The Center for Information Technology Research in the Interest of Society

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The Berkeley Roundtable on the International Economy

Working Paper

Energy systems and climate policy

Applying lessons from the adoption of coal to its elimination

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March 16, 2010

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1 Introduction

Climate change is now recognized as an urgent problem. Avoiding climate change will require an energy solution. In modern industrial societies, between 70-90% of electricity production and nearly all transportation requires the burning of fossil fuels, whose carbon dioxide byproducts create the greenhouse effects at the heart of climate change.[1] Thus any solution to the climate problem must begin with the energy system that has created it. This creates serious problems for both developed and developing economies. The same energy system that has put the global climate in imminent danger also provides for unprecedented levels of prosperity and well-being, which the developed world won't voluntarily give up and which the developing economies eagerly seek.

Therefore, solving the climate problem requires navigating the transition from a high-emissions energy system to a low-emissions one while preserving and increasing global prosperity. Inducing, managing, and optimizing this energy systems transformation creates enormous complexity. Unlike earlier environmental challenges, climate change cannot be solved through marginal changes to human behavior or patterns of economic activity. While lessons from past environmental policy successes can provide some guidance, the systemic nature of the climate problem requires us to look further into the nature and causes of systems transformations. Better understanding of how these transformations begin and evolve will contribute to better climate policy.

This paper argues that the climate policy frameworks that dominate current policy discussion fail to do this. These two frameworks–emissions pricing on the one hand, energy source replacement on the other–make incomplete or unsupportable assumptions about how energy systems transformations occur. Their policy prescriptions are thus incomplete. I propose instead that

[1]The major exception here is France, where zero-emissions nuclear power supplies nearly 70% of electricity demand.

the energy problem is best understood as a technological and social system that must be dealt with as a whole if we are to have any success in meeting the climate change challenge. This has serious implications for the policies currently in place to combat climate change, and for the structure of policies we pursue in the future.

My argument is consistent with the empirical evidence on the patterns of prior energy systems transformations, as shown in my discussion of two actual energy systems transformations. England in the 17th century faced a transition from wood to coal consequence of deforestation and skyrocketing firewood prices. Its stop-and-go transition over two centuries demonstrates that rapid progress in finding a new energy source in the face of rising energy prices can be frustrated by slow progress on how energy is distributed or used in the economy. Germany has since 1990 embarked on a massive switch to renewable energy, but until recently has pursued only new energy sources, not new modes of distribution or use. Technical evidence suggests that this policy is not sustainable in the face of the properties of renewable energy, a problem the German government has only recently recognized. Together, these cases suggest the incompleteness of policy that emphasizes only emissions pricing or energy source replacement. I conclude with the lessons of these two energy systems transformations for technologists as they pursue the innovations that will create the components of next energy system, and advise governments pursuing policy to encourage it.

2 Contemporary views on national energy technology strategy

As governments seek solutions to the climate problem that preserve economic prosperity, two perspectives dominate energy policymaking at the intersection of industrial competitiveness and emissions reduction. Both the externalities school, from economics, and the innovation systems school, from political economy, have long and successful histories in addressing problems that resemble the current climate challenge. Both have had significant influence on the advanced industrialized world as it attempts to confront climate change while preserving economic prosperity. Their attractiveness lies in their past successes in solving problems that look superficially similar to the energy systems challenge. But for reasons I will outline in this section, the lessons drawn from these earlier successes do not apply in full to the challenge of an energy systems transition. These shortcomings should be addressed if policy is to successfully deliver both ongoing industrial competitiveness and prosperity and emissions reduction.

The externalities school from economics views greenhouse gas emissions as a market failure.[2] Because producers and consumers are not exposed to the full cost of the damage done by their emissions, they emit with abandon. Solving this problem becomes a matter of correcting the market failure without distorting the rest of the economy. The externalities school recommends that countries adopt policy to assign a price to emissions commensurate with the damage they do. Higher prices will motivate firms and consumers to take steps to reduce their emissions, largely without direct intervention by governments.

This framework is notable for its simplicity. It says little about the complex details of technological innovation, business choices, consumer behavior, or governmental action. Each of these systems becomes merely one more cog in a machine that turns around the relative price of emitting versus non-emitting forms of economic activity. Increase the price of emitting, and, under the assumptions of this model, consumers and producers will adapt around it. Firms will invest in research on new technologies; consumers will change behaviors to reduce their emissions bill, and demand low-emissions

[2] The classic works here are Baumol (1972), updating Pigou's work on externalities and taxation; and Weitzman (1974), who extends the framework to include criteria for using taxes versus costly permits in the face of uncertainty on costs of compliance or inaction. Weitzman is in many ways the father of the cap-and-trade alternative to a carbon tax.

goods because they now cost less. These actions are largely uncoordinated; if coordination does occur, it is because firms or individuals found it cheaper to act in unison than as autonomous individuals, a choice that cannot be foreseen ahead of time.

The externalities model has proved successful in some environmental cases. The United States Acid Rain Reduction program used a system of tradable permits to reduce acid-rain-causing pollution from coal-fired power plants at much less than the initially estimated cost.[3] Many European countries have instituted significant gasoline taxes to reduce dependency on foreign oil. Emissions pricing dominates the present energy policy debate: it formed the core of the Kyoto Protocol on global warming, is actively in use in the European Emissions Trading Scheme, and would be the centerpiece of any United States action on climate change.

However, the application of the externalities framework to these problems is flawed for several reasons. It was originally developed with respect to marginal systems changes that bear little resemblance to the challenge of climate change.[4] Waste water treatment, catalytic converters for automobiles, or even sulfur dioxide scrubbers did not change the fundamental systems of industrial or energy production that created the need for them in the first place. The technologies required to reduce the ill effects of these pollutants were add-ons, albeit sometimes costly ones, to a complex industrial apparatus. They were applied to limited numbers of industrial installations[5], had few downstream impacts, and could operate successfully without large-scale integration across different plants, sectors, or geographic regions. In the case

[3]For a thorough assessment of the program's costs, benefits, and environmental consequences, see EPA (2005).

[4]This insight is credited to Prof. Michael Hanneman's presentation at the June 2008 Conference on Innovation, Climate, and Energy, in Copenhagen, Denmark.

[5]In particular, the United States Acid Rain Reduction Program began with only a few hundred power plants. Even today, nearly two decades after it was passed into law, it covers only 3500 or so industrial installations, mostly power plants in the northeastern United States.

of acid rain, all policy had to achieve was a change to plant owners' investment decisions: either install flue scrubbers to remove the harmful pollutants, or invest in new plants, whichever was cheaper.

In contrast, climate change suggests the need for an extensive reordering of the fossil energy system that caused the problem in the first place.[6] Carbon dioxide, the chief greenhouse gas, is the dominant and unavoidable byproduct of fossil fuel combustion. Short of a full program of carbon sequestration, which as of this writing appears technically complicated, extremely costly in both energy and financial terms, and politically fraught with questions about the costs and stability of long-term carbon storage, carbon dioxide cannot be simply "scrubbed out" of power plant or tailpipe effluent in the way that sulfur and nitrous dioxides were for acid rain reduction. If modern economies achieve the estimated 50-80% reduction in greenhouse gas emissions necessary over the course of the 21st century, it will occur through replacement, not marginal modification, of the fossil fuel energy system. Unlike the acid rain program, this will affect not just electricity generation, but also transportation, manufacture of basic industrial inputs like cement and steel, and even agricultural plowing and cultivation practices.

