Toward a Revolutionary Energy System

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Historically, the energy sector has been very slow to change. Yet huge changes will be needed in the future—at a rate much faster than ever experienced—if the sector is to make deep cuts in emissions and stop global warming. So far, however, there has not been much serious analysis of how such a transformation could occur in the real world—where governing institutions are far from perfect and where governments find it very difficult to establish clear and credible policies needed to guide investors to new technologies.

This essay argues that a technology strategy for transforming the energy system will require a global perspective because today, unlike even 2-3 decades ago, technology markets are global. Making that strategy work will be difficult, but one bright spot is the ability to devise global solutions in relative small "clubs" of countries and then scale up the best strategies to other countries in time. Only a few countries account for nearly all cutting edge investment in new energy technology, and a club that begins with those nations could be highly effective. The design of the club strategy will need to address not just the total level of spending on new energy technology but also the efficacy of national policies aimed at promoting innovation—suggesting that the club, if it is to be effective, will require a degree of cooperating on innovation policy that is so far unprecedented in most areas of the modern economy.

In 1970 the world's fastest business computer, the IBM Mainframe, operated at a speed of 12.5 MHZ and cost $4.6m. Today, that same processing power is 2 million times cheaper. Across the frontiers of

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modern economies similarly revolutionary stories abound. Wireless communication has spread from a few wealthy customers with car phones and the military to the world's poorest. In a world with population of 7.2 billion there are now 7.22 billion cell phone subscriptions, up from just one third coverage in 2005[1]. Four decades ago grocery retail was dominated by local neighborhood stores—with customer service often so doting that it was impossible to choose one's own vegetables. Today, three quarters of the US public buys at least some groceries from stores that aren't mainly in that business.

Meanwhile, the energy business has changed little. The average kwh in the U.S. cost 7.5 cents in 1970 and barely changed for thirty years—climbing a bit in recent years to about 11 cents. The grid system is little different—slightly higher voltages for some lines, more SCADA, and few other modifications. The fuel mix has changed a bit—thanks notably to the rise of gas and the exit of oil—but the rank of important electricity generation fuels in 1970 in the U.S. is nearly identical today. The supposedly revolutionary rise of renewables is not yet evident in the data—solar energy, for example, accounts for just 0.8% of the global energy mix even though it first started gaining market share more than three decades ago[2]. In the electric power industry, centralized fossil fuel-fired power stations reign supreme. And globally coal is the king of central power. Nor has there been much revolution in transportation where oil continues to dominate. Then as now, oil products dominate the market for transportation. Total annual worldwide sales of Tesla's electric cars equal just 14 hours of conventional vehicles in China. Across the energy system, efficiencies have gone up—but at steady rates typically measured as a few percent per year, if that. Hardly the stuff of revolution.

Although the energy business does not yet reek of revolution, calls for revolutionary change abound. The prime driving force is environmental—in particular climate change. Stopping warming will require cutting global emissions of carbon dioxide (CO_2) by four-fifths over just a few decades. Doing that means, most likely, the removal of nearly all fossil fuels from the energy system—and with that, radically new systems for power supply. Rethinking supply might, as well, lead to rethinking the whole grid system—

perhaps moving radically to more decentralized electric power. It may, as well, largely end the use of conventional oil.

It is hard to see how the existing energy system will rise to this challenge. Today, the energy industry is dominated by state-owned enterprises (SOEs) that are hardly paragons of innovation. The electric power industry, in particular, is heavily regulated—another force that often impedes change. Incumbents are extremely powerful politically and unlikely to welcome a revolution.

Why a revolution is needed and how it might arise is where I now turn.

THE SCALE OF THE CHALLENGE.

The field of research on the global energy system is complex, but three iconic results stand out.

First, the rates of change in the global energy system are very slow. Revolutions are century-scale phenomena. Typically, as shown in figure 1, whole energy infrastructures change on a time scale of about 70 years. Individual components might come or go quickly—for example, the recent rise of natural gas or the exit of oil from the US power supply system, both of which occurred with time constants of about 10-20 years. But the whole system is much slower to change because infrastructures are interlocking and those interlocking effects tend to reinforce the dominance of incumbents. New entrants gain small market shares and must work hard—usually failing—to make inroads[3].

Economically and politically these incumbency advantages are essential to understanding why rates of change in the energy business are so slow. For example, the late 19th century was the golden era of coal. That primary fuel came with a set of interlocking infrastructures, notably railroads, that further reinforced the advantage of a bulky fuel that required combustion in large plants—steam engines. The trifecta of coal, steam and railroads dominated the market for energy services—such as transportation—until a new cluster of rivals (automobiles, roads and oil) slowly took market share.

