From Religion to Reality:

Energy systems transformation for sustainable prosperity[1]

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From Religion to Reality

1 Green Growth: Moving the Discussion From Religion to reality?

There are compelling and varied arguments for moving to low-carbon, high-efficiency energy systems. Reducing emissions to limit or avoid climate change leads the public debate, but reduced dependence on imported energy, avoidance of conflicts over energy resources, and the rising price of fossil fuels also motivate action. Nevertheless, the potential cost and difficulty of making the transition to a new energy system have generated substantial opposition from entrenched economic interests and consumers alike. [i]

In this article we ask whether and how this transformation could become an economic opportunity rather than a costly burden. Could a transformation to a low-carbon energy system induce net economic growth that can ease the transition to a low carbon economy? Or must it only be a pricey impediment whose costs offer support to those who would resist change? We address three aspects of this problem:

1. What are the proper roles for markets, prices, and governments in the move to a new energy system?
2. Which policy interventions can become investments in a productive future, and which are just costs that we must bear to achieve our other policy objectives?
3. Can the shift to low-carbon, high-efficiency energy drive "green growth" and business opportunity?

As we shall argue, answering these questions must begin with the concept of an *energy systems transformation,* which we turn to in the next section.

To date, such discussions of "green growth" have been more religion than reality. For those convinced of the urgency of a low-carbon energy systems transformation, “green growth” holds out the hope that the investment and innovation required for this transformation can become the foundations of a new wave of economic growth. This would cut the Gordian knot of tradeoffs between economic growth and emissions reduction. In so doing, it would solve the political economy problems created by the transition to a low-carbon society, offering a world where a growing green economy rewards the winners of the green energy revolution and compensates to its losers. Given these advantages, it is no surprise that politicians from Brussels to Beijing have embraced the promise of green growth via energy systems transformation. [ii]

But the easiest arguments about Green Growth are not satisfactory. Indeed, both politically and technically, the green growth arguments are fraught with challenges. New “green collar” jobs may not be enough to offset the “brown collar” jobs they replace. Green growth wholly dependent on export of green energy products threatens a new green mercantilism where countries view Green Growth as a zero-sum game. And while green energy may offer new opportunities to the energy sector, it remains unclear what new prospects an energy system built on “green electrons” offers to the wider economy, which already enjoys abundant, dependable energy from otherwise indistinguishable—but cheaper—“brown electrons.”

Debates over energy policy remain rooted in issues of how much must be paid and by whom, and solutions mired in what appears to be diffuse, hard-to-identify benefits in the face of acute and easily observed costs. Whether right or wrong, those fears limit support for the transformation. Moreover, given the central importance of the energy system to modern industrial society, the effort to change the system will in any case encounter determined interests entrenched in the old order. In this context, it’s no wonder that change has been slow in coming for all but those economies most exposed to unstable energy prices and supplies.

2 "Green Growth and the Transformation of the Energy System: A First Step Toward Reality

The advocates of "green growth" may be correct. Indeed, we hope they are. But moving green growth from religion to reality will require going beyond jobs or exports to examine how changes in to the energy system can create pervasive economic growth. Earlier systems transformations—the railroads or information technology—drove growth by changing the possibilities for production in the broader economy. The opportunities that emerged from these transformations created powerful interests that sustained them, and generated the profits and employment to continue investment in the new system and absorb the workers displaced from the old. Green growth, if it emerges, must come from this kind of systems transformation.

By *system*, we refer to an array of separate elements complementary to one another and tightly inter-linked. In economic terms the widespread adoption of some technologies requires investment in related, complementary, technologies. Thus, as is now understood, widespread adoption of intermittent renewable energy resources will require complementary changes to modes of energy distribution and patterns of energy use.[iii] Those complementarities, in turn, are not merely technological but economic and regulatory as well. Absent adaptation of energy markets and regulatory systems along with the technological changes required for low-carbon energy, the energy system will not maintain its ability to provide reliable, predictable energy to the economy. The resulting difficulties will slow the transition to a low-carbon, high-efficiency economy. It is this complementary series of technological, economic, and regulatory changes that we refer to as an *energy systems transformation*.

This character of these complementary changes implies that policy must target a particular kind of transformation. That transformation must emphasize a shift to a different trajectory of energy development, not merely the improvement of the existing system. More efficient light bulbs, or better gas mileage for vehicles, can improve the efficiency of today's energy system. However, those changes will not fundamentally transform our dependence on carbon energy. Doing so will, instead, require an altogether new systems trajectory, one that promotes complementary innovations leading to a low carbon system that produces, distributes, and uses energy in new ways.

This will require more than just one-off technological breakthroughs. For instance, advances in wind power technology must be matched by developments in the power grid and energy use to accommodate wind power's fundamental intermittency. Likewise, an efficient, reliable electric car will require substantial increases in electricity supply from low-emissions sources, and a new network of refueling stations, even as it promises to radically reduce the role of oil in transportation. These problems demonstrate the importance of energy as a system, and inform against approaching treating the problem as one of isolated solutions. [4]

This article argues that political and economic success at such a green energy-led systems transformation can only come from the possibilities it would create for the broader economy. Facilitating those possibilities confronts policymakers with two problems: *first*, how to shift the development of the energy system from its present high-emissions, low-efficiency trajectory to a low-emissions, high-efficiency alternative; and *second*, how to enable the broader economy to discover and express the presently unknown—and unknowable—opportunities that such a new system may create. In the past, most of the value of systems transformations, whether the railways and transport or IT and communications, was created by network users rather than by the networks themselves. Green growth will require the same of this transformation of the systems and networks that power the economy.

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[4] This system transformation will require difficult changes in three distinct domains, 1) Energy efficiency can reduce demand, but those demand reductions make planning harder and diminish the requirements for new capital investments potentially embodying low carbon technology. 2) Renewable electrical energy sources are intermittent, creating new demands for grid management. Biofuels require significant alteration of fuel distribution systems; and 3) Decarbonizing existing fuel sources, as well as introducing renewables, comes at the price of higher energy costs. Those costs must be borne directly by energy users, but the benefits are quite diffuse.

This argument poses serious challenges to climate and energy policy. Given the need for coordinated transformation of the energy system's capacity to produce, distribute, and use energy, price alone may be insufficient in spite of prevailing policy wisdom. Moreover, the power of a network transformation may lie less in the particular technological characteristics of the new system than in the design of the markets, access rules, and standards that facilitate its exploitation. Finally, and in contrast to appeals for a one-size-fits-all approach to climate and energy policy, the link between green growth and energy systems transformation will depend critically on national circumstances and require distinct national strategies.

Hence green growth is by no means certain and poses serious challenges to the public and private sector. This article lays out those challenges, and explores how they can be resolved given the logic of the energy system itself. In particular, we emphasize that policymakers should exploit the critical role that the power grid will play in this transformation for strategic leverage over the entire energy system. Conceived correctly, both strategic investment and market reform, in the context of broader interventions including a carbon price, offer the best opportunity to exploit emissions reduction to generate sustained and sustainable economic growth.