This mismatch between the conditions present for successful emissions pricing policies in the past, and those facing climate policy today, suggest the shortcomings of the marginal pricing school. Climate policy does not aim for the marginal modification of an otherwise sustainable system. Climate change does not originate from a marginal byproduct of fossil fuel combustion, but instead from an essential part of the combustion process itself. That combustion process is not limited to a handful of sites, but is instead spread among millions of point sources. Removing the source of climate change

[6] Note that this remains largely true even in the presence of technologies that could significantly reduce the impact of fossil energy. Carbon sequestration, for instance, could extend the useful lifespan of coal-fired power plants. But other emitting sources, notably transportation, which accounts for a third of all emissions, would not be affected. In any case, carbon sequestration on a massive scale and at acceptable prices remains a distant possibility.

will alter the nature of energy production, with profound downstream consequences to energy users. Finally, it is widely believed that the ultimate solution to greenhouse gas emissions will require behavioral changes by end users, in addition to technological innovation, so that both the amount of energy used and the emissions given off in the process of producing that energy can decline. No such change was required to fight acid rain.

Among alternative frameworks, the innovation systems paradigm has gained some traction in thinking about the development and deployment of new energy technologies. Innovation systems analysis emerged from the initial work on evolutionary economics, which sought to improve the black-box treatment of innovation dominant in the neoclassical framework (Nelson and Winter, 1974), and gained traction in trying to explain the varied performance of highly industrialized economies after the economic stagnation of the 1970s.(Nelson, 1993; Lundvall, 1992)

In general, national systems of innovation comprise five major elements that determine a country's ability to sustain international competitiveness on a range of industries or technological domains (Lundvall, 1992, 13):

1. The internal organization of firms
2. The structure of interfirm relations
3. The role of the public sector in structuring the market and providing public goods like education or support for basic science
4. The institutional set up of the financial sector
5. The density and organization of private research and development

In addition to firms with the internal, private capacity to develop and deploy products based on new technologies, a fully functioning innovation system would include basic research and development funding, support for pilot programs, removal of implicit and explicit subsidies to incumbent technologies, and education and training necessary to support adoption and use.

It would stabilize a long-term investment environment for firms attempting to bring new technologies to market, particularly where those new technologies were in response to externalities addressed through public action.

The innovation system thus comprises a mix of both public and private goods. Because private industry or individual consumers often do a poor job of coordination across these many different aspects of an economic system, government action to provide coordination may be required for an innovation system to emerge that effectively deploys technology and gains market share. This analytical framework provided insights into the role played by diverse organizations like MITI in Japan, DARPA and the research university network in the United States, and the close system of interfirm relations in Germany. Each contributed to unique technological and innovation capabilities, with profound consequences for each country's ability to develop and deploy new technologies and compete successfully in international markets.

The argument presented in this paper shares affinity with the innovation systems paradigm. However, I will argue that understanding energy systems transitions requires different systems boundaries and metrics for evaluation than the original innovation systems literature emphasized. In part this is due to the focus of that literature on economic growth and industrial competitiveness as the primary systems goals. In the context of modern energy policy, this is only half the story. A fully-functioning energy innovation system could well deliver substantial gains in industrial competitiveness without making a serious contribution to a country's transition to a low-emissions economy. Analysis of the twin goals of modern energy policy–emissions reduction and economic performance–require some reinterpretation of the innovation systems literature.

Unfortunately, applications of the national systems of innovation analysis to the energy problem have not, to date, accommodated these differences. Notably, the work by Jacobsson and Bergek (2004) and Jacobsson and Lauber (2006) has suggested that energy transformations should be tracked as innovation systems at the technology level–in these instances, solar photovoltaics development in northern Europe, where they see signs of success. But this use of the innovation systems paradigm, by emphasizing one technology or application as the boundary of the system, does not consider whether that technology will enter a compatible and supportive technological and regulatory environment *at the energy systems level*. Their particular interest, the German solar industry, will be discussed in more detail in section 4.2.2. But to preview the problem in setting the system boundaries at the solar industry itself, consider the problem of intermittency. Fossil fuels can deliver power on demand because they depend only on fuel stocks. To increase electricity production, it is a simple matter to burn more coal or gas or oil. In contrast, renewables like solar depend on flows of solar energy which are subject to hourly and seasonal fluctuations that may not (and typically do not) match up with fluctuations in demand. Without changes in the downstream structure of demand, and the technologies and markets that are deployed to satisfy it, solar power faces serious challenges in becoming more than a marginal contributor in what would remain fundamentally a fossil energy system. But this could all occur alongside an effective, functioning, profitable solar power industry, supported by an active innovation system.

Indeed, as discussed in section 4.2.2, Germany's near-term success in deploying solar power and building an internationally competitive solar industry may face medium-term obstacles precisely because of a delayed focus on other parts of the energy system. Certainly, a functioning innovation system in renewable energy sources is necessary for a country to transform its energy system. But nothing about such an innovation system necessarily leads to that systems transformation. They are different policy goals, and require different policy tools. Systems analysis at the energy source level, while useful, does not generate these insights. Making use of the innovation systems paradigm insights requires adopting the right level of analysis. I now turn to this problem, and the definition of energy systems.

3 The Energy Systems Approach

This section defines an energy systems approach to policy formation and analysis.[7] In brief, I suggest that an energy system reflects an integration of the technologies and the political and economic systems that together determine patterns of production, distribution, and use of energy. These systems impose specific requirements on the entry of new forms of energy, and may limit the impact of technologies that address objectives that are orthogonal to the objectives implicit in the energy system itself. This approach suggests three things: that energy systems are self-reinforcing, which creates barriers to energy systems transition; that transformative energy technology research should emphasize integration of developments in production, distribution, and use; and that technologists in positions to influence policymakers should point out the tension between short-term economic objectives and longer-term environmental objectives, and help inform how both can be satisfied.

This tension reflects the inherent conflict in modern energy policy. As noted above, effective energy policy must serve two masters. It must deliver technological innovation and industrial competitiveness, while simultaneously managing the transition to a low-emissions economy. The challenge therefore is to create policy that conceives of the energy problem as an interconnected system, not a series of isolated technologies or a set of disconnected behaviors requiring correction. That system encompasses the technologies that produce, distribute, and consume energy; the markets in which these technologies compete; the regulation and legal frameworks that govern those markets; and the producers and consumers that make the daily choices that animate markets and put technologies to productive use. Achieving the transformation of the system implies the coordinated evolution of each of these elements.

[7]The analysis here benefits from an ongoing series of discussions at the Berkeley Roundtable on the International Economy (BRIE). For examples of similar analyses conducted at BRIE, see Zysman et al. (2008) and Huberty and Kelsey (2008).

Understanding the consequences of this systems approach for the tension between industrial policy and climate solutions will require closer examination of how it has influenced the development of energy use in practice. Before turning to that history, a closer definition of what I mean by energy systems is in order.[8]

3.1 Energy systems defined

I define an energy system as the entire set of installed, operational technologies, markets, and institutions that make a given energy source a practical choice for fueling economic activity. This spans the production, distribution, and use of energy. For electrical systems, this breakdown becomes obvious: the power plant, the power grid, and the electrical appliances or plant of the end user, plus the power markets and the metering technologies and regulatory systems that give structure to these markets. Likewise, the liquid fuels industry that powers transportation consists of the oil and gas wells, the regulatory apparatus that governs them; the pipelines and shipping infrastructure that transports the oil; the refineries that transform it into useful fuels and industrial chemicals; a second distribution system that brings the fuels to the network of final points of sale; and the combustion technologies, automotive markets, and regulatory apparatus that promotes the use of automobiles.

