impoverished enclaves even in the wealthiest countries, while at the same time reducing emissions of greenhouse gases (GHGs). They will have to devise political arrangements that foster innovation while dampening and diffusing opposition by interests that see their freedom of action, and their profits, threatened. Innovations in multiple systems in countries with widely varying patterns of economic output and energy consumption will be needed. Even if restricted to technology, the family of innovations in prospect for energy restructuring and climate mitigation would number in the millions, if counting were possible and incremental innovations included—and they must be, since ongoing incremental innovation is a primary mechanism in all forms of technological change.

Private firms will develop the necessary 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. Always and everywhere, innovation is messy, complicated, and contingent. Major questions begin with choice of technological pathways and choice of policy tools for guiding the world energy system along

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[1] Prepared for the workshop on "Opportunities in Crises: Technogoverning Sustainable Landscapes," University of Virginia, Charlottesville, March 18, 2015, drawing on work conducted by the Consortium for Science, Policy & Outcomes with support from the Clean Air Task Force, Bipartisan Policy Center, Nathan Cummings Foundation, and the David and Lucile Packard Foundation. See in general www.cspo.org/content/energy-innovation-further-reading#overlay-context=projects/dod-energy.

desirable pathways. While 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 will inevitably remain conjectural because of system-level complexity.

The basic dilemma for policy and politics has commonly been viewed in terms of externalities and the conflict between energy prices and presumptive climate mitigation costs. While this is narrowly true, the issues run much deeper. In wealthy countries, economic, political, and cultural forces have locked in place systems (for electric power, for transportation) based predominately on fossil fuels and representing enormous sunk costs and complex political and social arrangements. 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 sort of energy prices might be necessary to account for both the costs of environmental damages and necessary socio-technical change to move away from fossil fuels. Prices might well have to rise by an order of magnitude, which would cause its own set of highly unpredictable consequences for society and the environment.

When prices do rise, innovators respond on the supply side, making available not only new low-carbon energy sources, but new fossil fuel supplies as well, as illustrated by recent increases in North American production of unconventional oil and natural gas. Abundant supplies of low-priced natural gas encouraged fuel-switching by utilities; emissions declined as natural gas replaced coal (and also because of the economic slump that began in 2008). Rising energy prices also stimulate innovations that reduce consumption, through conservation and greater efficiency in energy conversion and energy distribution. Supply-side and demand-side innovations, working together, may have the unintended result of reducing the impetus for decarbonization and energy system restructuring and slowing the pace of innovation. Falling domestic coal consumption, for example, has led to rising US exports of coal.

1. Energy in Context

World population will continue to increase over coming decades, 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 worldwide need reliable supplies of low-cost energy to support increases in living standards.[2] Development simply cannot proceed otherwise, and as it does it will bring wrenching changes for billions of people; an absence of development, on the other hand, would bring, as predictable outcomes, poverty, misery, and conflict.

Since 1990 Nigeria's population has tripled and the proportion of people living in cities has increased from 30 percent to about 50 percent; even so, agriculture still accounts for around 70 percent of employment.[3] Over coming decades, wage labor in cities will replace agricultural employment, casual labor, and self-employment. In Brazil, with per capita income four to five times that of Nigeria, agricultural employment has fallen to around 15 percent of the total. Agricultural productivity is notoriously low in developing countries. So is productivity in informal, off-the-books enterprises.[4] As farms consolidate, mechanize, shift to cash crops, and adopt new practices, jobs disappear and people move to cities in search of work. With urbanization, shifting demographics, the decline of the informal sector, and rapid economic change more generally come new patterns of energy demand and consumption. South Korea's auto industry hardly existed in 1980. Ten years later production of cars and trucks exceeded that in Great Britain; over this same ten-year period, energy consumption in South Korea doubled, then redoubled in the 1990s.[5] Today, per-capita energy consumption in South Korea is more than five times greater than in North Korea. 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 energy-intensive industries such as steel and cement expand to meet demand for homes, schools, hospitals, office buildings and factories, roads, highways, and other public infrastructure. Given the tendency of urban growth to concentrate in coastal regions vulnerable to sea level rise, in countries that can afford it some of this steel and cement will also go into floodwalls.

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[2] 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).

[3] "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.

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

[5] "World Motor Vehicle Production, Selected Countries" (Washington, DC: Department of Transportation, Bureau of Transportation Statistics, n.d.); "2014 World Development Indicators," Table 3.6.

Many still-developing countries have opportunities to build out their energy systems with heavy emphasis on renewables, yet the poorer among them will justifiably gravitate towards low-cost sources of energy—which, at least for electrical power, continues to be coal, with which Earth has been abundantly supplied. Governments will also continue to subsidize energy, in part to mollify restive populations.[6] Even if poorer 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 substitutes of demonstrated sustainability as a transportation fuel have yet been found—will continue to be extracted and burned. Carbon dioxide (CO_2) and other GHG emissions will continue to rise. So will global average temperatures.