3 Why a transformation: decentralization, intermittency, and demand management

Most discussion of renewable energy and emissions reduction emphasizes the sources—wind, solar, nuclear, geothermal and others—that will provide the carbon-less electrons to power a clean energy economy. Why, then, do we speak of a transformation of the energy system, rather than a program for investment in new energy sources? We would argue that source replacement alone cannot achieve the scale of renewable energy adoption required for serious decarbonization of the energy supply. Moreover, viewed as mere source replacement, the green energy revolution would have only a limited impact on the economic activity of an advanced industrial economy. Technically, large shares of renewable energy pose serious challenges to today's centralized, constant-load, supply-equilibrated energy supply. Economically, mere replacement would have a defined and very limited scope, limiting further the growth prospects for replacement of cheap fossil fuels with expensive renewable energy. Thus any hope of both decarbonizing the energy supply and achieving economic growth via clean energy requires looking at the possibilities of the broader energy system.

Technically, renewable energy poses three challenges to the functioning of modern energy systems. Today's energy systems provide constant energy supplies through centralized distribution systems that treat demand as an exogenous variable. Tomorrow's renewable energy systems must manage both demand and supply to accommodate the variability of renewable energy generated by a wide range of distributed energy systems. These three challenges together imply an energy systems transformation. They also demonstrate the importance of the power grid to this transformation.

Centralization poses the first challenge. Since Nikola Tesla's alternating current system won out over Edison, large, centralized power plants have dominated modern energy systems.[iv] Improvements in long-distance transmission now mean that most generation plants are now located far from centers of economic demand. Electricity flows almost exclusive from the plant to the center of demand, via a series of transmission substations.

Renewable energy requires a very different structure for the energy system. Because plants must be located wherever renewable resources may be found, renewable energy frustrates any attempt at centralization. To accommodate distributed generation, a power grid designed around centralized power plants must be reconfigured to handle different inputs, of different scale, from a geographically disperse set of resources. This will require significant new investment in transmission and distribution capacity.[v]

These investments are closely related to the second challenge, intermittency. Fossil fuels sources provide electricity as stable as the supply of fossil fuels to their boilers. This has meant a reliable, stable, dependable energy supply for industrial societies. In contrast renewable energy resources like wind and solar are notoriously intermittent, in ways unrelated to the actual demand for energy.[vi] Stabilizing the energy supply from renewable energy sources therefore requires complementary measures of one of two forms. Geographic diversification provides one possibility. Intermittency is very weakly correlated over long distances: wind speed in North Dakota and solar intensity in Arizona don't vary in the same way at the same time. If transmission capacity can tie together sufficiently geographically dispersed markets, then energy supply can be averaged to match energy demand.

Alternatively, a range of new energy storage solutions can be added to the grid in order to stockpile energy generated at times of low demand for use at times of high demand. Again, however, this requires that the power grid have the ability to accommodate a much wider diversity of sources than it does at present, and to manage those sources in real time against the demands of industrial societies. In either case, however, the problem remains the same: moving away from fossil fuel dependence for the power supply will require a set of complementary changes to the electricity grid. Source replacement alone will not suffice to achieve a low-carbon energy systems transformation.

Whether some of this challenge can be made easier by demand management brings us to the third driver of energy systems transformation. Historically, the energy system treated demand as a given and worked to provide sufficiently flexible supply capabilities to satisfy it. But managing demand against supply may offer both price and performance advantages to the energy system. If some forms of energy demand can be adjusted in tandem with variability of renewable energy supplies, it could increase both the efficiency and the stability of the system. Such an approach would be vital to the large-scale incorporation of electric vehicles, which would simultaneously represent an enormous new demand on the system and a huge potential pool of electricity storage.

Thus three challenges—intermittency, distributed generation, and demand management—suggest that only a transformation of the energy system will suffice to decarbonizes the energy supply of modern industrial societies. Source replacement alone cannot achieve the level of renewable energy generation required without posing serious challenges to the stability and reliability of the electric grid. Taken together, this implies a threefold transformation for energy production, distribution, and use.

This transformation will require huge investments across the economy. A variety of popular and policy arguments has suggested that these investments represent the next technological transformation of the economy, implying manifold new opportunities for innovation, employment, and economic growth.[vii] If true, the economic possibilities they imply could more than offset the costs of investment. The "green growth" that ensued would turn the logic of climate change on its head, suggesting that climate change mitigation could generate real, material benefits in addition to the abstract benefit of averted global climate change. This would fundamentally change the terms of debate. But how should we understand the possibility of this outcome? For that, we turn to other instances of technological transformation in networked systems, to see where and how they supported sustained economic growth.

4 An Earlier Transformation: networks and the ICT Revolution

Significant infrastructure changes have often prompted broad investment to take advantage of them. Railways in the 19th century radically transformed time and space, drove transport costs to a minimum, and opened up vast new territories, resources, and markets to economic activity. Likewise, the information technology revolution built new business models and products atop radical changes to the structure and function of telecommunications networks. Both transformations provided the foundations for decades of sustained economic growth.

These earlier transformative epochs provide important lessons for thinking about how and where the transformation of the energy system—itself a network like rail or information technology—could do the same. In each case, two lessons stand out: first, that the network—power grids or rail infrastructure—played the critical role in each transformation; and second, that most of the growth generated by these earlier systems transformations came from the possibilities created for the broader economy, rather than from the investments in the system itself. This mismatch between the social and private benefits should lend caution to those predictions of pure market-based solutions.

We begin with the ICT revolution. In 1991, the United States National Science Foundation opened its internal, distributed information network that it had inherited from the Department of Defense to commercial activity (Janet Abbate xxxx). The Internet, as it came to be known, was born. By 2000, internet-related commerce accounted for at least $100 billion in annual turnover and 2.5 million jobs in the United States alone[viii], acounted for several firms in the Fortune 500, and laid the foundations for a second round of innovations in social media, communications, and logistics management that continue to this day[ix]. Thus, within twenty years of commercialization, the internet had radically transformed both communications and the broader economy, and generated significant economic growth and productivity improvements.[x]

Why did the digital revolution happen so quickly, and so smoothly? We argue that the economic transformation wrought by the Internet and ICT came in two phases. Both phases merged private-sector investment and innovation with public-sector market formation and rulemaking. While neither phase proceeded via some grand design, both shared critical features: support for basic research and development as well as early deployment, market rules that favored openness and access and checked monopoly. and tremendous private sector investments in experimentation both *within* and *on top of* the evolving network. That experimentation established a symbiosis in which rapid innovation in new ICT products created ever-new possibilities for incorporation of digital technology in production processes and products. Those new possibilities, in turn, drove new demand that funded subsequent waves of ICT innovation. This symbiosis, founded on the possibilities ICT created for the economy at large, made the revolution self-sustaining.

The first phase of the ICT revolution, lasting from the invention of the transistor in 1947 to the introduction of the personal computer in the 1980s, coupled private sector innovation to public-sector restriction on the ability of dominant market players to restrict the diffusion of those innovations. Many of the innovations critical to the ICT revolution came out of industrial giants, most notably AT&T and IBM. Left to their own devices, either firm might have used their monopoly positions to generate rents, constrain market competition, and compete on the basis of network access instead of product features. Instead, AT&T found itself the subject of ongoing antitrust scrutiny starting as early as 1947 – well this goes back to MCI and even answering machines. IBM came under scrutiny starting in the late 1960s. That meant that although AT&T's Bell Labs invented the silicon transistor in the 1950s, the technology quickly diffused into the market, rather than remaining trapped inside the AT&T monopoly. An ongoing set of decisions antitrust and network access decisions meant that AT&T could not use its ownership of the communications network to limit access to new competitors exploiting the possibilities in emerging digital technologies.