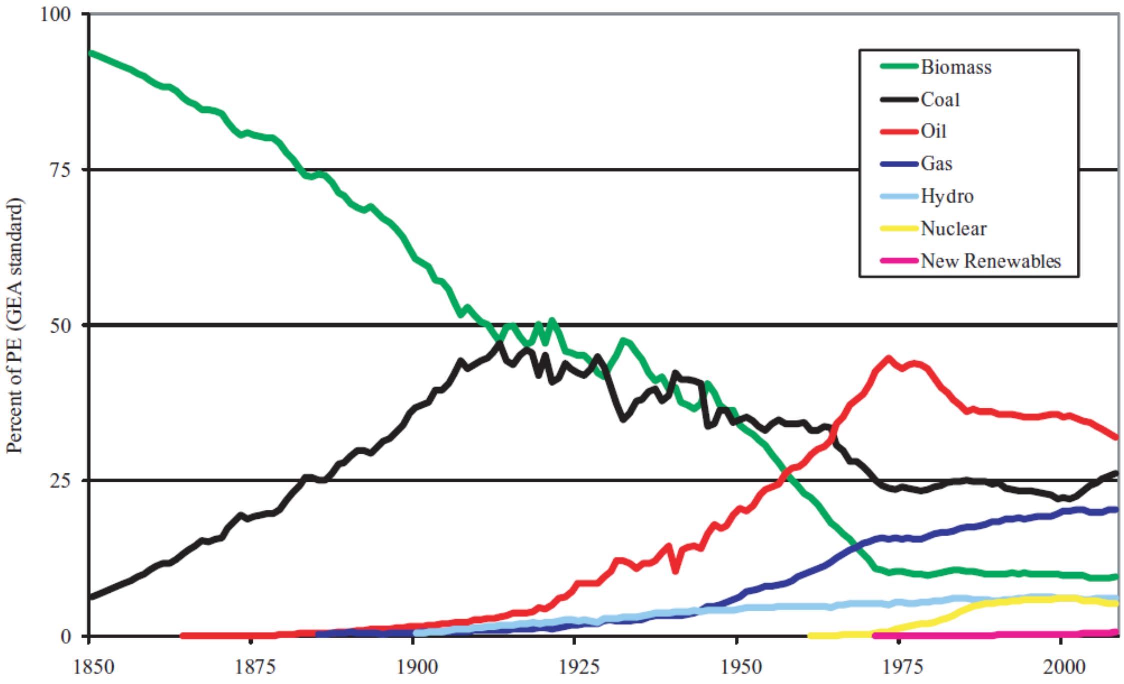

Figure 1. Structural change in world primary energy (in percent). Source: reprinted from figure 1.10 in Grübler, A., *et al.* Energy Primer, in *Global Energy Assessment - Toward a Sustainable Future* (Cambridge Univ. Press, & the International Institute for Applied Systems Analysis, 2012), updated from Nakićenović et al., 1998 and Grübler, 2008.

Clusters of reinforcing technologies don't determine which fuels dominate, but they put a big thumb on the scale. Efforts to shift away from favored fuels and infrastructures—which, in effect, is what is behind calls for revolution in the energy system—face strong headwinds and the need for an active push by policy makers. The heavier the thumb the stronger the headwinds and the harder it is for policy to make a difference.

Second, over time, energy systems electrify. In the era of coal dominance fuel was burned directly at the place where energy was needed—in a turbine located at a factory, on a steam engine connected to a long line of rail cars or in a pump used to remove ground water from mines. Electrification has made it possible to separate—financially and geographically—the investment in technology needed to make power from the places where it is used. It has allowed for much greater efficiency—big power plants are usually a lot more economical than many smaller ones. It has also made geographically dense consumption of energy—whether on the confines of a factory floor or in the concentrated living of a city—feasible because power arrives by wires with a tiny footprint while the pollution and noise of the venture is shifted to remote areas.

Indeed, all modern economies electrify. Figure 2 shows, for example, the case of the United States over the last century (top panel). At the beginning of the period essentially all primary energy was consumed at the point of use. Over time, very slowly and steadily the fraction of primary energy converted into electricity has risen—it is nearly half today. In effect, the energy system has largely bifurcated into two systems (figure 2, bottom panel). One is dominated by electricity, which is the main carrier of energy for stationary applications. The other is transportation, the one area where electricity—until perhaps recently—can't occupy because moveable systems are hard to wire. The rest of energy goes into more diverse applications.

Electricity could prove particularly important for deep and rapid decarbonization for two reasons. First, electric networks are designed for large power generators and thus well suited to the large engineering systems that might be needed for low- and zero-carbon energy supplies—such as carbon capture, advanced nuclear and central station solar systems. Second, and perhaps even more importantly, electric infrastructures can facilitate a more rapid change in emission profile—while the infrastructure has, in the past, been the handmaiden for a high carbon power system it is equally supportive of low carbon systems. If decarbonization happens through electrification then the 50-70 year time scales for change that have dominated in past might not apply.