Global warming will alter entire ecosystems, with consequences that resonate with other stressors such as deforestation and population growth and redound unpredictably across countries as well as internally. Some countries may run short of water for drinking and irrigation, others will be at greater risk from floods. Pakistan, one of the world's most troubled nations, is also highly vulnerable to climate change: over the years 2003-2012, only three other countries suffered greater losses, relative to national income, from natural disasters such as extreme weather events.[7] Scientists expect such events—drought, floods, storms—to increase in frequency and severity as Earth warms. Pakistan shares water from the Indus basin with India. Deep grievances divide the two countries and their governments routinely blame each other for monsoon flooding, which killed thousands of people in 2014 alone. India and Pakistan, both nuclear powers, have fought three past wars. Up to now, environmental stressors have not been listed among the proximate causes of war.[8] Yet that is no guarantee of the future. Climate change could well join disruptive socioeconomic and environmental shifts in altering the dynamics of active and latent conflicts both within countries and among them. Still, the most likely path for improving Pakistan's prospects is economic development underlain by significant growth in

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[6] An IMF study estimates the value of energy subsidies worldwide at about 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).

[7] *World Development Report 2014* (Washington, DC: World Bank, 2013), pp. 314-315.

[8] Nils Petter Gleditsch, "Whither the Weather? Climate Change and Conflict," *Journal of Peace Research*, Vol. 49, January 2012, pp. 3-9.

energy consumption. Success in this domain is to be hoped for, yet will add to global emissions growth.

2. Innovation in Context

Invention, commercialization of innovations, and diffusion work differently in different parts of the world, depending on "innovation systems" that reflect each nation's institutional structures, politics, and culture.[9] 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."[10]

Societal change, including innovations in government polices and industrial practices, and new patterns of life and work, interact with and accompany technological change. The societal and technological aspects can be uncoupled analytically, but any effort to do so must accept that prediction of societal change will remain conjectural. For example, market-driven innovations such as mobile telephony have spread swiftly in wealthy and poor countries alike even as seemingly scarce resources—human and organizational capital especially—hinder diffusion of other imported innovations in much of the developing world, as well as indigenous innovation. Widespread mobile telephone networks, for instance, may 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 plausible but hardly iron-clad explanations having to do, for instance, with entrepreneurial opportunity. Perhaps mobile telephony attracts a country's more capable technicians and managers, people who see the chance to build an enterprise of their own in a new industry without the burden of inbred practices, sunk investments, and established patterns of political payoff and patronage found in the electrical power industries of so many countries (or their fossil fuel industries).

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[9] See, e.g., Richard R. Nelson, ed., *National Innovation Systems: A Comparative Analysis* (New York: Oxford University Press, 1993).

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

Technological innovation can be separated without too much violence to analytical rigor 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 by social and natural scientists, has become relatively well understood, certainly compared to processes of social change. The common feature, analytically, whether the innovation is 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 later.[11] Policy innovation continues, taking forms that include new types of subsidies, such as feed-in tariffs in several European countries and US states that require electrical utilities to take and pay for power generated by solar panels installed on homes and commercial buildings, mandated biofuels quotas, and tax credits for purchasers of battery-electric vehicles.

New product concepts do not count as innovations until commercialization—marketplace introduction—and some efforts at commercialization then fail in the marketplace, as battery-electric automobiles did in the early years of the auto industry (as late as 1915 over 40 US firms manufactured battery-electric vehicles) and again in the 1990s. Twitter, a social innovation enabled by technology, succeeded, but no one could know initially whether users would accept and adapt to 140-character messaging. Twitter spurred other, follow-on innovations, as essentially all successful innovations do. New applications also emerge as "enabling" innovations spread. 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.

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

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 (automakers unveil new truck models in Texas for maximal impact); how birth control pills and other innovations in contraception influence individual behavior and collective phenomena including household formation and family sizes; 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. As such examples 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. As these examples also may suggest, energy innovation differs in one big way: people do not care about energy in the ways they care about pickup trucks, much less birth control. Rather, they care about what energy provides: heat and light, horsepower, do-everything smartphones. Leaving aside the energy sector itself and energy-intensive industries such as aluminum, cement, trucking, and air transportation, the concerns of most businesses go only a little further. For most of us, energy, so long as it is available at a price deemed reasonable, is little more than an incidental concern. And for wealthier households in many parts of the world, energy prices may be nearly invisible, except perhaps at the gas pump.

3. Three Levels of Technological Change

In the usual view, new technologies emerge from the combined 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. Government policies may strengthen technology push (e.g., though public investments in R&D), market pull (through subsidies to purchasers, as for electric vehicles), or both. High costs for infant technologies may mean that at first only governments will pay: US military and space agencies were the initial customers for integrated circuit (IC) chips and solar photovoltaic (PV) cells. After General Electric and Westinghouse developed nuclear propulsion reactors for the US Navy’s submarines, government subsidized the design and construction of the first commercial nuclear power plant, based on a similar (Westinghouse) design, at Shippingport, Pennsylvania.