Likewise, IBM initially thought that their control of the BIOS—the control logic of a personal computer—would allow them to control the PC, while they outsourced the operating system and other components. But IBM could not dominate semiconductor markets without falling afoul of its federal antitrust investigators. As a consequence, the personal computer became an open standards platform. This gave rise to the IBM clone market, massive competition and price pressures, and increasingly inexpensive computing power. Thus private innovations—the semiconductor, the transistor, and the personal computer—were coupled to public initiative to ensure that new technologies were not constrained by the market power of dominant players.

Finally, especially in the 1950s and 1960s, but less so thereafter, a number of the initial products of private sector firms were predominately purchased by governments with bottomless pockets and a perceived need for maximal performance—chiefly the United States Department of Defense and the space program—whose purchases at very high prices with enormous margins underwrote the early experimentation in the industry.

In the second phase of the ICT revolution, beginning in the mid-1980s, private innovation was again facilitated by public action, this time in the realm of standards-setting. Rapid growth in ICT depended on the interoperability of a range of devices. Absent standards, the large positive network externalities of the internet might not have materialized. Indeed, a network model along the lines of first-generation firms like AOL or Compuserve might have led to competition over network access rather than product features. Instead, the early emphasis of DARPA and the NSF on an open, redundant, standards-based network and, in particular, TCP-IP led to what became the Internet. Coupled to antitrust restrictions on control of telecommunications networks, those standards enabled a range of new competitors—from Cisco Systems to Microsoft to Google—to enter markets controlled by AT&T and IBM, disrupt them, and generate transformative innovation.

Those innovations, in turn, drove a series of investment booms in the 1980s, 1990s, and 2000s. In most cases, the investment in ICT technologies themselves were only a part of the overall investment in the new possibilities for business activity they created. The transformation of supply chains, for instance, merged the information monitoring capacity of ICT with fundamental transformations in the production processes and management structures of major firms. Those changes would not have been possible without ICT, but were nevertheless innovations in and of themselves.[xi] As noted above, this symbiosis between ICT-sector innovation and innovation in the broader economy drove a virtuous cycle of innovation, demand, and investment that sustained repeated and rapid waves of ICT-driven economic growth.

We can distill this history to five important points:

1. The ICT revolution built new industries, and later transformed older ones
2. The early construction of that industry was heavily underwritten—both financially and structurally—by the public sector, chiefly the United States Defense Department and the National Science Foundation

3. Regulatory intervention ensured that legacy market players could not use dominant market positions to limit competition through control of either technological standards or network access
4. The economic value of the ICT transformation came from both the networks themselves, the products they enabled, and the processes that they transformed
5. And the ICT revolution sustained itself because digital technologies meant that existing tasks could be done more cheaply and more effectively, and new value-added tasks could be envisioned

We would emphasize the point that, for the most part, the ICT revolution created entirely new industries. Most of the infrastructure that the revolution required had no real predecessor: the capabilities of the PC so overwhelmed those of the typewriter or adding machine that they are almost not comparable. As such, the industry faced few legacy barriers to entry. That lack of barriers created the latitude for experimentation, permitting the structure of the network to evolve free of constraints from legacy systems requirements. As we shall see, this condition, so important to the progress of the ICT revolution, is not reproduced for energy systems.

Thus the ICT revolution was predominately a systems transformation, in two senses. First, it marked a transformation of markets in order to support the development and diffusion of information and network technologies. Second, it generated massive spillover benefits by transforming the possibilities for economic activity in the broader economy. The economic growth generated by the ICT revolution was at the very least equally distributed between the ICT sector and the broader economy. Achieving this kind of transformative growth required both the private investments in new technologies and business models, and public support for open, competitive, standards-based markets in which those investments could thrive.

5 Challenges to Green Growth: Employment, mercantilism, and the limits to systems transformation

The core of the green growth argument suggests that the energy systems transformation described in section 3 can drive the same kind of economic transformation that ICT wrought.[xii] To date, however, neither policymakers nor policy analysts have paid attention to whether the conditions that made ICT into a revolutionary technology are also present in the transformation to a low-carbon energy system. Instead, most of the emphasis has concentrated on near-term benefits from jobs or capture of export markets for so-called "green" goods.

This lack of scrutiny poses serious problems not least because of the differences between ICT and energy that become apparent upon even cursory examination of these two systems transformations:

1. Unlike ICT, the energy system in the advanced countries is fully built-out, and new capacity will only be added slowly. Consequently, new approaches to energy must be implemented by retrofitting the existing system.
2. That retrofit must occur while preserving an uninterrupted supply of energy to the economy.
3. Both the public and private sector have limited resources relative to the scale of investment required compared with the initial era of semiconductor and ICT innovation
4. In many countries, certainly the US, the networks belong to a diverse set of owners operating in many different regulatory jurisdictions, frustrating attempts to enforce interoperability for new grid capabilities and open access for new technologies and market players.
5. The investment horizons don't support rapid adoption or iterated innovation. Investments in ICT depreciated over months or years, creating consistent demand for new innovation and investment. Investments in energy infrastructure depreciate over decades.[xiii]
6. Renewable energy does not, for the most part, offer immediate competitive advantage to early adopters the way ICT investments did.

Given these differences, the short-term focus on jobs is particularly damaging to the long-term prospects for green growth. Absent a renewed focus on how the investments in green energy might translate into broader opportunities for the economy, the contribution of green investment to growth—whether jobs, employment, or productivity—will necessarily remain limited. In this context, the real green growth challenge lies in how best to structure and support markets for green investment and innovation that can discover and express new opportunities created by low-carbon energy for the economy as a whole. Anything less risks an energy policy that achieves only short-term job gains and may inadvertently provoke a new wave of mercantilism in green products.

5.1 Mistaking jobs for growth: the myth of green jobs and the threat of green mercantilism

In the aftermath of the 2007-2009 financial crisis, the "green jobs" variant of the green growth argument gained currency across the industrial world. United States President Barack Obama, the European Union, and a range of American states and European countries have all sought to tie green energy investment to job creation.[xiv] As Barbier (2010) notes, this led to a significant quantity of economic stimulus funds directed to energy efficiency, renewable energy, and energy-related research and development. Support for these investments were buttressed by fears that insufficient domestic support for energy investment would lead to permanent disadvantages in a new green technology frontier, particularly vis-à-vis new economic powerhouses like China.[xv]

This emphasis on jobs and export competitiveness should raise immediate concerns on two fronts. First, a focus on job creation in the green energy sector alone cannot form the basis of sustained economic growth in advanced industrial societies. If those jobs result from Keynesian demand stimulus, as in 2007-2009, their viability necessarily fades as the economy returns to full employment. But even if those jobs could stand on their own, they would have limited potential for widespread employment. As already discussed, those societies have fully built-out energy systems and relatively modest growth in energy demand. In this case "green jobs" will necessarily replace "brown jobs" in operation of the energy system; and the new "green jobs" created for the period of system retrofitting will necessarily be short-lived, lasting only as long as the retrofit itself. Finally, those "green" jobs will have limited impact on the overall employment picture, as they emphasize the energy sector alone rather than the economy as a whole.[xvi] Thus even if the investment in systems retrofits will lead to near-term job creation, the timeframe for those jobs is necessarily limited.