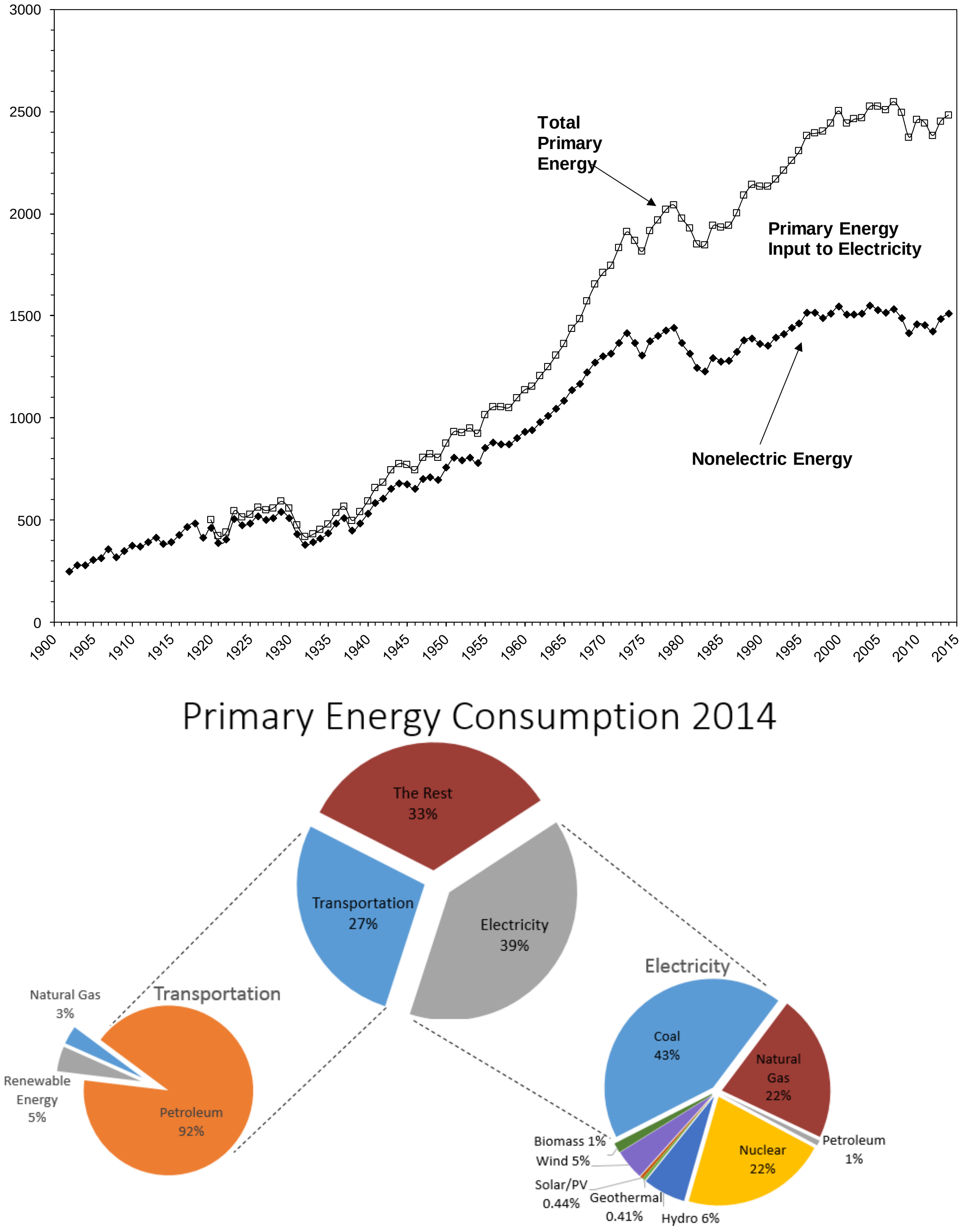

Figure 2. Source: ILAR analysis using data from EIA Monthly Energy Review, Table 1.1 and Table 2.6 (August 2015).

Looking globally, emission statistics reveal these dominant roles for transportation (and thus oil) and electrification. Figure 3 shows the allocation of all emissions of warming gases by sector. About one-quarter relates to agriculture, forestry and land use (AFOLU), a fraction that is declining steadily as deforestation slows and reverses. The rest are in transport applications (left side of the chart) and electricity (right side) along with a host of mainly industrial applications where large scale allows for direct combustion of fuels.

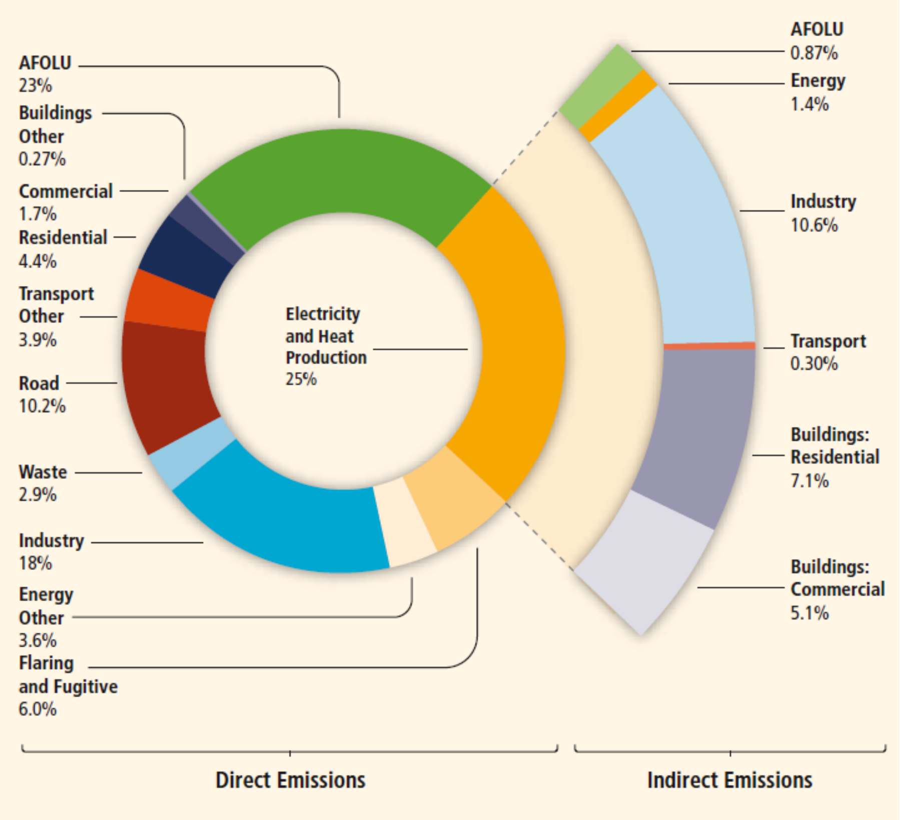

Figure 3. Source: reprinted from figure 1.3a in Victor, D. G. *et al.* in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2014).

These first two iconic results reveal that, over time, the greatest leverage on emissions and other side-effects of the energy system lie with electricity and transport. And they tell us that rates of change in those systems are likely to be many decades long.

The third iconic result from energy research is quite inconvenient. If the world is to stop climate warming then emissions from the energy system must reduce radically and rapidly. Figure 4, drawn from the latest report of the Intergovernmental Panel on Climate Change (IPCC), shows historical patterns of emissions (rising steadily) and future projections under different scenarios. Business as Usual (BAU) projections, which assume a continuation of historical patterns of gradual improvement in efficiency and evolution in energy infrastructures, lead to a doubling of emissions. Other research shows that doubling, in turn, can lead to climate warming of perhaps 4 degrees above pre-industrial levels, with catastrophic consequences[4].