In the pioneering analysis of Joseph Schumpeter during the first half of the 20th century, which continues to underpin our understanding of innovation, business entrepreneurs devise and bring to market new products (automobiles, telephones), learn to produce familiar goods or services with new processes (Henry Ford's assembly line, catalog retailing in the 1920s, Internet retailing today), and introduce new forms of organization (joint stock corporations, factory production).[12] 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. Not all the new firms succeed, but those that do push out the weaker and less productive. 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 that met 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."[13]

Technological innovation links business practices to market outcomes and scientific and engineering knowledge to indicators of performance: costs and productivity; energy conversion efficiency; contraceptive reliability; vaccine safety and effectiveness. These measures may be imperfect approximations, or otherwise flawed, but methodologies can be standardized for useable comparisons. We understand the processes of invention, innovation, and marketplace introduction, the seeds of "creative destruction" associated with particular inventors,

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[12] Schumpeter's *Theory of Economic Development* appeared in its first German edition in 1912; an English translation followed in 1934, by which point Schumpeter was a professor at Harvard. Schumpeter's hugely influential 1942 book *Capitalism, Socialism and Democracy* is the most closely associated of his works with images of creative destruction as the driving force of capitalism.

[13] 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.

entrepreneurs, and firms, far better than the cascading effects, cumulating and interacting over decades, that follow, where individual actors and cause-effect relationships tend to be submerged in large-scale social dynamics.

At the simplest level (Level 1—see the table), we can think of technologies as things that work and perform functions, some of them vital and others matters of convenience.[14] An Airbus flies us from New York to London with remarkable safety. Childhood vaccinations alter our immune system so we can expect to live to old age. Smartphones adjust automatically to London time and make it easy to reconfirm hotel reservations.

At Level 1, technologies evolve through ongoing interactions between those who develop the technology and those who use it. Two modes of interaction predominate. For capital goods such as commercial aircraft, interactive dialog between two sets of firms—manufacturers of airframes and engines on one side and airlines, especially those that opt to be lead customers, on the other—become part of the basis for design decisions by the manufacturers; final attributes may only emerge after years of information exchange, informal discussion, and negotiation—until, in other words, the market "ripens." Much the same is true for nuclear power 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, firms must make do with limited sampling of what they hope will be representative customers. Market research may yield useful predictions for a new type of breakfast cereal, less often for take-up of innovations such as Obamacare or, for that matter, mobile telephony, which grew for years at rates that greatly outstripped all expectations. Latent demand is difficult to gauge because potential customers cannot easily or accurately envision what the innovation will mean for them personally; individual consumers do not have "business plans" in their heads the way airlines do when shopping for next-generation planes from Boeing or Airbus.

Technologies, at the same time, function as parts of more complex networks—Level 2. An effective malaria vaccine would count as a scientific and medical breakthrough and would have profound effects in large parts of the world, and not just in preventing illness; economic output, for instance, depends ultimately on individual activity and disease-free people are more

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[14] For more on this three-level structure, see 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 based on conceptual designs).

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 Socio-technical 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 straightforward, familiar example. While aircraft are minor, not major, sources of carbon dioxide emissions, fuel costs make up one-third or more of airline operating costs, energy pricing and fuel-saving innovations have been significant factors in competition, and air travel has been extensively studied and extensively regulated because of accident risks.

productive. To gain the benefits of malaria or other vaccines, in turn, will probably require adjustments in health care delivery. Population-wide effectiveness depends on vaccination of a sufficiently large fraction of those vulnerable to achieve “herd immunity,” at which point a kind of threshold effect kicks in and the likelihood of transmission to individuals who have not been vaccinated falls to some very low level. Arresting and possibly eradicating communicable 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 who may be 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.

Generally speaking, societies have learned to design, build, and operate these Level 2 networks. When failures do occur, the causes can be diagnosed and future failures of a similar sort prevented, again in principle if not always in practice. Standard time zones famously came about in response to confusion causing train wrecks. As railway networks grew and service became more reliable, firms such as Armour and Swift could take advantage of the new capabilities to revolutionize meat packing and distribution, at the expense of local butchers. In practice, failures occur: trains and jetliners still crash, as do electrical grids. Yet 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 have access to 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. As parts of software-intensive digital systems, IC chips have contributed, inarguably if murkily, to jobless growth and wage inequality in the United States and elsewhere, and also to system-level failure modes, as when an undetected software bug triggered a cascading sequence of events leading to a major power blackout over the northeastern United States and Canada in 2003. All large software systems have such errors; with 10^{20} and more possible end-to-end execution paths, there is simply no way test all possibilities. The 2003 error will not recur, but other bugs no doubt lurk.

In the early decades of the US auto industry, hundreds of firms competed to sell vehicles powered by gasoline engines, electric batteries, and steam—Level 1 innovations, relatively straightforward 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) built them (financed in part by the policy innovation of per-gallon taxes on fuel). This network, or Level 2, 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 of a relatively straightforward sort. 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 in from rural America, as Level 1 agricultural innovations pushed up productivity and farm families that did not keep pace left the land for wage work in towns and cities. The trucking industry (Level 2) grew to supply a dispersed infrastructure of 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 manage sprawling 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 levels of counter-migration to high-density cities.