The quality of those jobs is also open to criticism. Some argue that an investment in green electricity generates more jobs per unit installed capacity than an investment in equivalent brown energy capacity.[xvii] But this implicitly suggests that the green energy industry achieves, at present, lower labor productivity than the fossil-fuel power sector. If the goal is pure Keynesian job creation to employ idle labor, then this justification may make sense. But as a long-term employment strategy, it cannot sustain high wages in advanced industrial economies.[xviii]

Moreover, the quality of these jobs in high-wage advanced industrial economies requires careful scrutiny. We can think of green jobs as coming in one of two categories: high-productivity producing the components of the energy system; and relatively lower-productivity jobs in the installation and servicing of these components and in other labor intensive domains such as energy efficiency improvements. The former, largely high productivity manufacturing and design jobs, produce largely traded goods. The latter, essentially construction and installation jobs, produce untraded goods. The advanced countries' stated goal of capturing the high-productivity "green collar" jobs as a path to industrial revitalization has given rise to risks of a new "green mercantilism." Countries now openly express concerns that the failure to create domestic markets in green energy will lead to loss of global competitiveness, particularly to the developing world. On the surface this is an excellent justification for domestic "green" investments. However, it risks improper direct and indirect subsidies at home and a conflict over international access to markets abroad. This view of "green growth" as a zero-sum game portends a counterproductive period of international competition that brings to mind the failures of the mercantile system of the late 19th century or the import substitution period of the mid-20th century.

5.2 Beyond jobs and exports: systems transformation and sustained growth

Short-term emphasis on green jobs or green export competitiveness will not lay the foundations for the "green industrial revolution" predicted by advocates of green growth. But as we have seen, systemic investment in disruptive technological innovation may create new opportunities throughout the economy. Industrial history provides many examples, beyond ICT, of situations where innovations in one sector or technology domain enabled dramatic growth in the rest of the economy. These examples underpin much of our understanding about the connection between disruptive technologies and long-term economic growth. A few examples[xix] will suffice:

- Steam power, which dramatically altered the amount of power that could be applied to a given task and created a platform for innovation in economic production and transportation
- Railroad transportation, which significantly lowered the cost of transportation and tied local markets into national economies. Railroads shrank time and space, creating much larger markets for goods that justified wholly new modes of firm organization and capital investment.
- Electrification, which enabled the reorganization of factories, and made possible the introduction of myriad new devices simply not possible with coal or gas.
- The internal combustion engine, which provided the energy efficiency and intensity necessary for the transportation revolution.
- Semiconductors and information networks, which enabled the information revolution and spawned entirely new forms of value creation based on information as a good. The internet changed fundamentally the ability to aggregate, access, process, and use information.

These innovations made possible products, processes, and ways of doing business that simply were not possible earlier . The network innovations in particular– railroads, the electric grid, the internet – all changed fundamentally the possibilities for the organization of the rest of the economy. The new market possibilities, and not just the networks themselves, generated economic growth.

There is a real question as to whether "clean energy" generates pervasive opportunity in the same way. Spectacular success in adding renewable energy to the energy system means the energy user will notice no difference between electrons generated by coal and those generated by wind or solar. A watt of electricity is a watt of electricity and joule of power is a joule of power. All the investment in storage, the smart grid, and new energy sources will go towards ensuring that today's patterns of energy use remain viable. It will do little to enable some new generation of energy uses. Even the invention of a whole new class of automobiles still only strives to produce a personal transportation device as good as automobiles available today.

Nevertheless, innovations in energy technology may reduce energy costs or provide value by correcting for negative externalities like pollution-induced health costs or extreme weather events related to climate change. But these benefits are largely about cost savings or avoidance of damage. These technologies do not, as of yet, promise radically different, more productive, more diverse forms of economic value creation.[xx] Thus green growth and the energy systems transformation on which it depends remain very different from these earlier epochs of transformative technological change.

These differences make it incumbent on those who advocate for green growth to demonstrate the systems advantages that would lead to repeated innovation in the private sector and that would drive growth through new possibilities for products, production, or productivity.[xxi]

We would point out that the economic significance of radical systems changes often comes in disguise. The advantages of a new energy system may not be evident immediately. In the 1940s, IBM is reputed to have suggested, famously, that it would only sell a handful of its new mainframe computers.[xxii] The enormous utility of the mainframe and its successors only became apparent through experimentation in the market. Microprocessors followed a similar pattern. Intel had to invest heavily in explaining to potential customers the possibilities of this new device to a lay audience. Indeed, its marketing manager at the time had a Ph.D. in electrical engineering—a qualification Intel considered necessary for articulating the potential of this new technology for tangible economic benefits to a lay audience.[xxiii] Last but not least, the commercial power of the Internet was hardly obvious at the beginning.

Similarly, the real advantages of "green" tech, and there may well be many, will be discovered in the marketplace. But the very different nature of this transformation, and the very large investments it will require, behooves the participants—private and public sector alike—to proactively identify the economic possibilities that may emerge from green energy. That discussion will prove a necessary precursor to policy that can go beyond merely driving the development and adoption of "green" energy, to enable the broader adaptation in the economy as a whole.

6 The policy challenge: energy systems transformation with an eye to green growth

Thus policymakers face real challenges translating green into growth. The emphasis on green jobs quickly runs into limits from employment and productivity. The attractiveness of export-led growth from green industry risks viewing the green energy systems transformation as a zero-sum game, leading to green mercantilism. Finally, the analogy to earlier transformations in high-technology systems shows how different the transformation to a low-carbon energy system may be. Those differences translate into real challenges in using energy innovation to spur a self-sustaining transformation of the energy system with large spillover benefits for the economy as a whole.

This problem should be addressed in three stages. First, we need to ask what policy must accomplish in order to achieve a successful systems transformation. Second, we need to determine what policy instruments best reflect these goals, and whether the conventional approach to climate policy is consistent with that determination. Third, we need to find policies that can be implemented, which is particularly the ease given the resistance to carbon taxes? Finally, if a self-sustaining, growth-inducing energy systems transformation is the ultimate goal, then we should consider how these policy instruments might be best deployed in service of that end.

Addressing the problem of energy systems transformation in light of this approach suggests that today's emphasis on carbon pricing fails to reflect the complexity of energy systems transformation, and may offer little opportunity to put that transformation in service of economic growth. Not only might prices fail to achieve meaningful decarbonization of the energy system, but they offer no sustained support for the complementary changes required to achieve an energy systems transformation of the form described in section 3.

6.1 Goals

Renewable energy-focused policy usually expresses a single goal: to reduce emissions via altering the dependence of industrial economies on fossil fuels. But as we saw in section 3, that goal really requires an energy systems transformation.[xxiv] That transformation, in turn, requires parallel and complementary changes to energy production, distribution, and use in order to adapt to the different technical and economic properties of renewable energy.

The near-term goal for policy in this context is not the completion of the transformation itself. The scale and degree of investment required to do so make such an outcome improbable. Rather, the real goal should be to shift the energy system onto a new and self-sustaining development trajectory. The nature of today's energy system provides large incentives to innovate within its constraints. The scale of the network means that such innovations immediately enjoy large markets and easy compatibility. Note of course that resistance is enormous in larger markets. Often .smaller markets are where new technologies gain a foothold. This of course poses serious problems for any attempt to transition out of the present equilibrium. But it likewise suggests that a self-sustaining process of investment and innovation in favor of a low-carbon energy system is possible, if only we can find the right policy levers to achieve the initial shift in the trajectory of the system as a whole.

Such an achievement may provide the best opportunity for green growth. As with past technological systems transformations, growth via a low-carbon energy systems transformation requires a self-sustaining pattern of innovation and investment in both the energy sector and the broader economy. At present, it remains unclear whether renewable energy can promise this kind of innovation. But it most certainly cannot if it continues to operate under the constraints of an energy system designed predominately around fossil fuels.