If aggressive efforts are made to improve efficiency then emissions still rise (purple scenarios). Only with deep cuts in emissions (blue scenarios) is it possible to stop warming at about 2 degrees above pre-industrial levels, a goal that has been widely discussed although is now essentially impossible to achieve[5]. Even scenarios that probably overshoot 2 degrees but at least stop warming at modestly higher levels (yellow scenarios) envision deep, prompt cuts in emissions[6].

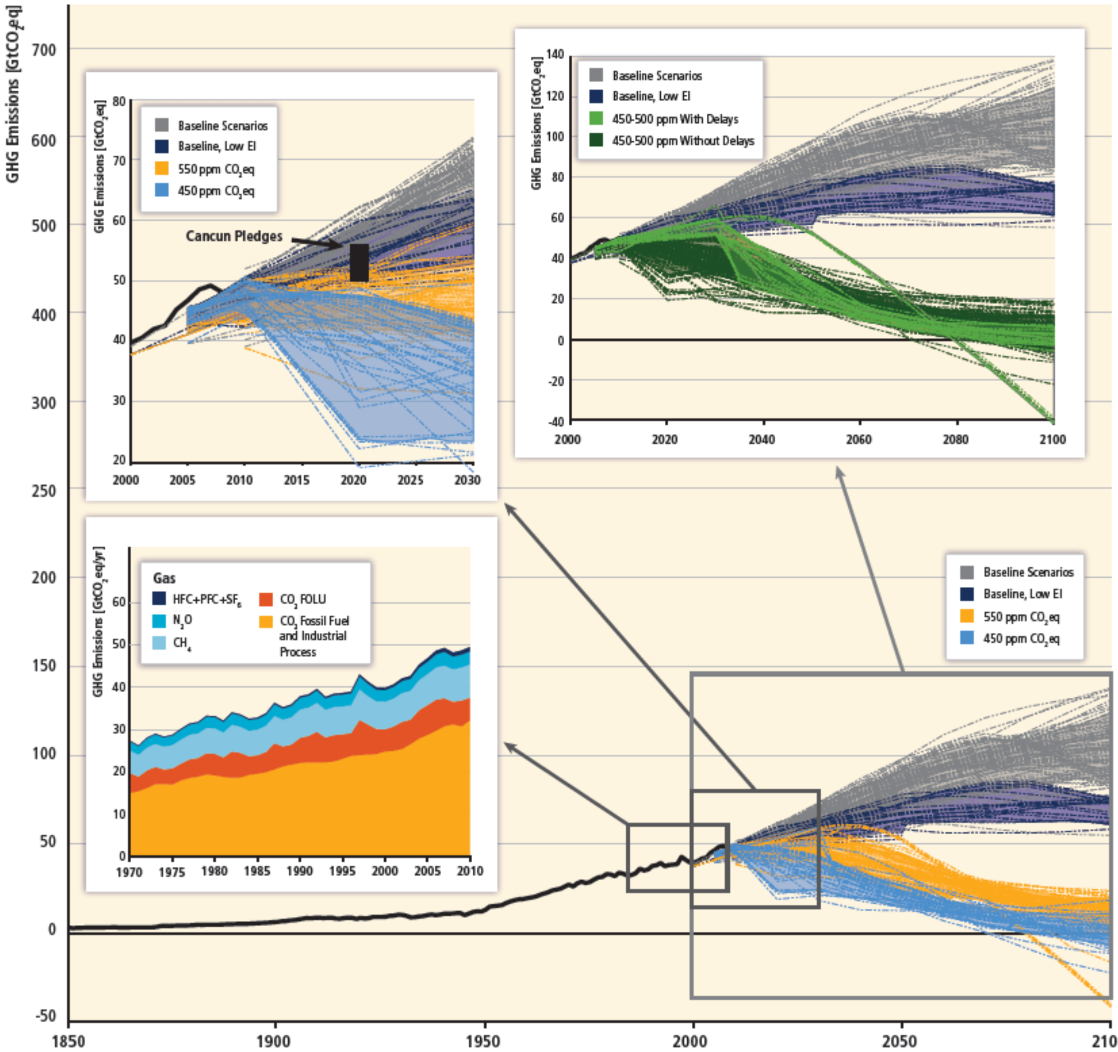

Figure 4. Source: reprinted from figure 1.9 in Victor, D. G. *et al.* in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2014).

The inconvenience in all this is rooted in the fact that deep cuts in emissions require rapid changes in energy systems—changes that must begin immediately and unfold over a matter of just a few decades despite the fact that energy systems don't normally change so quickly in history. Indeed, that awareness of history and of the feasible rates of change has been lacking in many analytical studies. For example, many models show that very deep and rapid cuts in emissions are feasible, but recent work probing the assumptions in those models find that they typically assume that new-fangled power plants will quickly appear and become pervasive in the energy system even though no such power plants actually exist today[7]. Studies that have added more real-world assumptions to these models—for example, giving the models information about how real firms invest in the face of large policy risks—show that actual rates of technological change are likely to be much slower and more in line with what has been observed historically[8].

There have been calls for revolution in the energy system for many other reasons as well, such as improved energy security and better control of local pollution. But none of those other demands has created the same level of challenge as climate change. Existing power grids can be built in ways that make them more reliable. Existing and new power plants can be built with more equipment to control local pollution. But carbon requires a revolution.

TOWARD A REVOLUTION

With luck, a revolution might happen on its own. Historically, new technologies periodically emerge largely on their own—because a new frontier is discovered and technologies, on their own, become “ripe” for change. The fundamental innovations around recombinant DNA and modern biotechnology emerged in this way. Much of the IT and computing revolution sprung forth autonomously as well—thanks to radical innovations in chip technologies and software. In energy, the revolution in gas supply emerged largely autonomously—bringing with it much cheaper natural gas that, in turn, displaced a large fraction of the coal-fired power market. Of course, when one looks closely at any of these autonomous revolutions the guiding hand of policy usually comes into focus—notably with investments in basic research[9-10]. But the technology, for the most part, followed its own nose.