Climate change too is a Level 3 phenomenon, the result of imperfectly understood mechanisms that encompass everything from wealth distribution patterns and appetites for luxury goods and services 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 while nuclear reactors provide dependable, CO_2-free electrical power, they were developed initially for making fissile material for bombs, leading to a Level 2 international system that attempts to regulate proliferation of bomb material and know-how. The system has functioned imperfectly, and its failures have increased the risks that nuclear warheads will be used in anger for a second time (although some students of international politics believe that nuclear proliferation enhances deterrence). Theory is a woefully inadequate guide to such Level 3 matters. Fukushima, moreover, had consequences far beyond Japan, for example in contributing to the political decision by Germany to switch from nuclear power generation to renewable sources, a risky attempt to break free of inertia and lock-in that, to date at least, has led to both rising energy costs and GHG emissions. Sweden made a similar choice, but later reversed it. If sustained and successful, Germany's approach will lead to significant advances in renewable energy sources that can be integrated into an existing grid system. Yet the benefits lie well in the future.

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. Nor can anyone know how high a price on carbon would be needed to induce significant restructuring of the world energy system, much less what forms this restructuring would take. With strong price signals, energy systems would certainly change, but not in straightforward and predictable ways. Carbon pricing would initiate numerous, cascading changes in many social dimensions. There would be innovation on the supply side as well as the demand side, because firms that managed to reduce the basic costs of supplying fossil fuels could expect to profit. Even if politically possible, high prices on CO_2 would greatly transform modern market economies. In poorer countries, such increases would be calamitous for billions of people. In principle, prices could be (further) subsidized within countries and richer countries could compensate poorer countries. In practice, promises to compensate those disadvantaged by rising energy prices would have little credibility within countries and agreements among countries have no credibility absent supranational authority, which is nonexistent. Would the 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.

4. Evolutionary Dynamics

At Level 1, and to some extent Level 2, energy-system innovation goes on continuously.[15] PV firms fine-tune their manufacturing processes to raise energy conversion efficiencies and production yields by fractions of a percentage point. Automakers reduce engine friction and accessory losses to increase mileage ratings by a tenth of a mile per gallon. Advances accumulate, resulting in moving targets for alternative technologies: battery-electric and fuel cell-electric powertrains must compete with the evolving technology of conventional internal combustion engines, including developments such as direct in-cylinder fuel injection that themselves represent considerable advances. From time to time, of course, more radical-seeming innovations do interrupt and disrupt established trajectories, shifting it to a new level, as when railroads replaced steam locomotives with more energy-efficient diesel-electrics.

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[15] John A. Alic, David C. Mowery, and Edward S. Rubin, *U.S. Technology and Innovation Policies: Lessons for Climate Change* (Arlington, VA: Pew Center on Global Climate Change, November 2003); *Innovation Policy for Climate Change* (Washington, DC: Consortium for Science, Policy and Outcomes, and Boston: Clean Air Task Force, September 2009).

4.1 Punctuated Equilibrium

By the end of World War II, military leaders everywhere could see that jet fighters had overwhelming performance advantages. The *idea* was not new. Gas turbines, the basis for jet propulsion, operate on a thermodynamic cycle patented in 1872; reduction to practice, then, depended not on new knowledge from science so much as cut-and-try engineering. In the late 1940s, the jet engines were far more costly to purchase and operate than piston engines for aircraft; they were also prodigious guzzlers of fuel and unreliable. Over time, jet engines improved on these and other measures, moving from military fighters to bombers and then to helicopters and civil aviation. Higher internal operating temperatures made possible by superalloys and more accurate methods for predicting service lifetimes raised thermal efficiency and reduced fuel consumption. Improvements in aerodynamic design of compressor stages at the front of the engine and the turbine itself at the back end made further contributions, first on the basis of slide-rule methods and later with the aid of enormously powerful, and costly, computers. Much experimental testing was necessary too, also at great cost. In the United States, defense agencies paid many of the bills, through contracts for procurement and increasingly for R&D itself.

With military operations providing concrete evidence of acceptable performance, airframe manufacturers began to design commercial aircraft around jet engines and airline experience began to make its own contributions to greater fuel efficiency and reduced maintenance requirements, an aspect of innovation often called learning by using.[16] Turbofans boosted propulsive efficiency further and the “winglets” now ubiquitous on commercial aircraft reduced energy consumption by increasing the lift-to-drag ratio of the system as a whole. Starting in the 1950s, several companies also explored gas turbines as power units for cars and trucks; some built prototypes, and Chrysler went on to place 50 turbine cars in the hands of selected motorists in the mid-1960s (a kind of beta test). No company attempted commercialization. In road vehicle applications, operating efficiency could not be raised to satisfactory levels, as it had in 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

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

operating conditions for aircraft during cruise but not in autos, where light and variable loads combined with modest power ratings (a fraction of those for jetliners) to yield abysmal fuel economy without compensating advantages. In the 1980s, on the other hand, electric utilities, with operating conditions more like those of aircraft, began to buy turbines based on aviation designs for peak generating capacity.