These combinations of technologies, policies, and markets are systems in two senses. First, removal or significant alteration of any component would

[8]Work by Unruh (2000, 2002) envisions a similar analytic framework for considering the relationship of energy systems and the climate problem. He views the energy system as a techno-industrial complex composed of technologies, firms, and public sector actors. That complex creates internal efficiencies that create barriers to transformational change. This paper includes these factors, but further views the energy problem as one of unique but complementary challenges for energy production, distribution, and use. The empirical evidence presented here suggests that this extension provides traction on the course of energy systems transformations. This paper is also less optimistic about the contributions of marginal changes to the climate solution. Nevertheless, the two analyses arrive at broadly similar conclusions.

render all or part of the system inoperable or superfluous. For instance, United States oil refineries consume approximately fifteen million barrels of oil per week. Approximately 45% of this is refined into motor vehicle gasoline, which then is sold through a network of 161,000 gas stations throughout the country.[9] Firm decisions on how to allocate refinery time, purchase trucking and transport capacity, and franchise retail stations are driven by the presence of a large private motor vehicle fleet. Alteration of the fleet could, absent its replacement by a very similar technology with a similar demand structure, render much of this capacity superfluous. Likewise, the continued existence of the fleet is predicated on the presence of the system for production and distribution of retail gasoline. Imagining transformative technologies that only affect the automobile without affecting where its fuel comes from, how it is produced, and the market conditions under which firms and individuals make a host of purchasing decisions ignores the systemic nature of the industry in question. Moreover, the presence of the system creates powerful barriers to the entry of new technologies. Plug-in electric vehicles could operate much like existing cars, but without a dense network of recharging points analgous to the network of gas stations, they would be hobbled by short range. Thus their widespread entry into the market is forestalled by the characteristics of the existing system.[10]

Second, energy systems contain logics of operation that influence future developments.[11] The existence of energy systems makes further innovation

[9] Total station count taken from *NPN MarketFacts 2008*, available in summary form at `http://www.npnweb.com/ME2/dirmod.asp?sid=A79131211D8846B1A33169AF72F78511&type=gen&mod=Core+Pages&gid=CD6098BB12AF47B7AF6FFC9DF4DAE988`.

[10] Note that this is not suggesting that such a system is necessarily a market distortion, or exists due to some form of private collusion, or governments "playing favorites." It only points out that systems of technology generate large positive network effects that influence the price structure and investment and purchasing decisions for any one part of the system as well as for the whole. Since deploying a new system all at once is nearly impossible to coordinate, this creates near-term barriers to entry for new technologies even without private collusion or public favoritism.

[11] This argument at the market level is similar to that made by Zysman (1994) at the

inside that system less costly than innovation outside it. The energy system thus tends towards incremental innovation within the system's interior logic. Incremental improvements may result from sophisticated technologies, and the firms that deploy those technologies can deliver jobs and prosperity. But they continue to exist within the same energy system, having not affected its whole, and as a result do not achieve the hoped-for reductions in total consumption or emissions. In contrast, technologies that are introduced from the outside, that do not fit well within the existing system, either find themselves marginalized, or face high barriers to entry from both the initial cost of entry–the cost of constructing a parallel energy system–and the marginal cost of operation.

Energy systems are therefore analogs to Hughes' arguments on the interrelatedness of technological systems. His discussion of the electrification of New York City provides a typical example.(Hughes, 1979) He explains that Edison's development of an appropriate filament for the electric light bulb was not, as is sometimes portrayed, a random walk across several thousand different materials. Rather, evidence from Edison's laboratory notebooks shows that had a particular goal in mind, one tightly coupled to his plan to electrify Manhattan. The properties of the filament were set by the expected market demand for electric lighting, the electrical load that this demand would place on Edison's coal-fired dynamos, and the resulting resistivity required to match his ability to supply electricity to the physical properties of the demand system at a scale set by the market. Edison's filament design did not emerge in a vacuum; rather, in Hughes' argument, it emerged to complement the particular properties of the energy system he was trying to create. Take away the structure of market demand, the characteristics of the electric grid he had envisioned, or the capabilities of his power generators, and a very different filament may have resulted. Likewise, Hughes (1962) points out that electrification in Britain, despite enjoying access to

national level.

the same technologies as the United States, and operating with the benefit of the American experience in power grid deployment, experienced serious shortcomings due to a mismatch between the technology and the financial and regulatory apparatus. Treating electrical power just like municipal water and sewer programs ignored the different demands the former system placed on the legal, regulatory, and market apparatus in which it functioned.

Moreover, the systems approach suggests that change occurs at the rate of the slowest component of the system. Hughes (1983) showed this was true for the creation of energy systems where none existed in the past. I argue that this also holds for transitions between energy systems. As the discussion of the English wood-to-coal transition will show, the adoption of coal occurred much slower than the potential rate of increase in coal supply, because the energy distribution system did not evolve at the same pace. This uneven development meant that England took two centuries to make the complete transition to coal as its primary energy source. Climate science indicates that we do not have the luxury of time in making the transition to a low-emissions economy. Deploying policy with this in mind will require that we recognize the systemic nature of the problem, and draw lessons from earlier experiences, like that of England, on how to overcome the challenges that it poses.

The nature of these systems suggest that arguments that depend either on marginal prices or on single-technology systems are incomplete. Marginal prices must in this case be very high, to overcome not only the social externality of the pollution at stake, but also the network effects present in the existing energy system. Even then, the English case shows that even very substantial energy price increases, far in excess of anything under consideration today, still took many decades to have their full effect. Furthermore, single-technology systems by definition will not bring about systems transformations. The first option appears politically untenable; the second does not fulfill the desired climate policy outcome. Thus the need for different ways of thinking about the transition to a low-emissions economy.

3.2 Implications of the systems approach for energy strategies

The systems nature of the energy problem poses at least three challenges for energy policies attempting to achieve both economic competitiveness and emissions reduction. The first problem is one of incentives. Energy policy as industrial policy generates more short-term gains for both politicians and society. It can provide near-term job creation and economic growth, and often generates employment using skill profiles from declining industrial sectors– these are the so-called "green jobs" so loved by politicians. While these short-term goals are not incompatible with the longer-term goal of energy systems transformation, they are, as noted, not the same thing. If industrial policy concerns alone capture climate and energy policy, they could forestall the pursuit of policy to induce the full set of changes required.

Second, we must confront a problem posed by the differences between the systems examined by Hughes and those today. Two stand out. First, the electrical power system, the latest to emerge in modern societies, did so when earlier systems imposed only weak constraints on the installation of new technologies. Cities, geographical regions, and industrial demand were less dense, developed, or institutionalized than today. For instance, Edison built his Pearl St. generating station in Manhattan, and the power grid to go with it, in a period of only a few years. Now the construction of a new power plant may take a decade from conception to design, permitting, and construction. Second, when Edison and his counterparts built the electrical system, an individual inventor or laboratory could capture all the necessary details of production, distribution, and use at once.[12] Because their invention did not

[12] In fact, the history of Edison's laboratories shows that they did just that. Edison's research staff built fully-operational scale models of the planned electrical system to test its properties prior to construction.

have to fit into an existing system, they could optimize to their own designs. Modern energy demand is much more complex, the range of innovations needed much more vast, and the cost of innovation and deployment much greater. Solving the coordination problem that ensues between government regulation, technological innovation, and firm and finance decision-making becomes a new problem for modern energy systems transformations.

The third problem, on the proper role of government policy in a systems transition, derives from the second. The systems approach suggests that the state cannot have both regulation and free markets in the way implied by the externalities school. Arms-length emissions pricing may not be politically sustainable at the prices required to induce transformative change. Moreover, the emissions pricing school says nothing about how the coordination problems imposed by modern systems transformations are to be solved. Nevertheless, the alternative vision of a series of interlinked innovation systems marching in lockstep towards a new energy system appears to close to a command economy. Clearly, we require some policy paradigm between non-interventionist externality pricing and top-down economic planning.