A major revolution across the whole energy system seems unlikely to emerge on its own. A steer from policy will be needed. But how? The answers lie on two fronts—at the micro level with policies aimed at individual technologies, and at the macro level with coordination across countries.

Micro-incentives

At the micro-level, the central challenge is to get firms and other users of technologies (e.g., governments, armies, schools) to invest in better systems. In most economies, most efforts to create incentives for innovation and investment focus on firms since it is thought that the private sector makes most decisions related to the deployment of new technology and the private sector is more skilled at making those decisions wisely.

I will focus on the private sector in this essay, but I note that a singular focus on the private sector might not always be best for at least two reasons. First, governments often have a hard time developing the administrative skills and political consensus needed to adopt and implement policies that affect the private sector. Thus governments often pursue "second best" policy strategies—such as orders by government officials that government, itself, procure new technologies. In California, for example, there are policies in place to require the whole state economy to reduce emissions of warming gases by 15% by year 2020[11]. However, an order from the Governor requires that state facilities do more—a cut of 40% by 2030[12]. Second, in many countries the private sector isn't that important in the energy business—state owned enterprises (SOEs) reign supreme, often because governments don't trust the private sector to manage vital national resources or don't have the administrative systems in place to be able to regulate private firms effectively. In those countries, national oil companies (NOCs), state owned power companies, and other forms of SOEs occupy the commanding heights of the energy system.

In the private sector, the incentives to adopt new technologies can arise either from a "push" or a "pull." The best policy strategies blend the two.

Policy can "push" new technologies into service by funding research—often basic research into fundamental new technologies. That was the insight from early government investment in information technology, software and health—that sponsorship for fundamental research from the National Science Foundation (NSF), the Office of Naval Research (ONR), DARPA, DOE's Office of Science, NIH and other basic science enterprises pushed new ideas into viability. Some of these agencies were interested in basic research for its own sake. Others had directed missions that happened to overlap with the interests of basic science. ONR, for example, was interested in improving the capacity to detect enemy submarines and thus funded basic research in acoustics and ocean propagation—leading to whole new branches of science as well as unforeseen applications[13].

One of the central challenges in fostering a revolution is creating a big enough push. Figure 5 shows total federal spending on energy-related research development and demonstration (RD&D)—a broad category that includes basic science as well as applied ventures such as demonstration projects. RD&D data are, in many ways, flawed measures of how much a country actually spends pushing basic ideas, but they are a good place to start. In real dollars, spending has been flat since the early 1980s. (Other data show that the focus of spending has shifted quite a lot—away from nuclear power and toward renewables, for example. Globally, nuclear power accounted for more than half of all energy-related RD&D spending in 1980; today it is about one-quarter. Renewables and energy efficiency account for about half of today's energy-related RD&D spending globally, up from about one-fifth in 1980[14].) The stimulus package in 2009 caused a huge pulse in spending, but when that ran dry the patterns reverted to much lower levels. Figure 5 also shows several proposals for the level of RD&D that the country should pursue—typically twice to three times current levels. Many have called for such changes but the budget has not followed.

Government has central roles to play in pushing new ideas into service—especially as funding shifts from basic research (where it is important to spend money widely) to more costly demonstration projects where winners must be chosen. It is fashionable to say that government should not choose winners when, in fact, such choices are essential. It is also fashionable to say that government performs this task poorly when the track record is, actually, better. Failures such as Solyndra are not, by themselves, evidence that government can't choose the right technologies and firms—instead, they are usually evidence that government is rightly taking risks. Taking risks is not the same as blind faith, of course—a point that will be tested in the coming years with carbon capture and storage (CCS) technologies. A large number of studies point to CCS—including negative emission bioenergy CCS (BECCS) technologies as pivotal to deep cuts in emissions. Yet the actual investment in CCS has been slow to respond, and costs remain high—problems that are even worse for CCS schemes that would utilize natural gas, a suite of technologies that would be particularly pivotal in a world that is awash in natural gas. Some hard decisions about picking winners are long overdue on CCS.

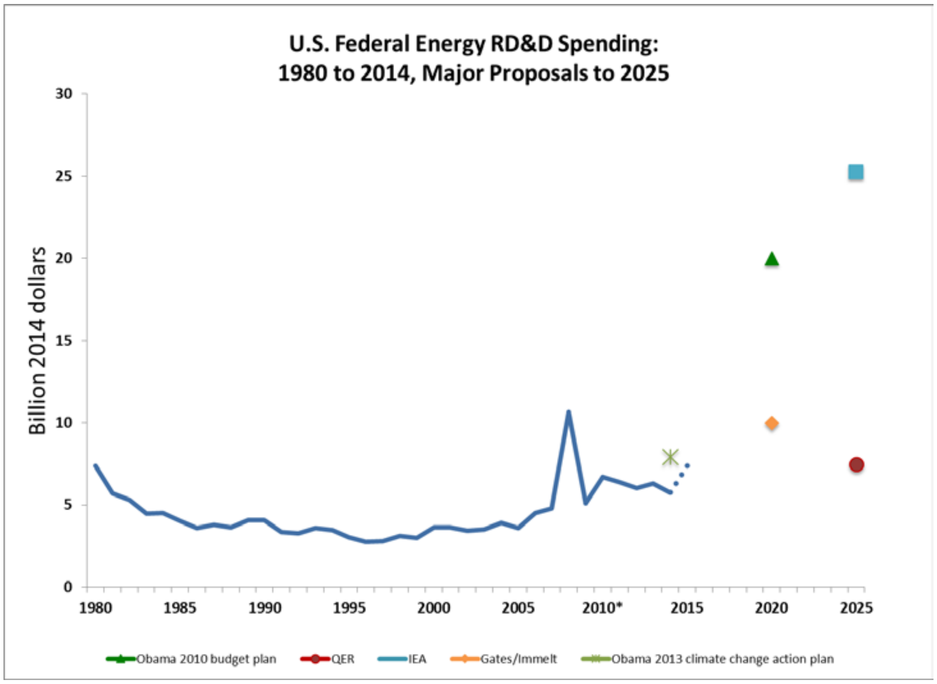

Figure 5. Source: ILAR analysis using data from International Energy Agency Energy Technology RD&D; The President's Budget FY2015 & FY2016; American Energy Innovation Council "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities" (2015); The President's Climate Action Plan (2013).