As learning by using in aircraft operations shows, even at Level 1 the sources of performance gains go beyond the narrowly technical. Nuclear power plants too performed poorly in their early years. Capacity factors—the fraction of power theoretically available in continuous operation at design load—averaged only 50-60 percent in the middle 1970s; by the early 2000s, the 100 or so plants then in service were averaging 90 percent.[17] 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 managers, engineers, technicians, and operators identified operating and maintenance practices that reduced unexpected outages and extended the intervals between scheduled 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, Level 1 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.[18] 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 for ICs by Moore's Law (not of course a natural law but simply an observed regularity) and the equivalent PV "learning curve" bring reductions in costs and prices, gains in functional performance, and expanding applications. Moore's Law itself reflects a great many quite fundamental technical advances, including whole new families of IC chips, such as CMOS, or complementary metal

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

[18] 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.

oxide semiconductor, technology—cheap to fabricate and consuming little power, hence ideal for products such as digital watches and hand calculators, which comprised the first big markets for CMOS chips. Only the most detailed depictions of the Moore's Law trend reveal the consequent bumps and jerks due to such developments.

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 biological mutations), and selection, post-commercialization winnowing as customers pick and choose among products that reach the marketplace (analogous to survival, or not, 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 (some web apps), along with more routine sorts of business planning ("new and improved" laundry detergents). As Edmund Phelps, 2006 Nobel laureate in economics, put it: "[O]nce in a while there is a big leap which creates the ground for a surge of innovations to follow. Nowadays we realize that an awful lot of innovation just comes from business people operating at the grass roots having ideas on the basis of what they see around them. Nothing to do with science—it's just creative mankind chipping away at things.[19]

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 (variety). At that point, utilities had to decide whether or not to believe the promises of government agencies proffering subsidies and suppliers such as General Electric and Westinghouse (selection). Many utilities did invest, initial performance did not live up to expectations, and the nuclear power boom flatlined. A few older plants have now been shut down and 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 nuclear plant designs could attract private capital and government subsidies, although in countries such as the United States that bought into the 1960s

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[19] Howard R. Vane and Chris Mulhearn, "Interview with Edmund S. Phelps," *Journal of Economic Perspectives*, Vol. 23, No. 3, Summer 2009, pp. 109-124; quotation from p. 123.

vision of cheap and abundant non-polluting nuclear electricity it seems at least as likely that memories of earlier overpromises and cost overruns will check such prospects.

4.2 Technological Uncertainty and Market Uncertainty

Even though incremental innovation is ubiquitous, and central to technological advance, enthusiasts urging greater investments in radical, disruptive innovation sometimes downplay or dismiss these seemingly mundane portions of innovation ecosystems.[20] 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 and how much money to spend on the chase. A breakthrough such as cold fusion, which is still a subject of research, might make decarbonization and GHG reduction easier to achieve. On the other hand, highly touted research findings sometimes languish indefinitely. When President Ronald Reagan introduced his administration's program for commercializing high-temperature superconductivity in 1987 he called the phenomenon a "new paradigm." Lossless transmission (and storage) of electrical power and ultrahigh efficiency machinery and equipment were to follow. Although scientists have produced a steady stream of research results, the promised innovations have not appeared.

Market behavior too routinely confounds predictions. Food and diet fashions come and go, defeating the best efforts of firms at product design, at prediction by market research groups, and at persuasion through advertising.[21] In mobile telephony, Motorola, Nokia, 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 dropped back below $5 billion; the main reason, according to a former manager: "People just didn't like it anymore."[22]

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[20] 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.

[21] 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).

[22] 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. The firm, then named Research In Motion, went public in 1997.

Contrasts between the PV and auto industries illustrate some of the ways in which technology and markets interact. PV cells and systems are not quite commodities, but differences, in the eyes of most customers, tend to be minor, chiefly a matter of pricing. Without too much oversimplification, the several hundred companies worldwide that make PV cells can be said to follow one of two strategies: either they make conventional single-crystal silicon devices, trying to push down costs as fast as possible through process innovation and scale, or they seek to develop novel device structures and materials, such as compound or organic semiconductors, that promise superior combinations of production cost and efficiency (here, 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 personal vehicles, which automakers differentiate in ever-proliferating profusion, with more and more brand names, model designations, special editions, and levels of performance, comfort, convenience, and cosmetics—leather seats, web connectivity, fuel mileage, powered lift gates and running boards for SUVs and pickup trucks. Personal vehicles are far from commodity products, as disappointingly low sales in India of Tata’s Nano microcar indicate: even in this low-income market, potential customers shied away from a purchase they feared would brand them as unable to afford anything better.

Entry barriers differ, too, being much higher in automobile production. A single assembly plant can cost $1 billion or more, several times the price of a PV factory, and while automakers purchase many parts and subassemblies from suppliers, they generally manufacture their own bodies and powertrains, which adds billions of dollars more to front-end investments. Tesla’s “gigascale” battery factory, to be built in Nevada, is expected to cost an estimated $5 billion.[23] Unsurprisingly, 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. On the other hand, Tesla, put together with Silicon Valley flair by Elon Musk, a classic Schumpeterian entrepreneur, seems to have ample financial resources.

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[23] 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.”