To illuminate how these challenges manifest themselves in actual energy systems transformations, I now turn to consideration of how mankind has managed these transformations in the past, and what lessons that holds for the future. Over the next several sections, I show that the problems faced by England during the first energy systems transition, centuries ago, differ little from those facing Germany as it attempts to wean itself from fossil energy today. It behooves the United States to pay attention to the common lessons of these cases as it embarks on the transformation of its own energy system

4 Energy systems transitions, then and now

Energy systems transitions are rare in recent history. The internal combustion engine, steam turbine, electrical power grid, or transformer have all existed, in various forms and at significant scale, since before 1950. To learn about energy systems transformations and their implications for climate policy, we need to look to history to see what earlier transformations can tell us about the present challenge. I use two examples, one historic, one modern, to show that the energy systems view has great power in considering how one energy system replaces another, and to demonstrate the potential pitfalls, delays, and dead-ends that may accompany this replacement. From 1600 to 1800, the English switched from burning wood to burning coal, in so doing laying the foundations of the Industrial Revolution. But this transformation proceeded in fits and starts, despite price increases for wood-based energy that dwarf anything under consideration for climate policy today. The English case will demonstrate how rapid transitions in components of the energy system can be frustrated by slow changes elsewhere, and that the energy systems transformation occurs at the rate of change of its slowest component. With these lessons in mind, the modern German case provides a picture of a country whose energy systems transformation has begun. Countries like the United States, who are only now beginning their energy systems transformations, should learn from the experience of modern counterparts like Germany and the lessons of the past.

First, however, a note. The comparison of the English transition to coal with the modern renewables transformation is obviously not perfect. Four differences immediately come to mind. First, unlike today, 17th century England had no particular goal in mind when making the switch from wood to coal. Some substitute for wood was needed; coal was readily available; and so Englishmen used as much coal as was necessary to provide for their energy needs, subject to the constraints of the supply chain. Second, the switch from wood to coal was conditioned by the intrinsic advantages and disadvantages of each. Renewables, in contrast, are attractive based largely on significant externalities–mainly perceived security risks and the dangers of long-term climate change–that don't factor into technical or market decisionmaking.

To discover a grand Elizabethan or Georgian policy plan for coal on par with that required to correct the market failures for modern renewables would go too far. Third, price incentives for the use of wood and coal were driven by endogenous supply and demand characteristics. Price incentives for the use of coal or renewables will, at least for the near future, come from policy interventions to fix perceived market failures. Finally, and perhaps most importantly, coal (with some technological innovation) was a better fuel than wood in almost every way: it had more energy per unit weight, could survive transportation better, and could drive hotter and cleaner furnaces, stoves and engines. Renewable fuels are, by and large, no better than fossil fuels, and in many cases are imperfect substitutes. For these reasons, among others, the comparison must remain only approximate.

Nevertheless, perfect correspondence between the English and German cases is not required for us to learn from patterns of transformational activity. Rather, we can still question whether pricing alone, in a situation where most technological incentives encouraged transition, accomplished one of the most significant industrial energy transformations of the modern era. In doing so, we can gain some insight as to whether a similar policy could succeed when the technological winds blow the other way, or whether policy interventions in addition to price incentives will be required.

4.1 The English coal transition and the foundations of the industrial age

England's transition from wood to coal as its primary energy source lasted from around 1600 until the 1830s, and can be best characterized as two separate transitions. The first, lasting from 1600 to 1730, replaced wood with coal inside the existing wood energy system. The second, running from the mid-18th century to the dawn of the rail age, put in place the foundations of a wholly new coal energy system and the industrial revolution that built upon it. Over these two centuries, changes to energy use (the steam engine), distribution (the construction of canal systems that opened the development of the Midlands coal fields and their associated industrial towns), and production (deep-shaft mining and the Newcomen engine) were all part of the construction of a wholly new economic order underpinned by a new energy system. Later, after 1830, the railroad cemented all these features in place in a national energy system, by reducing energy distribution costs to trivial levels; but the core components of that national system were already in place by 1830.

As we shall see, the length of this transition was caused in large part because the transition could only proceed as fast as its slowest component. The delay in matching coal production with a distribution system able to completely match supply and demand hobbled the full adoption of a coal energy system. This limitation remains a characteristic of energy systems transformations today, making the English case a clear demonstration of the complexities of transformation and the need to account for them in modern energy policy.

4.1.1 The first coal system: 1600-1730

Over the course of the 17th and early 18th centuries, England's homes and industries embraced coal for most day-to-day activity. But the content of those activities changed rather little. This period saw the adaptation of coal to the purposes formerly fulfilled by wood, and as such represents innovation inside the energy system, not its transformation. Not until the second period, considered below, would England adapt its energy system to exploit the unique properties of coal, with all the tremendous consequences that made possible.

England's economy of 1600 was a wood economy in more way than one. Wood warmed Englishmen sitting on wood stools in wooden homes plastered with lime made by heating seashells over wood fires. Wood, oak in particular, made the great fleet that held off the Spanish Armada. Wood fed the charcoal kilns that produced the favored fuel for the very nascent iron industry. Ash left from burning wood made potash for use in glass made in wood-fired ovens. Wood fires boiled the sea water that, until the discovery of rock salt, was the major source of salt (and thus food preservation) for the island. Wood built the water mills in which wheat cultivated with wooden implements and delivered in wooden wagons was turned to flour. These uses, and myriad others, made wood a central source of energy, industrial chemicals, shelter, and tools. They also made it an object of immense importance for the national security of a rising naval power, whose interests increasingly lay abroad in far-flung places like North America and India.

The wooden economy rested on a wood energy system which, though primitive compared with modern energy systems, contained the same elements. Energy production occurred in the forest, perhaps with the aid of intensive forest management techniques. Production could include a second step, conversion to charcoal, which burned hotter and with less off-gassing than firewood. Energy distribution was synonymous with transportation, whereby the firewood or charcoal were taken from the rapidly receding frontiers of the forest to the point of consumption. In mid-millennium England, transport meant either inexpensive and rapid travel down navigable waterways or costly and slow overland wagon shipping. The forms of energy use were detailed in the introduction: heating, cooking, early industrial production of basic inputs like iron, glass, lime, salt, and potash; and some more sophisticated industrial production such as blacksmithing.

The character of the system structured the sustainability of the economy. The energy system survived as long as the cost of wood at point of consumption, and thus the combination of production and distribution, remained tolerable. This logic proved challenging for population centers, which could not move with the receding treeline. Other uses, particularly light industry such as glass making, could and did travel. In either case, the high cost of overland transport meant that a wood energy system was largely regional, with boundaries determined by the cost of transport relative to the market price. For firewood, this meant a radius of perhaps 20-30km at most.(Nef, 1932, vol. 1, p102) For charcoal, which disintegrated rapidly when subjected to rough handling, perhaps 7km was the limit.(Sieferle, 2001) Whether for population centers or local industry, a large army of laborers and stock was deployed to move wood and charcoal out of the forests and to the final point of demand.(Lewis, 1951)

Rapidly growing populations or rapidly increasing industrial activity would quickly strain the ability of such a constrained energy system. Evidence suggests that this strain began to show in England at the turn of the 17th century. The Lord Mayor of London reported as early as 1542 that firewood had become dear, and that he was "daily at every wharf where wood lyeth and distribute [sic] to the poor at a reasonable price as much will go around…" (Nef, 1932, vol 1, pp196). Clark (2004b) has developed price indices that indicate the price of firewood rose 250% over the period 1500 to 1600. Sieferle suggests a 4-500% increase.[13](Sieferle, 2001, 86) Price increases would have been greater in large population centers like London, which by then lay far away from the forest frontier, than for the rural population. These increases occurred despite the introduction of intensive coppicing to increase timber yields.[14] Hammersley (1973) indicates that nearly a quarter of the Crown's 200,000 acres of forest were coppiced as of 1608.