In some fields, proving the existence of a new scientific concept can be enough to bring the new idea into service. In pharmaceuticals, for example, many ideas for new drugs spring directly from basic science—which helps to explain why profit-seeking pharmaceutical firms spend so much money on basic research whereas most firms tend to view basic science as a public good that government should provide. But few of the innovations that are likely to cause a revolution in the energy system will spring forth directly from basic research. The "push" helps to improve the supply of new ideas. But a “pull” from the market is needed to convince firms to invest.

Pulls can come in many forms—here I will focus on two broad categories. One comes in the form of direct regulation—a requirement that firms install new technology, such as the mandate under the Clean Air Act that all new power plants install scrubbers to cut emissions of sulfur dioxide (SO2). When those mandates first appeared no utility knew exactly how to comply so they invested in research and demonstration projects—notably investments by Southern Company and by a consortia of utilities through the Electric Power Research Institute (EPRI)—that proved scrubber technology, lowered costs and improved reliability. Absent the regulatory mandate that investment would have been much slower to unfold.

Another form of pull comes from market incentives—such as pollution taxes or tradable emission credits. The US and a few other jurisdictions have experimented with emission credits with mixed but encouraging results. What is clear is that these schemes are very good at encouraging firms to find least cost ways to comply—often cutting total costs by half when compared with a plausible regulatory alternative[15]. What’s more hotly contested is how these different systems affect innovation. There is some evidence to suggest that strict regulatory mandates promote more innovation—perhaps because firms treat them as more credible and the very inflexibility forces innovation[16]. (Often these are called, in fact, technology-forcing standards.) Economists, for the most part, have been very uncomfortable with these findings because the boost for innovation can come at a huge economic cost—in effect, forcing firms to comply through innovation rather than hunting for the cheapest strategy.

Whether regulation or market-based, the effectiveness of forces that pull new technologies into service is based on credibility. If firms believe that new standards or market signals will come into force then they will make anticipatory changes in behavior. When the US sulfur trading program was created in 1990, for example, firms immediately saw this legislation as credible and had assumed (erroneously) that permit prices would rise over time. They invested, in anticipation, in new scrubber technologies. One of the reasons that emission credit systems for CO_2 and other warming gases have not yet had much impact on innovation is that firms do not know whether these schemes will yield credibly higher prices. Europe's Emission Trading Scheme (ETS), for example, generated high prices for several years and inspired firms to look at new technologies such as carbon capture and storage (CCS). But when policy makers allowed ETS prices to fall sharply and offered no credible solution that would raise prices in the future firms lost faith that market signals, by themselves, merited much investment.

Macro-coordination

Back in the late 1980s, when the climate change issue appeared on the agenda, the macro dimension of this story was not particularly important because individual countries—notably the US but also Japan, Germany, France and the U.K.—could have a huge impact on technologies within their borders through policies that operated at the level of the nation-state. If those countries pursued a strategy aimed at creating a revolution in energy supply systems then the revolution would follow—first in those lead markets and then eventually in the rest of the world. But the rest of the world didn't matter much since it accounted for a much smaller share of global emissions.

Today that is quite different. The advanced industrialized countries that have traditionally been the epicenter of innovation account for much less than half of world emissions—perhaps one-third or less—and that share is declining. Real leverage on emissions requires looking to other economies, notably the emerging economies. Moreover, the market for energy technology is fully globalized. Korean firms are building nuclear plants in Abu Dhabi. The frontier of innovation in advanced coal-fired power plants has shifted from western Europe to China. Advanced smart meters are being built from components sourced in many countries and deployed at frontier markets as diverse as Italy, California and India.

Put differently, knowledge is a global public good. This globalization of technology is an opportunity because it means that the most efficient technologies can quickly spread from centers of innovation to the rest of the global economy. But it creates a huge new challenge for policy makers since national governments, looking at their own incentives, will tend to under-invest in global public goods. Everyone benefits from additional knowledge, but since those benefits are difficult to exclude in a global economy individual nations will be inclined to free ride.

Figure 6 illustrates this shift by showing global investment in innovation (measured in dollars) for the IEA regions. And figure 7 shows the lagging pattern in the actual output of new ideas (measured in patents—in this case, patents filed in the U.S.).