6.2 Instruments

Climate change mitigation confronts policymakers with a wide range of choices in service of both "green growth" and a low-carbon energy systems transformation. The most vibrant policy debates today concern the role that four different policy instruments should play:

1. Carbon pricing to incentivize both technological development and low-emissions energy adoption;
2. Technology policy to support research and development;
3. Regulatory policy to change market rules to favor new forms of energy production, distribution, and use[xxv];
4. Direct state action for public infrastructure investment and industrial policy.

6.2.1 Carbon pricing and its shortcomings

Conventional policy wisdom for carbon emissions mitigation argues in favor of a credible, sustainable, and high carbon price, perhaps supplemented with subsidies to basic research and development for new energy technologies.[xxvi] Such policy, its advocates argue, will allow the economy to discover the most efficient way of reducing emissions. In contrast, other options—such as industrial policy, subsidy of renewable energy sources, or mandates in favor of energy efficiency—are seen as inefficient meddling in the market that will ultimately cost more than a policy reliant on price alone.

This conventional wisdom falls short of the goal of changing the development trajectory of the energy system. Three shortcomings stand out:

1. The self-identified preconditions for a successful carbon pricing policy—a universal, sustainable, high carbon price—appear politically impossible either domestically or internationally
2. It is by no means clear that the efficient carbon price, equal to the marginal cost of emissions, is high enough to overcome the substantial network externalities present in the energy system
3. The carbon price offers little support for the substantial coordination and market reform issues that will play a critical role in the viability of future energy innovations

William Nordhaus' "carbon price fundamentalism" argues that a "universal, sustainable, and high" carbon price is a sufficient condition for the innovation and investment required for a low-carbon energy systems transformation. Realizing those conditions today appears impossible. Moreover, those conditions appear internally contradictory.

Since any price on carbon is entirely a political construct, the durability of the carbon price depends entirely on the ability of a given political system to sustain it. Sustainability will depend entirely on the relative ability of winners and losers created by carbon pricing to either erode or protect the price level. A carbon price will hurt concentrated interests like energy firms and large energy consumers (and, to a less concentrated degree, individuals and households). Even if the benefits it generates from emissions reduction entirely offset these costs, they come far in the future, and are broadly distributed across the entire population—and even beyond state borders. This is the classic definition of an externality. Standard political economy arguments from a range of cases show the extraordinary vulnerability of policies that generate acute, concentrated costs for powerful interests while producing weak, diffuse benefits. And those problems worsen with higher, and more punitive carbon prices. Thus "high" undermines "universal" and "sustainable."

This mismatch between political reality and policy theory undermines the edifice of carbon pricing. The absence of a long-term, credible, and increasing carbon price dilutes the incentives for significant investments in innovation and infrastructure. Absent those investments, the changes required to transform the energy system will happen more slowly or not at all.

The demand for complementary changes to achieve an energy systems transformation poses the second obstacle to a price-driven approach. This approach has emerged out of a line of economic argument that treats emissions as a market failure, a negative externality. That approach implies the belief that the market already contains the ability to produce what we need for a low-carbon energy system, but under-produces it because of the mismatch between private and social costs. Under that assumption, correcting this mismatch generates the most efficient incentives for the market to increase its production of the components necessary for a low-emissions energy system.

But the energy systems transformation we've outlined suggests that the present market is locked into a trajectory in which it *doesn't* produce the elements needed for a low-emissions energy system. A long history of economic research has suggested that technological systems face serious barriers to systemic change because the existence of the system itself provides large incentives not to invest in alternative technologies and business models.[xxvii] In a scenario where we have a reasonably good idea of the broad outlines of what that alternative looks like—a low-emissions energy system capable of supporting the needs of industrial society—these large barriers to entry may impede progress at all but very high prices. Moreover, that price must be high enough such that all three domains of the system—production, distribution, and use—have incentives to generate the complementary changes required of them. Given the size, scale, and complexity of modern energy systems, it's reasonable to argue that these barriers might be very high, such that absent more directed state intervention in the markets, new innovations might not emerge or be adopted at scale.[xxviii]

Appropriate pricing policy, technology strategies, regulatory programs, and infrastructure policies are essential. Each of these policy tools has a role to play. But none constitutes a comprehensive solution on its own. Moreover, we emphasize that national variation in the regulation of the energy sector, the ownership structure of its firms, and the dynamics of finance create opportunities and constraints that will affect each of these three policy tools differently. Hence we should expect, and accommodate, distinct national solutions to systems transformation.

6.2.2 Technology policy to support research and development

Proponents of public support for research and development argue that these policies can achieve the goals that carbon prices cannot. Certainly the need for innovation in renewable energy, energy distribution, and energy efficiency will require significant public investment. How best to make those investments remains the subject of spirited debate.

Traditional technology policy can take at least three forms: 1) intensive support of narrow innovation priorities, as in the Manhattan project, 2) diffuse support of research and development through research institutes and universities, and 3) policies to promote the adoption and diffusion of the new technologies. Manhattan Project-style efforts may be appropriate for capital-intensive, high-risk problems like nuclear fusion or carbon sequestration, but are of little use in delivering diffuse innovations for efficiency across a spectrum of sectors. Diffuse innovation, in contrast, is enormously successful when the standards for interoperability are already settled, and thus coordination among researchers is unimportant. Similarly, policies for adoption and diffusion of technologies, whether through public or private mechanisms, assume reasonably mature technology development. One must emphasize that technology policy does not necessarily constitute "industrial policy" since it need not determine technology choices in the market.

6.2.3 Regulatory intervention

Governments can successfully use regulatory incentives to drive the adoption of new energy technology where, again, the technological targets are well-understood and where the regulators have significant weight in the marketplace. Many countries or U.S. states have already done so, via Renewable Energy Portfolio requirements for power generators, energy efficiency programs for homeowners, and changes to energy tariffs. Regulation can affect the deployment and diffusion of technology, but does not necessarily create the framework for sustained private investment. Without considerable regulatory will the incentives to continue these programs may fade. Unless an energy systems change can be achieved, the impact of these regulations would be limited.

6.2.4 Direct state action: infrastructure and industry policy

Government, of course, may act in energy markets directly, as in building out new energy infrastructure or obligating private actors to do so. The question becomes whether energy systems transformation requires directed state action in addition to the less intrusive policies noted above. Importantly, infrastructure policy need not be directed industrial policy; it need not dictate or support the success of particular firms or of particular technologies. Nevertheless, the classic questions arise of how to best organize state action, whether through administration, public companies or public-private partnerships. There will be a variety of national answers. Similarly, the issue raised throughout this discussion remains: which elements of the energy system, such as the electricity grid, if altered, will induce a significant shift in the energy system?

7 Points of Leverage for the Green Energy Systems Transformation

Given the complexity of these systems, policymakers face difficult choices about where to apply these policy tools. With limited resources, policymakers should seek points in the energy system where limited interventions can change the trajectory of development, by altering the choices of actors throughout the system. We have noted that the railroad and the telecommunications network played this role in past economic transformations. Do similar levers exist for energy, which if pulled would induce broad private investment to capture the diverse advantages of the new system?