[13]For comparison, consider that the price of retail gasoline in the United States rose 63% in real terms from 1949-2008, a compounded annual growth rate of 0.8%. Continued for a century, this rate of growth would raise prices 128%.(AER, 2008, Table 5.24). Moreover, the American economy in this period grew much faster than the English economy of the 1500s. Thus the additional cost of firewood in 16th century England would have represented a much greater burden on household incomes than the increased cost of gas did to American incomes in the postwar era.

[14]Coppicing is the practice of routinely cutting the rapid new growth that arises from the stumps of larger trees. Routine harvesting increases the rate of production of timber, but that timber is only suitable for certain uses, such as small woodwork or combustion. In England, coppicing was commonly used to provide wood suitable for charcoal.

					Coal	
Time period	Wage	Firewood	Charcoal	KC	E	W
1501-1600*	-0.25%	0.94%			-0.18%	
1601-1700	0.09%	0.68%	0.57%	0.75%	0.78%	0.41%
1701-1800	-0.26%	-0.04%	-0.07%		-0.57%	-0.47%

Table 1: Compounded annual price and wage changes, 1500-1800. Sources: Wages, Officer (2009); Firewood prices, Clark (2004b); coal prices, Beveridge (1939), deflated with the RPI index from Officer. For coal prices, **KC** refers to the King's College, Cambridge series; **E** to the Eton College series; and **W** to the Westminster Abbey series. *Coal prices for Eton College begin in 1550.

	Firewood		Coal					
Year	W	C	W, low qual.	W, high qual.	KC, low qual.	KC, high qual.	E, low qual.	E, high qual.
1600			0.64	0.40	0.67	0.40		
1625			0.84	0.51	0.80	0.49		
1675	1.58		0.90	0.55	0.81	0.50	1.27	0.78
1700	2.00		1.01	0.63	1.06	0.65		
1725	2.12		1.23	0.75			1.31	0.81
1775			1.16	0.72			1.51	0.93
1800			0.87	0.53			0.92	0.57

Table 2: Price per million btu for different fuel sources. Sources: Firewood, (W), for Westminster Abbey, from Beveridge (1939), and (C), from Clark (2004b); Coal, Beveridge for W (Westminster Abbey) and E(Eton College), and (Nef, 1932, vol. 2, p404-405) for KC (King's College, Cambridge). Conversion rates: Firewood was calculated at 134 faggots/cord and approximately 25 million btu/cord for hardwood; Coal was calculated at between 16-26 million btu per ton, depending on the type of coal and its purity. All prices in constant 1600 shillings, per the price deflator provided by Officer (2009). For Westminster, all prices are for Brewery coal except after 1780. Prices for Brewery and College coal prior to 1780 are comparable.

Allen (2009) argues that Britain's industrial success owed much to being a high-wage country relative to its counterparts in Europe. Combined with plentiful coal close to the surface (compared with scarce coal in France or plentiful but deep coal in the Ruhr region), this gave England a leg up in the move to an energy-intensive industrial economy. Is this description of industrial success based on cheap energy compatible with the assertion made here, that rising energy prices were part but not all of the story as to the growing use of coal? I believe it can, for two reasons. First, as Allen (2001) suggested, the energy budget for an English household was a stagnant 5 million BTU prior to 1800. Second, as the wage series show, wages for the average English household changed relatively little in this period. Allen (2001) estimates that the welfare index for craftsmen and laborers in 1800 was about that of 1500; the major growth in working-class wages didn't come until the 1800s, and in particular until after 1850.[15] Thus the increases in energy costs for a given energy carrier ate into a relatively stagnant wage, and thus should have prompted relatively rapid substitution. Therefore, as firewood rose in price, particularly at rates high relative to alternatives, households faced strong incentives to switch energy sources. Arguably, they did, as the discussion of home heating in both Nef (1932) and Allen (2009) suggest. But the broader systems transformation, which drew in not only residential but also industrial uses, took longer.

These price increases, reflecting the increasing difficulty of supply, occurred despite the continued existence of significant timberlands. Hammersley (1957) and Buxton (1978) have both shown that the total timberland available in England at this time could have supported another century of industrial production at going rates. Annual growth alone would have satisfied a significant amount of the demand of the iron industry. Yet, in a distinction that goes noticed by Hammersley but not Buxton, the possibility of energy

[15] Allen's broader point, that the London working class was better off than its counterparts on the Continent, remains. But we are concerned with relative prices within England, and not comparative wages across nations.

production meant little in the absence of a system of energy *distribution* that could satisfy the needs of users at acceptable prices. It mattered not at all that England possessed sufficient forest for its energy needs, when that forest lay beyond the capacity of the distribution system to connect production and use. Thus, where the size of the population centers outstripped the localized ability of the forests to provide for their energy uses, the energy systems transition began. This made the first transition period largely regional, in two senses: first, that the problems of shortage and adaptation first appeared in concentrated population centers like London; and second, in that those effects influenced the regional development of other parts of England.[16]

The large-scale transition to coal that began in the early 17th century was complicated by coal's physical properties. Coal had been known as an energy source prior to 1600. Nef (1932) notes that coal had long been used in areas of England close to exposed coal seams. It was known to have several desireable properties for more general exploitation. It contains more energy per unit weight than wood, making it a superior and more readily transportable heat source. It was also less friable than charcoal, and could thus travel longer distances on rough roads without breaking down. However, before the mid-17th century, it was viewed as inferior to wood, and seldom saw use very far away from the source. Burning coal produced noxious fumes in addition to smoke, which sickened residents of houses and tenements that often did not have dedicated chimneys.(Nef, 1932, vol.1, p158ff) Numerous reports from London suggested that residents viewed coal fires with disdain, and coal smoke as a nuisance. Unlike wood or charcoal, it could not be used for direct-fire cooking because of the ruinous effect of its fumes on food. Chemical reactions between these gases and iron or glass fouled the smelting and glassmaking processes, lowering the quality of the final product. In other words, for an immediately pre-industrial economy, coal wasn't an

[16]The regional nature of the fuel problem is confirmed by separate accounts from Leicestershire, in the 18th century, which suggest that the fuel shortage was felt later there, during its early period of industrial development.(Temple-Patterson, 1951, p99).

obvious substitute for wood. These barriers appear to have proven stronger, in the near term, than price incentives to switch from wood to coal.

The glass industry is an important case study in this regard. Making glass consumed vast quantities of wood. Wood was required to both heat the sand that was the primary input, and, as wood ash, as a source for the chemical input potash. The cost of timber transport led glassworks to locate close to timber stands, where a single glassworks would consume 60-80 cords of wood a year. The resulting strain on timber supplies angered local communities. These social pressures occurred in parallel with the rapid increase in firewood prices documented above. In contrast, separate price indices suggest that glass prices rose much less; Clark (2004a) suggests increases of less than 50% between the Middle Ages and the early 18th century. Nevertheless, these social and price pressures had not, by 1610, induced a wholesale shift in the glass industry to an alternate source of fuel.