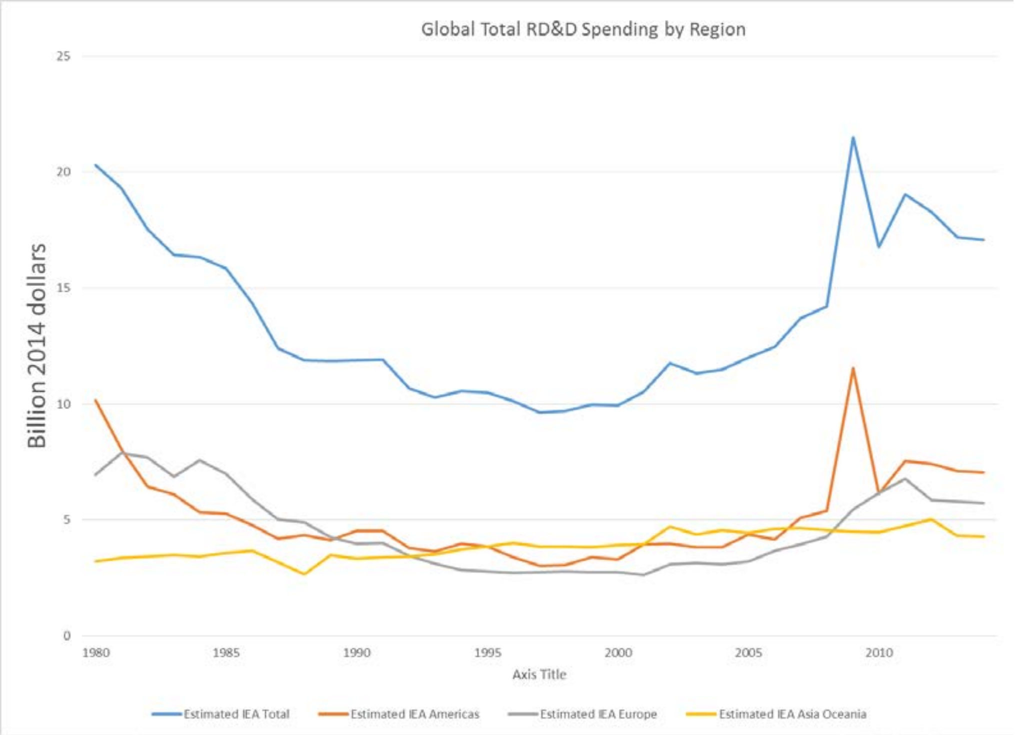

Figure 6. Source: International Energy Agency Energy Technology RD&D

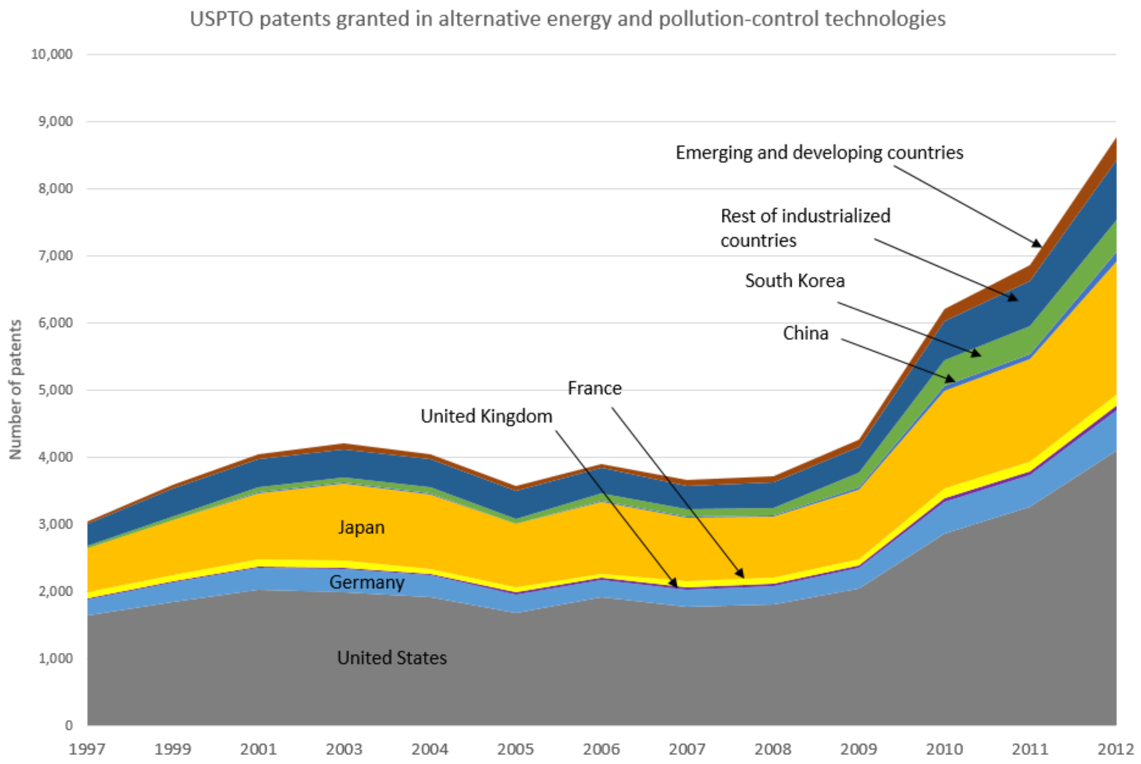

Figure 7. Source: The Patent Board (2013) & NSF *Science and Engineering Indicators* (2014)

Because knowledge is a global public good a measure of cooperation is needed. Each nation that is relevant in the production of knowledge should adopt national policies that help to address the tendency to under-invest in energy-related technologies and ideas. And each nation, seeing that others are doing the same, will be more likely to do more on their own than if they evaluated their policies solely from the perspective of the individual country. This is the essence of a global collective action problem—a problem that is familiar in international trade, coordination of mitigation of climate emissions, protection of the ozone layer, and a host of other challenges that require global cooperation[17].

Because international cooperation is implicated, crafting effective energy innovation policies will be more difficult than in earlier days when one country (the U.S.) was so dominant that it could set the global tune through its own actions. The good news, however, is that the number of countries relevant to energy innovation is small. Unlike cooperation on the control of emissions—which must involve at least a dozen countries and eventually many more—coordinating policies on innovation can work effectively in a much smaller club. Figures 6 & 7 suggest that perhaps half a dozen countries matter.

Getting the club together will not be easy, but nothing in the realm of climate policy has proved easy so far. Worse, very few efforts to build an innovation club have actually been tried. Instead, for more than 20 years international climate diplomacy has focused on mitigation of emissions—so far, achieving very little in that realm. Now there is more attention to the need to prepare for climate impacts—a field known as adaptation. But technology and innovation have been essentially ignored. Outside the institutions focused on climate change—such as the United Nations Framework Convention on Climate Change (UNFCCC)—there also hasn't been much real attention to building a serious innovation strategy globally. In the International Energy Agency (IEA) a series of excellent reports on energy technologies have been issued regularly[18], but not much else has happened on innovation. The G7, G20, MEF and other forums for high-level political discussions have largely ignored the topic as well.