Other barriers remain: legislation passed up to a century ago in nearly all US states bars Tesla, like all automakers, from direct selling—the company'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 dealers from competition and allowed automakers to avoid the upfront costs of showrooms and repair facilities. Today they are an example of a phenomenon discussed by the historian Thomas Hughes and others: system-level inertia, or momentum, the tendency of large-scale socio-technical systems to continue along established trajectories, sustained by interdependencies among the components of technological systems and the institutions, interests, and practices that surround, contain, and constrain them.[24]

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

Two things. Energy is a commodity. Second, physical laws impose upper bounds on energy conversion processes. Both constraints operate chiefly at Level 1. Systems and equipment that consume energy—pickup trucks or smartphones—can be differentiated. Gasoline and electricity cannot; they are commodities like sweet corn or Muzak. Energy carriers—electricity, jet fuel and gasoline (within grades)—sell on price alone, restricting opportunities for marketing based on product characteristics, narrowing private incentives for innovation, and reinforcing justifications for public policies to strengthen incentives. Private firms do have strong motives for seeking advances in energy technologies that promise meaningful end-product performance advantages, as by extending recharge intervals for smartphone or electric vehicle batteries. Still, residential solar systems will never diffuse like mobile telephones, which served a new function. Energy is a necessity; but it is a backdrop to peoples' lives.

Smartphone apps can multiply without limit. While Moore's Law for ICs has yet to bump against the limits set by quantum mechanics, physical principles imposed ceilings on PV

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[24] "[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 people, historians and especially economists, have of course discussed technological lock-in. Examples include Paul A. David, "Clio and the Economics of QWERTY," *American Economic Review Papers & Proceedings*, Vol. 75, No. 2, 1985, pp. 332-337; and W. Brian Arthur, "Competing Technologies, Increasing Returns, and Lock-In by Historical Events," *Economic Journal*, Vol. 99, No. 394, 1989), pp. 116-131. We adopt Hughes's language, less mechanical-seeming, to keep the focus on institutions and politics rather than more strictly economic phenomena.

efficiency almost from the beginning, and also tell us that batteries, no matter how the design of lithium-ion cathodes might be tweaked, will always and necessarily give back less energy than put in during charging. Radically new energy technologies have been widely spaced, with solar PV cells and nuclear power, the most recent, dating from the late 1950s. Most of today's battery systems have been around for years if not 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; wind energy and hydropower go back centuries. No matter the future increments in performance of such technologies, they hold little potential for sparking waves of Schumpeterian transformation. The most recent energy technologies to do this were steam power in the 18th century, electric power generation in the 19th century, and oil and gas in the first half of the 20th century. When assessing the effects of technological change, starting points do matter. Two centuries of advance in artificial lighting, including shifts in innovation trajectory as gas replaced candles and whale oil before giving way to incandescent lamps, fluorescents, compact fluorescents, and now light-emitting diodes, have yielded cumulative gains of around three orders of magnitude.[25] But absent totally unexpected advances in chemistry or physics these sorts of gains are not on the horizon for energy technologies. No one should count on technological breakthroughs, by themselves, to alter the momentum of carbon-intensive energy systems by much. Momentum will be shifted by means of many innovations, individually small and few of them with much visibility.

6. Breaking Systemic Momentum

Germany's effort to pull back from nuclear power in favor of renewables provides a concrete illustration, still unfolding, of complications following from a deliberate effort to alter momentum in electrical generation and distribution. Wind and solar installations produce power only when the wind blows and the sun shines, which makes them ill-suited for base-load generation or dispatch-on-demand unless interconnected over very large geographic areas or supplemented by storage, which adds costs and dissipates energy.[26] For the next decade or so,

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[25] William D. Nordhaus, "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not," *The Economics of New Goods*, Timothy J. Bresnahan and Robert J. Gordon, eds. (Chicago: University of Chicago Press, 1997), pp. 29-66.

[26] Capacity factors for wind and solar power vary geographically and seasonally. On an annual average basis, US wind power installations produce at 30-35 percent of rated output; the limited data available for solar suggests figures a bit lower. *Electric Power Monthly* (Washington, DC: Energy Information Administration, January 2015), Table 6.7. Storage raises capital costs and also operating costs, since as much as 30 percent of input energy is lost during the round trip from generation through storage to grid dispatch.

and perhaps longer, Germany must rely more heavily on coal 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, and entire towns are being moved for strip-mining of lignite, a soft brown coal abundant in Germany that is one of the most polluting of all fuels.[27]

Large-scale technological and institutional change bring risks and rewards, and German utilities are understandably worried about their profit-and-loss statements. The more extensive the Level 2 networks and Level 3 systems into which Level 1 innovations fit, the greater the potential losses and gains. Risk/reward balances also depend on whether momentum is still being built or is to be redirected. When momentum builds, entrepreneurial opportunities loom large and losers may not be fully aware of their position. When a mature system is threatened, conversely, losers usually get plenty of warnings and mobilize in opposition. For such reasons, developing nations, even if constrained financially and by limited stocks of human and organizational capital, can expect more freedom and flexibility—assuming relatively open political and economic settings—in choosing energy system pathways than high-income countries with established industries and interests. In countries such as the United States, sunk costs underpin systemic inertia.[28] Many US utilities, for example, spent far more in building nuclear plants than originally estimated. If they now earn steady returns from these investments, managers will have no wish to change directions. (Some utilities, seeking sympathy, have tried to rebrand sunk costs as stranded costs in efforts, no doubt survey-tested, to preserve or increase regulated rates of return.) Utilities in the United States have also been decommissioning older, inefficient, and maintenance-intensive coal plants. Some of these units may be unable to meet regulatory standards for release of pollutants such as mercury and sulfur dioxide (SO_2), at least without costly retrofits. Others, perhaps held in reserve for back-up capacity, may simply cost

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[27] 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).