Then, in 1612, Parliament granted Sir Robert Mansell a patent, or charter, for the monopoly to produce glass in England. Three years later, Parliament forbade him from using wood to fire his glassworks.(Nef, 1932, pp181-182) Thus began a geographic and technological shift by the glass industry, until it settled in northern England, proximate to the coal fields there. Along the way, Mansell had to adopt the covered crucible, which kept coal's noxious fumes from fouling the final product. In the case of glassmaking, then, the contrast between input price increases, relatively much smaller output price increases, and ongoing industrial reliance on wood suggest that price alone did not induce the transition to a coal-fired energy system. In this case, two direct market interventions–granting of monopoly rights and an outright ban on use of a particular fuel–drove industrial change that had not taken place even with a prior century's rapid increase in the primary energy input. Mansell changed when he did, at the pace he did, in large part because he was made to.

In contrast, for industries that did not see direct intervention, the transition occurred more slowly. Charcoal had dominated iron smelting because it could reach the necessary temperatures, which wood could not, but did not produce coal's sulfurous fumes. Initially, iron produced with coal was not amenable to conversion to steel, and thus could be used only as pig or wrought iron. This situation remained throughout the 17th century, during which time the price of firewood increased an additional 84% (Clark, 2004b), and charcoal 278% (Beveridge, 1939, pp707-709), while iron production remained nearly flat.[17](King, 2005) The technological innovation in blast furnace design required to allow the use of coal in mainstream ironmaking did not occur until the early 1700s, when Abraham Darby II began to use coke (a pre-processed form of coal that produced fewer fumes when burned).[18] Even then, this new furnace design was slow to diffuse. (Hammersley, 1973, 611) indicates that coal did not come into common use for iron smelting until after 1750, forty years after Darby's first successful coke-fired furnaces came on-line and over a century after coal had begun to be used in copper smelting.

The coal energy system that emerged in the partial transition induced by this period of wood scarcity had three important components. Coal production occurred largely at the exposed coal seams or in shallow mineshafts in the large coalfields proximate to the Tyne river in northern England.[19] From

[17]The specific reasons for the stagnation in iron production remain open for debate. Flinn (1958) provides a complete account. They include localized shortages of fuel, inadequate supplies of the right kind of iron ore for the production of high-quality steel in the absence of more sophisticated metallurgy, and unreliable river conditions that deprived the ironworks of the power that drove their bellows.

[18]The exact details of Darby's furnace are unknown. In another instance of the fuel properties affecting the energy system, his furnace works were moved to Coalbrookdale, in the Midlands, whose collieries produced lower-sulfur coal compared with the Tyne collieries. The higher purity of this coal compared with other sources may have played an important role in the success of his furnace.

[19]The anecdotal record is replete with descriptions of coal-pits that had filled with water upon being dug deeper, or had become unworkable because of high concentrations of firedamp (natural gas) in the mineshafts. This problem would go largely unsolved until the invention of the steam engine, discussed below.

there, it was distributed by boat, either down navigable inland waterways or, at much higher volumes, by sea to London via the Thames river. Little coal was distributed by overland shipping, which remained cost-prohibitive until much later. The third set of changes had two sub-elements. First, the great industrial migration to the north of England had begun, taking the glass-works, blast furnaces, and other energy-intensive operations closer to the coalfields. Second, the residential demand in London had reordered itself to both use and prefer coal. The disdain for coal apparent in the early 17th century, particularly in upper-class houses, was replaced by widespread demand for coal and the eventual relegation of firewood to ceremonial purposes.

Thus, the early phase of the energy system replaced wood with coal rapidly in areas where little technological development was required; or where Parliament forced the hand of industry. Replacement occurred more slowly in established areas of production where coal was an imperfect substitute. New industries possible only with coal, such as steel production, widespread adoption of the steam engine or railroad, and other archetypal aspects of the industrial revolution did not develop until much later. Moreover, the essentially regional nature of the economy remained rather unchanged. From an energy systems point of view, there had been a dramatic change in energy production, a moderate change in patterns of energy distribution, and little fundamental change in patterns of energy use.

4.1.2 The second coal system: 1730-1850

By 1700, the broad outlines of a new energy system were apparent: coal was mined in the Tyne valley around Newcastle, and either consumed by industry close to the source or shipped by sea to the London population center. But this system still bore only the faintest resemblance to that ultimately in place during the high Victorian industrial revolution. Lancashire, eventual home to the world's textile mills, remained isolated far from the sea lanes, and thus from reliable coal supplies. The major Midlands coal fields similarly lay dormant. The great industrial cities of Birmingham and Manchester were as of yet underdeveloped. This future system of the English Industrial Revolution was a coal-fired one, dependent on a coal energy system, and thus the evolution of the proto-system of 1700 to the full-fledged system of the 1800s needs explanation. What emerges is a story of uneven development in energy production, distribution, and use, that restricts the rate of systems transformation to the pace of its slowest step.

The most significant factor driving the systems transformation appears to have been the transportation revolution, which radically changed the cost of energy distribution and made possible the cheap delivery of coal to the future industrial heartlands of England. The emergence of a distribution system that matched the nature of coal production to the structure of energy demand bears striking resemblance to the complementarity between the expansion of renewable energy via intelligent power grids adapted to the particular characteristics of the energy source. In both cases, avoiding a dead end to the energy systems transformation required, or will require, pairing the energy source with new technological and economic systems of distribution and consumption. But where England took two centuries, the present challenge doesn't permit such a languid transition. Hence the need to pay attention to the consequences of England's slow transition, the better to understand the choices needed to avoid its repetition. What follows is a brief description of innovation across the energy system, in the context of rapidly changing patterns of governance that had particular effects on energy *distribution*.

Prior to 1700, energy production had been limited in particular by the limited practical depth of coal mines. Reports of the era indicate that many productive mines had been abandoned due to groundwater flooding. Early attempts to deal with this problem, including horse-powered winding engines, allowed only marginal improvements. The practical solution came through the most famous of the Industrial Revolution inventions, the steam engine. Newcomen's engine appeared in 1712. Despite low fuel efficiency and a scant 1-2hp, the engine proved cheaper and more effective than horse-powered pumping and its alternatives. Watt's significant improvement on this engine appeared during the period 1760-1780 and made dramatic advances in both power and fuel efficiency. The combination of economy and power provided by these engines enabled the sinking of deeper mine shafts. They ran the winding engines that removed the mined coal from the shaft, and eventually powered the air circulation systems that kept miners deep in the shaft supplied with fresh air.

These new modes of energy use required suitable supply mechanisms to connect them with the coalfields. As we saw in the earlier phase of transition, energy distribution had always formed a barrier to the wider adoption of coal. Transport by any means other than ocean shipping quickly became prohibitively expensive. Thus while coal deposits in the Midlands and Wales had been exploited locally for centuries, they remained minor players in the 18th century coal trade compared with the Newcastle coal fields and their access to the Tyne river route to the sea. This distribution system only served industrial and population centers that enjoyed ready access to navigable rivers or protected bays.

After 1730, this situation changed dramatically. Output growth in the Midlands coal fields exceeded that of the northeastern fields, and Britain as a whole, in the latter part of the 18th century. Turnbull (1987) offers significant evidence to suggest that this growth was in no small part due to the expansion of the transportation network with canals; and that those canals, having a fundamentally regional nature, then contributed to the growth of the new industrial cities of the Midlands. They did so in large part by connecting industry to the coalfields that fueled it. Further enhancement of the distribution system came through the growth of inter-city toll roads, or turnpikes, built by companies that received monopoly rights to their operation. Bogart (2005) finds that the turnpike trusts led to reductions in over-land shipping costs of up to 20%.