Certainly there must be a debate about whether there is such a lever and what it might be. We define a lever to be a change or set of changes to part of the system that, if carried out, will induce or enable complementary changes in the rest of the energy system. For the case of the energy system, the power grid provides an excellent example of such a lever. The grid is central to choices about how to produce, distribute, and use energy; and changes in the grid alter options in all three dimensions of the energy system. Consequently the grid provides significant leverage for policies intent on accomplishing energy systems transformation. Energy policy should use tightly focused technological innovation, coupled to regulatory reform and standards-setting processes, to develop and deploy a power grid capable of handling significant change to technologies for production and use. For example, the introduction of a "smart" grid—the integration of digital intelligence and power transmission—can support not only more efficient transmission, but also more and different forms of renewable energy and improved energy efficiency. Standardization of the networks may also enable the grid to operate as a platform for further private sector innovation. That innovation, in turn, can drive both the technological advances required for the adoption of new energy sources, and the investment and employment required for green growth.

8 Climate policy in comparative perspective: a diversity of responses

We have advocated for a transformation of the debate about "green growth" from a justification for environmental policy into a search for the absolute advantages of a lower-emissions energy system. Doing so would frame the green growth problem in terms similar to earlier eras of transformative economic change. But, like those earlier eras, the initial expense of the transformation and the interests of those who profit from current arrangements have often delayed action. "Green energy" sources are, at least in the short-to-medium term, more expensive than conventional ones. Their "green electrons" have no obvious and automatic advantages over "brown" ones. The higher costs of "green energy" pose a burden for those who use energy, potentially lowering productivity and slowing growth. Unsurprisingly, then, most existing energy suppliers of energy and energy equipment have been as content to continue providing low cost, dependable, reliable fossil-fuel energy as their customers have been to consume it.

Consequently the push for a low carbon energy system has required a policy strategy capable of addressing an array of problems created by today's high-carbon system—many of which have little to do with emissions *per se*. The structure of the current system implies one set of winners and losers, groups that benefit from the configuration of today's energy system and others that suffer various forms of harm. The transition to a new system will create another, different, set. But there, the losers from the transition to a new system are obvious and powerful, while the winners are often unknown, weak, or both. This bias in favor of inertia lies at the root of prominent examples of inaction. In the American case, America's overwhelming dependence on domestic coal for electricity and significant domestic coal and natural gas deposits have created a foundation for resistance to a de-carbonized energy system. Similarly, in China, the inescapable need for energy to fuel economic expansion and rising living standards—the basis of both political stability and prosperity—has made the government reluctant to part with fossil fuels in any meaningful sense. Indeed, given such a thorny political economy problem, a cynic might ask why we observe any progress at all.

Elsewhere, however, "green growth" strategies are much in evidence. Denmark has committed to a fossil fuel free economy by 2040.[xxix] The South Korean government has embarked on the development of a broadly rooted growth strategy intended to reorient the Korean economy around green technology, public transport innovation, and efficiency-improving uses of information and communications technology. Despite the broader American inertia, California and Colorado have both embarked on economic growth strategies that emphasize the link between action on climate change mitigation and new economic opportunities.

This variation in both openness to and action on green growth as an economic strategy cannot be viewed only as an outcome of enthusiasm for environmental protection. Rather, it reflects important differences in national prerogatives for domestic energy systems. In cases where "green growth" has received significant attention, that attention is in every case motivated by significant non-environmental domestic interests—whether economic development, energy security, or competitiveness. Because those interests can provide immediate counterweights to resistance from those who benefit from today's system, they help overcome the policy inertia generated by the pre-existing structure of domestic energy production, distribution, and use.

Two dimensions appear particularly critical in shaping national positions on energy systems transformation. *First*, a country's choices on energy policy in particular derive from a set of idiosyncratic national goals—whether for energy security and independence, reliability, affordability, emissions reduction, or other goals. *Second*, those goals are viewed through the lens of a country's domestic resources, natural or otherwise. For example, as Kelsey et al (2011) make clear, the sharp contrast between China and Denmark reflects sharply different priorities.

> "**Denmark's** core problems and objectives have to do with: (1) ensuring predictable availability of energy at an acceptable long-term cost, ideally by achieving energy independence; (2) driving economic growth; and (3) lowering emissions. Choosing to make green industry a core of Denmark's economy – and choosing to structure its economy and infrastructure to take full advantage of this industry – creates a unified solution to all of Denmark's problems.
>
> **China**, by contrast, needs to do the following: (1) achieve massive, near-future increases in energy availability; (2) continue growing economically at a rapid rate; and (3) very much secondarily, deal with a growing particulate emissions problem. Moreover, it is well-endowed with coal, a cheap-but-dirty energy source. Given the current state of technology, these objectives mandate both green technology *and* brown growth. Denmark's solution would not solve China's problems."[xxx]

We observe a diverse set of "green growth" strategies, and a variety of instruments employed to accomplish the distinct goals. Amidst the diversity, we propose, that there is a common political foundation. That foundation requires a deal between industry and those who would advocate for significant transformation of the energy system. Sometimes those advocates will be environmental or energy consumer groups, as in California or Colorado. In others, as in the case of Korea, the advocates will include or be led by government strategists concerned with security—either energy security in a narrow sense, or national security more broadly—or with finding the basis of a new trajectory of economic growth. No matter where the initial impetus comes from, however, the energy system transformation cannot be sustained by environmental consciousness alone. Rather, it requires a broader deal that brings economic interests inside the coalition in favor of a low-carbon energy systems transformation.

The origins of those deals have, in the past, varied significantly. In some cases, as in Denmark and California, the deals grew from the synthesis of historic concerns about energy security and modern priorities for economic development and environmental protection. For the Danes, the initial problem was one of energy security, when following the oil crisis of the 70s the country's political elite recognized their vulnerability to dependence on imported energy. Policies at that time gave rise to a wind industry that has been a global leader and generates nearly 10% of Danish exports. Those policies also set a framework in which the major energy producers found advantages in moving both to renewable energy sources and more efficient energy generation technologies.[xxxi] In contrast, for California the initial problem was urban smog, particularly in the Los Angeles basin, that contributed to a strong environmental movement in the state. Resistance to nuclear power when Jerry Brown was first governor gave rise to the energy efficiency programs.[xxxii]

In contrast, political realignment enabled change in Colorado and policy realignment underpins South Korean strategies. In Colorado, an initial grass-roots push for clean energy quickly garnered support from major energy companies who stood to benefit from the shift from high-emissions coal electricity generation to lower-emissions gas and renewable energy-based generation. In Korea, the need to respond to both increased competitive pressure from developing countries and a stagnant global economy promoted a drive toward a broad reorientation of the economy in the direction of "green" goods. That reorientation was secured by positioning policy measures as a solution to energy security, unsustainable congestion and transport-related pollution, and the possibilities for capturing global markets in green goods. In both the Californian and Korean cases, then, the initial push for environmental policy was secured through a set of bargains that brought industry inside the coalition and created near-term and acute incentives for policies that otherwise generated only long-term, diffuse benefits.

Thus the real policy challenge at the heart of green growth lies in securing effective, stable alliances for industrial redevelopment. Those alliances must support a broad transformation of the energy system. Stabilizing that transformation will require compensating those who will lose from the transformation to a low-carbon, high-efficiency energy system. That compensation, in turn, must come from the economic opportunity and value created by the transformation itself. In short, the same challenges that confront economic restructuring in other guises—whether during industrialization, or in response to changing international competition, or technological change—will challenge the transformation of today's energy system.