[28] Hughes, in “Technological Momentum in History: Hydrogenation in Germany 1898-1933,” *Past & Present*, No. 44, 1969, pp. 106-132, emphasized the financial pressures on the firms he studied, along with the human and organizational capital these firms had built up in the form of knowledge and skill acquired by key 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 embedded within it and financial management receded; as a historian of technology, he perhaps also wanted to differentiate his approach from that of business history.

more to run when needed than they bring in. By replacing old coal plants with high-efficiency gas turbines burning cheap natural gas, utilities expect to increase profitability. CO_2 emissions also fall, but this is incidental and contributes only modestly to climate mitigation.

Although a number of technical approaches to carbon capture and storage (CCS) have been demonstrated, so that utilities could if required remove CO_2 directly from the flue gases of plants that burn coal or natural gas, or for that matter biomass, they have no reason to do so unless forced. CCS would add considerably to costs, in part because some of the electricity generated would be consumed in running the needed equipment for capture and sequestration. In the United States, it would take a considerable feat of political architecture to force CCS on unwilling utilities and their customers.

Still, we can envision transformation of electrical power systems such as those in Germany and the United States, at least in principle, at a relatively slow pace and at relatively high costs. Technical means exist, and much innovation would follow should they begin to be implemented on any very large scale. Transportation, by contrast, second to electric power generation as a source of CO_2 and other GHGs, poses far greater difficulties, technical and infrastructural. (Industrial energy consumption and environmental conditioning of residential and commercial buildings, which accounts for a good deal of electricity consumption, make up a third major source of GHG emissions.) Put simply, there are no obvious, foreseeable replacements for fossil fuels in transportation. Some 550 sites house the entire US fleet of coal-burning power plants, the first candidates for CCS, and perhaps 1800 for natural gas-fired plants (some co-located with coal-burning units), the other major source of CO_2 from electrical power generation.[29] By contrast, Americans own some 250 million cars and trucks; individually, each is a minuscule source of CO_2 and in any case there is no way to modify them to reduce their GHG emissions. Ongoing advances in vehicle technology will improve fuel efficiency, slowly, and eat away at CO_2 emissions, gradually. Unlike in developing countries, where rising affluence drives sales, many US households already have several vehicles, which limits penetration of new vehicles with new technology; the fleet is barely growing and turnover rates have been falling.[30] The

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[29] The most recent figures are those in *Electric Power Annual 2012* (Washington, DC: Energy Information Administration, December 2013), Table 4.1.

[30] Average US vehicle age has roughly doubled since the mid-1970s, from 5-6 years to 11-12 years. Don Pickrell and Paul Schimek, *Trends in Personal Motor Vehicle Ownership and Use, Evidence from the Nationwide Personal*

federal government has tried to increase penetration of advanced conventional powertrains through tighter fuel economy standards, subsidies for battery-electric vehicles through tax preferences, and fuels made from biomass through means including mandated quotas. So far, most of the biofuels subsidies have gone for ethanol made from corn, which reduces net CO_2 output only slightly (and is anyway incompatible with many existing vehicles and most distribution infrastructure except as a low-percentage gasoline extender). Battery-electric vehicles may finally establish themselves in a defensible market niche, perhaps along with the fuel cell powertrains that a number of automakers plan to introduce over the next several years, and sustainable biofuels at reasonable costs may eventually appear as well. Yet fuel cells would run on hydrogen made from natural gas, while electric vehicles recharge from grids that, today, get over two-thirds of their power from fossil fuels and only about 5 percent from renewable sources other than hydroelectricity (another 6 ½ percent).[31] Technology itself, at Level 1, poses far greater obstacles to decarbonization for transportation than for electric power generation. Energy conservation in buildings too, seems more straightforward, with a large inventory of effective Level 1 technologies available, given sufficiently powerful incentives, for new construction and retrofits.

Decarbonization, then, will come about through innovations occurring piecemeal in many different technological families—electric power generation, transportation, energy-intensive production operations such as cement-making, building energy conservation. To considerable extent, and depending on policy impetus, the pace will be set by life cycles for Level 1 technologies: coal-fired power plants; personal vehicles (commercial trucking companies replace equipment more frequently because fuel costs affect their profits directly); residential and commercial buildings with leaky windows and poorly regulated heating and air conditioning systems. The alternatives to this gradualist approach seem limited to direct removal of CO_2 from Earth's atmosphere, technically possible but at present very costly, or some sort of risky venture into geoengineering.

Transportation Survey (Cambridge, MA: Volpe Center, Department of Transportation, 1998), p. 18; "Polk Finds Average Age of Light Vehicles Continues to Rise," August 6, 2013, www.polk.com/company/news/polk_finds_average_age_of_light_vehicles_continues_to_rise.