The difficulties in building an effective international innovation strategy lie on two fronts. First, few governments are under much pressure to act. In democratic countries—and in authoritarian countries where leaders fear for their survival—public pressures about energy-related topics have focused more directly on emissions and on locally visible environmental harms. That focus has inspired political leaders to concentrate on mitigation and on making bold promises but not on the hard work of devising long-term emission control strategies. Second, real innovation policies are complex. They involve not just spending of money on RD&D but also protection of intellectual property, the creation of credible market "pulls" for new technology that can complement the push from RD&D, and in many cases reform of governing institutions such as the firms that are dominant in the energy sector. Not surprisingly, these are tasks for which individual countries vary in their preferences and capabilities. Even if governments act in good faith they may not know exactly what they can achieve—making it hard to offer credible (let alone binding) promises to other countries.

In other realms of international cooperation problems of this type—where the gains from cooperation are huge but spread far into the future, where preferences vary across the key players, and where there are high levels of uncertainty about the best policy strategies—are solved not through big, global diplomatic conferences. Those conferences lead to deadlock because the process of bargaining is too complex and the enterprise is highly vulnerable to just a few countries blocking progress—a particularly severe problem when diplomacy occurs within the UN system where consensus is usually required for decisions[19]. Instead, progress comes from working in smaller groups focused on particular tasks. In effect, governments and firms run experiments to see what works (and not) and then use what they learn to make more precise commitments over time. In other terms, what is needed is an experimental governance (XG) approach to policy coordination[20-21].

The XG approach to policy coordination is on display, perhaps, with the US-China bilateral cooperation on climate change[22]. While most press attention has focused on the emission pledges made in November 2014 when the bilateral agreement was announced, much more important for the long-term is probably technology cooperation. The US and China are top spenders of RD&D. China is rapidly increasing its output of new knowledge as well—such as measured by patents. China offers the partnership, as well, a convenient location to build demonstration projects since large-scale engineering projects are much less expensive (by a factor of 2 to 3) in China when compared with the west[23].

Making an XG approach to technology innovation actually work will require an agenda that is much more focused than most of today's diplomatic discussions. Real experiments require real areas of policy action—including real projects. The membership in policy clubs will usefully vary with the substantive topic. China will be a pivotal member of clubs that involve demonstration of advanced coal technologies since that country is a leader in the field and has also proved its ability to build large projects at low cost. Korea, among others, are logical partners for advanced nuclear projects. And so on.

One challenge will be to find the right balance between tangible projects—such as demonstration of advanced technologies—and coordination around supporting policies. Striking this balance may prove most difficult is in intellectual property (IP). There has been a tendency, especially for American policy analysts, to equate innovation with protection for IP and to assume that more IP is always better—despite all the evidence that IP can often be overly protective in ways that stifle innovation. IP has a role to play, but the full range of relevant policies is much broader.

MAKING IT HAPPEN

The climate problem is plagued by a string of inconvenient facts about the energy system. Most emissions come from the production of useful energy services, and changing that will require fundamental changes in energy technology. Over history, those changes have happened—but only over many decades and at a rate that is about two to three times slower than the rate of reduction that many climate scientists have said would be needed to protect the climate system. Directing that change with policy, rather than just letting it happen autonomously, will require very complex policies that vary across countries. Innovation is central, but so far the countries that do the most on innovation still probably under-spend by a factor of two to three. And politically, no government is under much pressure to be bold about innovation.

Putting all these inconvenient facts together explains why politicians have been good at talking about climate change and energy revolutions for more than 20 years but not so good at doing much.

Today, some governments may be on the cusp of a shift. There is now widespread recognition that the diplomatic strategy followed for the last two decades on climate change has failed. It has tried to do too much within a framework that is too inflexible. In its place is a new strategy based on breaking the climate problem down into smaller, manageable pieces and into smaller groups[19].

One of the central problems that should be on the agenda of these small groups is innovation. It won't be possible to make deep cuts in emissions without new technologies that make it feasible to provide useful energy services without all the warming pollution.

There are some auspicious signs for technology clubs already. Those include the fact that most innovation actually occurs in just a few countries—making it easy to identify and gather the nations that matter without (at least initially) the complexities of engaging a much larger group of nations with diverse preferences. In addition, some technology clubs are already taking form—most notably the US-China bilateral partnership announced in November 2013.

At the same time, there will be many difficulties in actually making these clubs work. An XG strategy will require that governments be willing to fund (and assess) many experiments to see which technology policies actually work—something that some governments have done but have not, so far, been willing to share fully and openly through international peer review. And the clubs will need to include commitments of many different types. Some will relate to the level of funding for energy RD&D that each club member makes—assuming that countries are willing and able to spend those resources, that should be straightforward. But equally important will be commitments to spend RD&D resources efficiently—and to coordinate, to some degree, national RD&D portfolios internationally. There are some precedents for that—such as when countries are required to coordinate because they are physically joined together at a single large facility, such as a space station, telescope or collider. But serious cooperation of this type in energy is relatively rare—when models are sought the architects should look to fields such as the human genome project where countries have actually achieved a measure of coordination while still preserving a large degree of autonomy for themselves.

This is not the first time that countries, dissatisfied with global cooperation on climate change, have shifted to small groups. The Bush administration did that with the Asia Pacific Partnership. Other countries, in alliance with the US, did that with the G20 and the MEF. And those smaller efforts have, so far, achieved very little.

Whether the same thing happens, again, after Paris will depend on whether countries see tangible value in cooperation on technology. Small groups, such as the US-China bilateral, must pivot from being places where there is talk about innovation to being vehicles for generating tangible new ideas as well as sufficiently exclusive markets where there are gains for the firms and countries that make an investment.

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