Of course, the canal system remained predominately regional, and thus the energy system retained strong regional characteristics. Canal journeys averaged 15-25 miles, far short of the distance from the Midlands to London. Prices for canal-shipped coal rose rapidly the farther a factory was from the canal banks; in this sense, the new distribution system retained some characteristics of the old. Meanwhile, Newcastle collieries, supported by ocean shipping, remained the primary source of coal for London. This regional character would persist until the railroad–itself first invented as a means to bring coal out of the mines–appeared in the form of Stevenson's Rocket in 1829.[20] Nevertheless, it was this regional system of energy distribution that made possible the industrial towns of the British Midlands, by linking them with nearby sources of energy production at economical rates. By the time the railroads brought about the precipitous decline in the cost of long-range shipping of coal, the fundamentals of a complete coal energy system were already fully established.

In summary, the period 1730-1800 and beyond saw the completion of the coal energy system through significant changes in the character of energy distribution, which enabled changes in the location and volume of energy production. These changes then made possible the creation of patterns of energy use that would persist until the postwar era. Canal transportation systems opened up the Midlands and Welsh coalfields to consumption in the new industrial towns of the Midlands and Lancashire. Those towns would become the fulcrum of the Industrial Revolution, and the namesake of Britain's later claim to be "workshop to the world." Clearly, neither could have persisted without the other; canal revenues were dominated by coal traffic; and coal traffic would not have existed without the parallel development of sources of demand matched to the capabilities of energy supply. The completion of the

[20]Notably, the Stockton-Darlington railway, Stevenson's crown jewel, was itself constructed largely for the purpose of coal transport from the coalfields around Darlington to the Tees port of Stockton.

coal energy system in Britain required that each of these pieces come into being in parallel.

4.1.3 Lessons from the English coal experience

Because the English Industrial Revolution occurred, by definition, at the onset of the emergence of patterns of industrial organization, it does not map neatly onto the structures of industrial organization and national political economy identified by the innovation systems literature dicussed in section 2. Nevertheless, several important lessons can be drawn from how the energy system emerged, and with what consequences.

First, in response to the taxation school of modern climate policy, price appears to have played an important but not all-encompassing role. Rapid increases in energy prices between 1500-1600 did not produce, on their own, the shift to coal. Moreover, subsequent increases after 1600 appeared to have forced adaption through the temporary stagnation of production of critical industrial inputs like iron, a kind of adaptation that the relative pricing school hopes to avoid. In contrast, direct government intervention in the glass industry produced a fairly rapid transition involving both geographic and technological adaptation.

Second, where price did play an important role, it did so over a very long time scale. While the institutions of modern industrial economies are almost certainly better tuned to expose producers and consumers to changes in relative prices than those of 17th century England, and to provide them with more choices for adaptation, the English experience nevertheless begs the question of how pliable social patterns of production, distribution, and use of energy really are in the face of price shocks.

Third, this long transition time occurred despite price increases for wood energy that far exceed anything under consideration for present climate policy. Energy price increases on the order of those estimated by Nef or Sieferle (between 200% and 500%) have no apparent political viability in the advanced economies today. With the exception of retail gasoline, energy prices have fallen on average every year since the early 1950s.[21]Indeed, most climate policy in the immediate future appears loath to impose any price increases at all. The vast majority of the emissions permits used in the European Emissions Trading Scheme are given away for free. In any case, the EU has imposed statutory limits of 5-10% on the proportion that member states could auction off if they so desired. The Waxman-Markey bill, currently pending consideration in the United States Senate, foresees a long period of permit giveaways to legacy emitters, contrary to the express desires of many for a fully-auctioned system of permits. Thus the political reality in the advanced industrial countries informs against expectations of significant emissions prices in the near future, contrary to the scientific evidence weighing in on the urgency of near-term emissions reductions. Paired with the historic evidence of the pace of technological and institutional innovation in the presence of much more significant price shocks, these political trends suggest that a purely price-based solution may be expected to deliver the necessary system of innovations, but not on the timeframe required by most estimates of the climate problem.

Finally, the scale of systemic change required to steer the English economy onto a coal trajectory was, in retrospect, vast for a late agrarian or early industrial country. Responding to the wood energy shortages required not only the identification of a new energy source, but also the remaking of the economic and physical infrastructure that structured the production, distribution, and use of that source. Near-term innovation in use forestalled the immediate shortages by replacing wood with coal in its most common, pre-existing functions. But the long-term solution to the energy problem required further innovation in technology (the Newcomen engine, canal engi-

[21]See table 3 in the appendix. Retail notably, however, these prices don't reflect energy efficiency. Thus the cost increases for a gallon of gasoline would be muted by efficiency improvements that reduced the amount of gasoline required to go a given distance. The relationship between price, consumption, and efficiency here is complex.

neering, domestic furnace and stove design), business models (the industrial organization of factories, the structure of canal and turnpike trusts), and policy (the direct regulation of Sir Robert Mansell's glassworks, the changing role of Parliament in chartering new companies, the policing of monopoly power over coal production) that matched the characteristics of the new energy source. It was only through these parallel developments that the energy systems transition actually occurred.

4.2 Contemporary energy strategies and the dynamics of transformation

The next energy systems transition is likely to look much like the its predecessors. Coal had unique properties whose full exploitation required new systems of energy production, distribution, and use. Likewise, renewable energy sources differ quite substantially from fossil fuels, and their full exploitation will require downstream changes. In England, this process of comprehensive transformation of the energy system to exploit coal took two centuries. Climate policy, if it is to prevent the worst consequences of climate change, does not enjoy the luxury of such time. Effective policy thus needs to consider how and where the transition process could stall, and attempt to proactively address these delays.

Germany provides an instance of how an energy transformation proceeds in a modern industrial economy. German renewable energy policy has been in operation for nearly two decades, and has achieved remarkable growth in both the size of the German solar photovoltaics industry and in the contribution of solar energy to Germany's energy supply. But until quite recently, this policy has not taken into account the systemic changes required to enable the complete transformation of Germany's fossil fuel energy system to a low-emissions alternative.

As I show, this has the potential to create in Germany delays similar to those that transpired in England. As in 18th century England, inattention to the energy distribution infrastructure in modern Germany could, if unaddressed, delay the ongoing expansion of renewable energy there. Fortunately, it appears that the German government has recognized this potential problem and begun to consider responses.

This recent experience in energy systems transformations should inform policy in the United States and other advanced economies as they consider how to structure energy policy. In the sections that follow, I discuss the problems of introducing solar, wind, and similar renewable energy sources into a fossil fuel energy system. I then show how German policy has managed the expansion of renewables in its energy mix over the last two decades, and show that this policy hasn't always mapped well onto the demands of an energy systems transformation. I close with a discussion of how recent German activity has begun to address this problem, and how the history of this modern energy transformation should inform policymakers in the United States and elsewhere.

4.2.1 Photovoltaic technology

The work of Thomas Hughes on electrification, and the historical case study of England's wood-to-coal transition, both show that switching energy sources creates new requirements for energy distribution and use. These requirements and the solutions to meet them constitute the energy system that, when fully functioning, makes an energy source a reasonable choice to provide power to a modern industrial economy.

Solar energy is no different: although it produces electricity–perhaps the most generic of all forms of energy–the characteristics of energy supply are fundamentally different from those of electricity resulting from coal, gas, or even hydroelectric power. This, as I will show, has profound consequences for how much solar energy can be used in the absence of changes to the nature of distribution and use; and imposes requirements on the kinds of systemic changes that must be considered in order to enable the fuller exploitation of solar energy.