[31] *Electric Power Monthly* (Washington, DC: Energy Information Administration, January 2015), Table 1.1. It is worth recalling that the original motive for subsidizing electric vehicles was reduction of urban air pollution; emissions of smog-causing nitrogen oxides and hydrocarbons from gasoline-fueled vehicles have now fallen enough that electrification for this reason is not nearly so compelling as in the 1990s.

Almost inevitably, climate change mitigation will play out over lengthy time periods because existing energy systems have so much change-resisting inertia. Over time, aggregate costs and benefits will amount to meaningful fractions of world economic output. Gains and losses cannot be identified in advance. The unpredictable nature of the rewards dampens innovation, all the more so because current energy technologies do their Level 1 job quite well and most of the currently available replacements do not. Attempts to restructure the existing system provoke intense opposition among those who cannot win, only lose: as the United States moves away from coal-fired power plants, jobs for miners vanish, communities suffer, and entire regional economies may decline. The losers know who they are and fight to block change; those positioned to win may be dispersed and unaware, hard to identify and organize. Broader social impacts (from, say, slowed warming) will never be directly perceived by anyone, and in any case will play out gradually over future generations. In such settings, innovators and entrepreneurs may face years of work in assembling and then holding together political coalitions that are both willing to back their plans, positions, and preferred policies, and sufficiently powerful to do so successfully, without compromises that give too much away.

7. The Future of Energy-Climate Innovation

When policy goals cannot be adequately monetized, as for environmental impacts or national security, only governments can drive innovation. Unsurprisingly, the World War II Manhattan project and Cold War Apollo program have sometimes been put forward in the United States as models for energy-climate innovation. They hold few positive lessons. Both had concrete objectives and tight schedules to guide managerial and budget decisions focused on Level 1 technological artifacts. 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 that few US officials realized until later, with the presumption of a space race helping keep the Apollo project on track. Both Manhattan and Apollo came to successful conclusions because of mission imperatives; these disciplined managerial decisions much as market imperatives do in the private sector. There can be no comparably simple, unitary goals for energy-climate technologies and—of great importance—no single, strong managerial hierarchy, which both these projects had (with highly capable people in many of the key positions). Perhaps CCS for fossil fuel-burning power plants or the development of modular nuclear power plants could be approached as “big engineering,” like Apollo and fissile material production for the Manhattan project. Otherwise analogies with these programs hold little beyond a somewhat misleading hortatory value.

Similar lessons follow from two unequivocal accomplishments in control of harmful atmospheric emissions, the Montreal Protocol on Substances that Deplete the Ozone Layer and the US Clean Air Act amendments limiting SO_2 emissions from power plants. The Montreal Protocol, a global treaty that mandated timetables for ending production of offending chemicals such as Freon, a common refrigerant also in widespread use as an aerosol spray propellant, worked for three primary reasons. Ozone depletion was well understood scientifically and uncontroversial. Second, firms including DuPont, the manufacturer of Freon, had substitutes well along in development. And finally, while the substitutes cost more, the increases could be largely hidden in end-item pricing; the new chemicals added only a little to the price of a refrigerator or an automobile air conditioning system and the customer would never see the bill (unlike paying at the gas pump). Much the same was true for SO_2. Evidence that power plant SO_2 caused of acid rain was hard to deny and the effects on lakes and streams were visible to all. Technical solutions in the form of stack-gas scrubbers were available. With mandated installations, costs came down and performance improved quite rapidly, another illustration of incremental innovation at work. Unpredictably, railroad deregulation helped to keep coal prices low, one reason the added costs had little effect on household electrical bills. These were Level 1 solutions to Level 2 dysfunction. With increasing scale, symptoms appeared and research could identify the causes.

Climate change differs in that the scale of the problem is far greater and the solutions promise to be far more expensive. Those solutions will have to come with Level 1 and Level 2 innovation. Level 1 advances in electrical energy storage, for example, would feed Level 2 innovations in reengineered, interconnected “smart” grids. Level 1 technologies for removing CO_2 from power plant stack gases will not be adopted without Level 2 systems for sequestration that the public regards as acceptably safe.

We end with a logically powerful point. If one understands climate change mitigation as a Level 3 problem of complex socio-technical 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 predictable and desired outcomes*. This situation feels unsatisfactory and paradoxical: 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. If one takes the essence of the mitigation problem to be a Level 1 technology problem—a problem of innovations, mostly incremental but in large numbers and widely implemented that directly reduce greenhouse emissions—then the history of innovation teaches us that the most productive 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 CCS), rather than efforts to steer the complex global energy system, in its entirety, in a new direction, as attempted by the Kyoto Protocol. The history of politics also teaches us that major public investments can be justified in terms of their capacity to deliver a public good. This has been the case for large public investments in Level 1 technologies for national defense (aircraft carriers and spy satellites), public health (from sewage systems to vaccines), transportation infrastructure (the Interstate Highway System), and even for energy supply (the electrification of the American West). The politics of such investments in innovation are radically different from the politics necessary to incentivize widespread behavior change.