9 Governments, Markets and Green Growth: Concluding Remarks

There are compelling and varied arguments for moving to low-carbon, high-efficiency energy systems that include climate change and energy security. The notion of "Green growth" expresses the hope, or ambition, that such a transformation can be compatible with or could even drive sustained economic growth. We argue here that the concept of an energy systems transformation must underpin discussions of and policy for climate and green growth. By *system*, we refer here to an array of separate elements complementary to one another and tightly inter-linked. In economic terms, the widespread adoption of some technologies requires investment in related, complementary, technologies and policy innovations to facilitate or permit their diffusion. It is this complementary series of technological, economic, and regulatory changes that we refer to as an *energy systems transformation*.

There are three significant implications of our argument.

* First, with limited resources, policymakers should seek points in the energy system where limited interventions can change the trajectory of development, by altering the choices of actors throughout the system. We defined such a lever to be "a change or set of changes to part of the system that, if carried out, will induce or enable complementary changes in the rest of the system."
* Second, enduring economic and political success at a green energy-led systems transformation can only come from the possibilities it would create for the broader economy. Emissions reduction is principally motivated by the need to avoid the damaging consequences of the existing energy system. But achieving emissions reduction presently provides few immediate benefits. "Green" electrons differ from brown electrons largely by being more expensive and requiring the expensive replacement of a significant infrastructure. Green jobs will often simply replace brown jobs. The acute costs and diffuse benefits of emissions reduction pose serious challenges to sustained progress. Consequently, policy discussion must also focus on the advantages of a low-emissions energy system. Those advantages, if they exist, will come from enabling the broader economy to discover and express the presently unknown—and often unknowable—opportunities that such a new system may create.
* Third, achieving this transformation will require a complex set of offsetting deals that often compensate those discomfited or disadvantaged while allowing market incentives to induce the enormous private investments that will be required. Governments will need to play a role: setting technology standards and market rules, balancing losers from the transition, investing in technology development and often in the deployment of critical infrastructure.

In sum, moving Green Growth from religion to reality, and thereby exploiting the redeployment of the energy system as the basis of sustainable prosperity, will require a technological and economic transformation akin to those of the emergence of steam, or rail, or—more recently – information technology. That transformation will not come through a focus on one technology or another. Rather, it will require attention to the restructuring of the energy system as a whole, and the role that policy must play in structuring and facilitating that systems transformation.

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[i] Certainly, climate change mitigation will require significant reductions in carbon emissions over the next century. The enormous carbon footprint of fossil fuels suggests that this goal will require the transformation of today's energy system. Dependence on imported energy poses for many countries significant economic and political security risks, quite apart from the impact on their balance of payments. Conflict over energy resources will, very likely, become more intense as the energy requirements of the emerging economies particularly the new titans – China, India, Brazil – expand. Apart from conflicts over access to resources as demand pressures mount fossil fuel prices will rise and often spike. A broadly cast solution will be needed to contain emissions, limit import costs and political vulnerability and help stabilizes energy cost. Just adding energy efficient lighting or solar panels to the existing system will not solve any of these problems. The changes required will be significant.

[ii] For a full review of the debates on green growth and the evidence for the positions in that debate, see: Mark Huberty et al, *Shaping the Green Growth Economy: a review of the public debate and prospects for success*, report prepared for the Mandag Morgen Green Growth Leaders Forum, April 2011. Available at greengrowthleaders.org/wp-content/uploads/2011/04/Shaping-the-Green-Growth-Economy_report.pdf. Last accessed 9 May 2011.

[iii] Roger Noll writes " As a result, many prospective technologies that might contribute to reducing the cost of curtailing GHG emissions are complements of either other potential green technologies or other investments that must be made to accommodate their widespread adoption. " See "Encouraging green gnergy: a comment", *Energy Policy*, forthcoming.

[iv] See Thomas Hughes' excellent treatment of the interaction of technology, social structures, and politics during electrification, in *Networks of Power: electrification in Western society, 1880-1930* (Baltimore: The Johns Hopkins University Press, 1983) and "The Electrification of America: the system builders", *Technology and Policy* 1979, pp124-161.

[v] Indeed, European Union Energy Commissioner Günther Oettinger has called for € 1 trillion in new energy infrastructure investment in the European Union over the period 2011-2020, in order to accommodate new renewable energy capacity. See "Energy Infrastructure Priorities for 2020 and beyond – a blueprint for an integrated European energy network" (The European Commission, November 2010).

[vi] Most studies of the manageability of high-renewable-energy systems suggest 20% as the limit for renewable energy penetration in the current system. See, for instance, "Accommodating High Levels of Variable Generation" (Integration of Variable Generation Task Force, North American Electricity Reliability Corporation, 2009). Denmark already obtains 20% of its electricity from renewable energy, mostly wind. At high-wind periods, the flood of wind energy into the power grid can destabilize the grid and drive electricity prices below zero. As a consequence, the Nordpool energy markets, of which Denmark is a part, have imposed a -€ 200/MWh tariff on Danish wind farm operators who do not shut down their turbines at periods of high energy demand.

[vii] See, for instance, Van Jones, *The Green Collar Economy: how one solution can fix our two biggest problems* (San Francisco: HarperOne, 2008); The European Commission, "An Energy Policy for Europe", Communication to the European Parliament and European Council no. SEC(2007) 12, 2007; and United States President Barack Obama, "State of the Union Address", January 27 2011.
[viii] See the summary of *Measuring the Internet Economy* in John Leatherman, "Internet-based Commerce: Implications for Rural Communities" *Review of Economic Development Literature and Practice* 2000:5. The United States Census Bureau puts the total value of e-Commerce related shipments in 2004 at $996 billion. See "E-stats", 27 May 2005, at http://www.census.gov/econ/estats/2005/2005reportfinal.pdf. Last accessed 9 May 2011.
[ix] Tyler Cowen would argue that this last series of innovations marks the erosion of the long tail of investments made in the 1960s and beyond. Whether this holds true or not remains to be seen; though Kondradieff-wave style arguments would suggest this to be true. See *The Great Stagnation: How America ate all the low-hanging fruit of modern history, got sick, and will (eventually) get better* (New York: Dutton, 2011).
[x] Those productivity improvements have been famously hard to track. For attempts at quantification, see Bart Van Ark, Robert Inklaar, and Robert McGuckin (2002) ""Changing Gear: Productivity, ICT, and Services: Europe and the United States" Research Memorandum GD-60, University of Grönigen Growth and Development Center; and Sinan Aral, Erik Brynjolfsson, and Marshall Van Alstyne "Information, Technology and Information Worker Productivity: Task Level Evidence". Econometricians have been skeptical of these claims. For an earlier attempt at establishing ICT-based improvements to productivity, see Alan Krueger (1993) "How Computers Have Changed the Wage Structure: Evidence from the microdata, 1984-1989" *The Quarterly Journal of Economics* 108(1) February 1993, pp33-60. John DiNardo and Jorn-Steffen Pischke (1996) responded to this attempt by using the same methodology to show similar productivity gains from pencils, suggesting that the identification strategy contained severe flaws. See "The Returns to Computer Use Revisited: Have Pencils Changed the Wage Structure Too?" NBER Working Papers Series no. 5606. National Bureau for Economic Research.
[xi] For a complete discussion of the process of the revolution and its implications for firm strategies, see John Zysman and Abe Newman, eds *How Revolutionary was the Digital Revolution* (Stanford: Stanford University Press, 2006).
[xii] In some cases, advocates make this analogy quite explicitly. See, for instance, the internet-energy analogy made by Randy Katz and co-authors in Katz, et al (2011) "An Information-Centric Energy Infrastructure: the Berkeley View" *Journal of Sustainable Computing* 1(1) 1-17.
[xiii] Varun Rai, David Victor, and Mark Thurber make this point for carbon capture and sequestration in particular. The large financial and technological risks that CCS presents, coupled with the huge investment cost and regulatory uncertainty, promise to forestall innovation and investment. See Rai, Victor, and Thurber, "Carbon capture and storage at scale: Lessons from the growth of analogous energy technologies" *Energy Policy* 38(8), pp 4089-4098.

[xiv] For the United States, see (). For the European Union, see The European Commission (200), *ibid*. For the Danish emphasis on job creation from renewable energy, see The Danish Government (2011) "Danish Energy Strategy 2050" (Denmark: Danish Climate and Energy Ministry). For related arguments from prominent figures in the public debate , see Van Jones, *ibid.*; and the European Green Party (2009) "A green new deal for Europe: manifesto for the European election campaign, 2009".

[xv] Chinese competition in renewable energy industries featured heavily in this debate. In 2010, the United States referred China to the World Trade Organization on the basis of allegations that its subsidies to its domestic wind turbine industry constituted unlawful state aid. China's rapid expansion of capacity in renewable energy also led it to capture 90% of the California solar cell market. For the solar market, see Woody (2010) "China snaps up California Solar Market", *The New York Times Green Blog*, 14 January, at http://green.blogs.nytimes.com/2010/01/14/china-snaps-up-california-solar-market/#more-38129. For China's rapidly emerging wind industry, and Western responses, see Keith Bradsher (2010), "To conquer wind power, China writes the rules", *The New York Times*, 15 December 2010, page A1; and Mark Scott (2010), "GE, Vestas fall behind in China's 'Tough' wind market", *The New York Times*, 14 May.

[xvi] The scale of the energy sector points to the limits of job creation in that sector alone. For instance, Denmark obtains about 10% of its overall exports from its wind energy sector. But that sector employs only 24,000 people, or about 1% of the Danish workforce. In most Western economies, the total value of energy consumption runs about 2-4% of GDP; not insignificant, but also not very large compared with the economy as a whole. As such, betting on massive job creation through renewable energy rings hollow.

[xvii] Daniel M. Kammen and Detlev Engel (2009) "Green Jobs and the Clean Energy Economy" Thought Leadership Papers Series No. 4, Copenhagen Climate Council. At http://www.copenhagenclimatecouncil.com/dumpfile.php?file=ZmlsZWJveC8xODk=&filename=VExTMDQgX0dyZWVuSm9icy5wZGY=. Last referenced 1 March 2011.

[xviii] This argument has re-appeared in the European Green Party's Green New Deal, which explicitly calls for a substitution of productivity for employment in pursuit of energy efficiency improvements and renewable energy installations, among other changes to the economy. While such substitutions may make sense in the guise of lots of labor rendered idle by an employment shock, it doesn't justify high wages characteristic of the living standards present in the advanced industrial economies. See Philip Schepelmann, Martin Stock, Thorsen Kosta, Ralf Schüle, and Oscar Ruetter (2009) "A Green New Deal for Europe" Green New Deal Papers Series vol. 1, Green European Foundation.

[xix] Carlotta Perez treats these as successive Kondratieff waves. We need not engage in the debate over the relevance of the Kondratieff concept to acknowledge that its core contention—that some technological innovations provide the foundation for a huge spectrum of subsequent growth—holds in each of these cases. See Perez (1985) "Microelectronics, Long Waves, and World

Structural Change: New Perspectives for Developing Countries" *World Development* 13(3), pp 441-463.

[xx] There may be some exceptions to this. Renewable energy sources such as solar and wind do permit decentralized energy production, reducing energy users' dependence on the grid. Whether this translates into radically new forms of production or the organization of production is as of yet unclear.

[xxi] The problem runs deeper than that. Growth may be the only thing that can sustain the energy systems transformation. No one believes that the policy goals of emissions reduction and energy security will be satisfied in the first generation of new energy technologies. Rather, it will require waves of innovation in energy production, distribution, and use. The scale and diversity of investment these goals will require can only come from a private sector that sees economic opportunity in ongoing energy innovation. Politically, commitment to energy systems transformation will only endure if it creates economic opportunities and not merely costs. Public investment must therefore set the foundation that enables this investment, by building a platform for growth along a low-carbon, high-efficiency trajectory. Only green growth along this trajectory can accomplish the energy systems transformation.

[xxii] The source of this story and similar stories are unclear and may be apocryphal. Nevertheless, in the early years few computers were bought or used, and it was by no means obvious that something that would later be called the digital revolution had just begun.

[xxiii] Bill Davidow, recounts this story from his time as head of marketing at Intel. See William Davidow (1986) *Marketing High Technology: an insider's view* (New York: The Free Press). There are other versions about how the Microprocessor spread. Some contend it spread amongst hobbyists first rather than existing businesses. The two stories are, of course, compatible.

[xxiv] Advocates of nuclear energy or carbon sequestration technologies might object that either or both together provide real alternatives to intermittent renewable energy sources, and don't require the kinds of systemic changes we outline. In the case of nuclear energy, this is in fact true. But nuclear energy faces a range of other environmental, economic, and political difficulties that have made it unviable at large scale in most industrial economies. In the case of carbon sequestration, the technology is largely unproven and significantly decreases the delivered power of any power plant (due to the substantial energy required to sequester the carbon in the first place). Thus while either or both technologies may contribute on the margins to energy decarbonization, neither appear politically, economically, or environmentally viable as of this writing.

[xxv] These three elements of the energy system are configured differently in each country by regulation and ownership structure, creating distinct national dynamics of demand and supply. Hence there will not be one universal trajectory to a low carbon future and cannot be a single best regulatory strategy.

[xxvi] See here William Nordhaus (2010), "Designing a Friendly Space for Technological Change to Slow Global Warming", at http://nordhaus.econ.yale.edu/documents/sm_052610.pdf. Referenced 1 March 2011. This is the latest and most comprehensive review of what Nordhaus styles "carbon price fundamentalism."

[xxvii] See Michael Katz and Carl Shapiro. "Network externalities, competition, and compatibility". *The American Economic Review*, pages 424–440, 1985; "Technology adoption in the presence of network externalities". *The Journal of Political Economy*, 94(4):822, 1986; and " Systems competition and network effects." *The Journal of Economic Perspectives*, 8(2):93–115, 1994.

[xxviii] For a parallel discussion of this problem, see Roger Noll (2011) "Encouraging green energy R&D: a comment" *Energy Policy*, forthcoming.
[xxix] This and subsequent country cases are based on Kelsey et al (2011),
[xxx] Ibid.
[xxxi] Information based on interviews and correspondence with executives and staff at DONG Energy and Vattenfall, Inc. Denmark, February-April 2011.
[xxxii] California's energy efficiency programs are generally credited to have contributed about 25% of the state's reduced energy input to a unit of GDP. The rest of the gains are attributed to other factors including shifts in industry composition and away from heavy manufacturing, mild climate, and other particular demographic statistics. For a more complete analysis of these policies see Anant Sudarshan and James Sweeney. "Deconstructing the 'Rosenfeld Curve'". Precourt Energy Efficiency Center Working Paper, 2-17, 2008.