Solar photovoltaic technology exploits the semiconducting properties of silicon and similar materials to transform incoming light into electrical current. The first solar cells were built at Bell Labs in the 1950s. Efficiency[22] of early cells ranged from 4.5-6%. Since then, solar cell efficiency has increased dramatically. Reported laboratory efficiencies exceed 30% for single-crystal silicon and 20% for thin-film technologies, though observed efficiencies in the field are somewhat lower.(Kazmerski, 2005) These increases in efficiency have brought about significant decreases in the cost of installed solar. Researchers at the Lawrence Berkeley Lab have documented an average annual decline of 3.5% in the price of installed photovoltaics.(Wiser et al., 2009)

Despite these significant gains, solar energy retains several physical limitations that complicate its expansion as a power source. Today's energy systems require stable baseload power supplies to meet the relatively constant demand of modern industrial society. Additional peakload power, supplied from sources than can be rapidly brought online, covers demand spikes. Markets are structured to encourage demand smoothing: purchasing the marginal unit of power on the spot market to satisfy peak-load demands is extremely expensive compared with prices available through long-term contracts.[23] In contrast, because solar (and wind) energy rely on power flows resulting from natural phenomena, power supply varies with natural variation in solar intensity or windspeed. This power intermittency implies that a solar power system may provide excess power at demand troughs, and insufficient power at demand spikes. Absent a power storage and distribution system that can buffer this intermittency, solar and wind energy must be complimented by power generation that can respond on demand to bridge gaps between

[22]Efficiency for photovoltaics is defined as the ratio of electrical power output generated to incident solar power on the cell.

[23]However, these price fluctuations are typically only observed by large commercial customers and public utilities. Marginal pricing for residential customers has not been widely deployed. Tests in California following the statewide power crisis in 2000 suggested that residential consumers would respond to price fluctuations in these markets.

power supply and power demand. In practice, this usually requires fossil fuel-powered electricity generation, often in the form of natural gas generators that can sustain rapid on/off cycles. Excess power produced by solar or wind at periods of low demand is in this case wasted.

This distinction between fossil energy, dependent on stocks, and renewables that depend on flows, can be taken a step further. Fossil fuels are stocks in one sense–they contain the aggregated chemical energy of a few millennia' worth of organic matter–but getting them to the power plant turns them into flows. Mile-long freight trains full of coal are a common sight around large power plants; the petroleum equivalent is a supply chain stretching from Alaska or Saudi Arabia to the midwestern United States. But these flows, such as they are, are amenable to productivity improvements through the more efficient application of capital and labor to the problem of mining and transporting coal or drilling and shipping oil. In contrast, the flows that create solar and wind power are purely natural phenomena; we can be come more effective in using them to their full extent, but they are much less susceptible to productivity increases because their existence is independent of human labor.

To create a low-emissions or emissions-free energy system with a significant contribution from renewable energies like solar or wind would therefore require systems of energy distribution and use that could manage asynchronous variation in supply and demand with minimal reliance on supplementary fossil-fuel generators. Such a system implies changes to the electrical power grid and to the structure of energy demand. Without such changes, the intermittency introduced by flow-dependent renewables would disrupt the economic and social system that currently relies on power sources that do not share these properties. The Integration of Variable Generation Task Force (2009), consistent with the United States Department of Energy, estimates that 20% may constitute the limit for solar and wind power as a share of total electricity production before this intermittency becomes problematic. Near-term transitions to renewables via lower-emitting natural gas and renewables/gas power mixes pose similar problems.(NERC, 2008)

These distribution issues show that the transition to an energy system with a much higher share of solar or wind power faces challenges similar to the much more primitive switch from wood to coal in England. There, the satisfaction of Elizabethan and then Georgian energy demands required not only substitution of the energy supply, but also changes to the energy distribution system, in order to match the structure of consumption to the physical, chemical, and geographical properties of the new energy source. As in the first phase of the coal transition, solar and wind in their present form, absent changes to the rest of the system, can contribute marginal but not transformational levels of energy.

4.2.2 Photovoltaic policy in Germany

The evolution of the photovoltaic industry in Germany demonstrates some of these issues in operation in a modern economy undertaking an energy systems transition. Germany has since 1990 become a model of effective renewable energy policy and emissions reduction. Gross domestic product has increased 30% in that period, while overall emissions have fallen 20%.[24] These emissions reductions have accompanied commitments from first the Schröder and then the Merkel governments to retire Germany's nuclear power facilities, which currently account for a third of electrical power production. Renewable energy of all forms now constitutes approximately 14% of the German electricity supply, up fourfold since 1990. Solar electricty supply has grown at an annually compounded rate of 57% over that period, faster than all other forms of renewables, and now supplies approximately 5.7% of German electricity.(Arbeitsgruppe Erneuerbaren Energien - Statistik, 2008, 16)

[24]In comparison, United States emissions have risen 18% over the period 1990-2006, as GDP has risen 59%. Emissions data are from Boden et al. (2009). GDP data are from Maddison (2009).

As industrial policy, promotion of renewable energy has yielded significant dividends. The German solar industry reports that the photovoltaic industry now includes up to ten thousand firms employing as many as forty-eight thousand workers. German firms have become important players in the global solar industry, exporting more than 40% of their output and controlling 20% of global market share.(BSW-Solar, 2009) Altogether, photovoltaics now generate €7 billion in income to the country annually. Building on this record of success, the renewables industry has argued that renewables are on the verge of another period of rapid expansion, and hopes to capitalize on the present economic crisis and the stimulus response to consolidate and expand its position.(Jaeger et al., 2009)

German unification complicates the assessment of this impressive economic and emissions-reduction performance. Baseline emissions as of 1990 included the extremely inefficient East German industrial base. Its inevitable retirement cut emissions dramatically, but has also produced economic stagnation and extremely high unemployment in the former East Germany. This reality makes Germany an imperfect case for establishing the compatibility of significant emissions reductions and continued economic prosperity. Regional emissions data are inconsistent between sources and thus difficult to decipher. Absent these sub-national emissions statistics, it is impossible to dis-aggregate the geographic loci of emissions increase and reduction. That said, there are well-established correlations between emissions reduction and economic stagnation in traditional industrial economies.[25] Since East Germany as of the early-to-mid 1990s would not be expected to have engaged in significant innovation that decoupled emissions from economic performance, it is reasonable to assume that these correlations hold in this case.[26] Thus

[25]Indeed, the Great Recession of 2007-2009 appears to have had a substantial emissions reduction effect, due to the decline in economic activity and the concurrent reduced demand for energy.

[26]In comparison, Poland's emissions fell 25% from its 1990 levels; the Czech Republic's fell 12.5% over 1992-2006. (Boden et al., 2009) These are of course not perfect counterfactuals for the German economy, but their similar economic histories prior to 1989 make

it's reasonable to assume that much of Germany's substantial emissions reduction came via the dismantling of an outdated industrial sector in the East, and its subsequent economic stagnation. In any case, this complicated emissions situation exists alongside a picture of a strong and established renewable energy industry with a solid footprint in the electricity markets.

The creation of a German solar industry combined both market incentives and direct government intervention. Despite the efficiency gains discussed above, solar power continues to be more expensive than both fossil fuel energy and other forms of renewable energy. Building a solar power market thus required altering market conditions to encourage investment in solar installations. As documented by Jacobsson and Lauber (2006), this took four forms in Germany. The first, in 1990, established a feed-in tariff for renewable energies that guaranteed renewable energy providers both access to the power grid and electricity sales prices reflective of their higher production costs. The second major action, the Renewable Energies Law of 2000, reformulated and expanded this program to offer both wider coverage and a graduated rate of decline in the guaranteed tariff rate, to encourage price convergence in the electricity generation market and wean renewables off subsidies over time. Both the 1990 and 2000 legislative actions were justified in two ways. First, it was argued that the feed-in tariff harmonized the terms of competition between renewables and fossil fuels by offsetting the subsidies for the use of domestic coal which had begun in the 1970s. Second, renewable energy was seen as an important industry for industrial development, in which early domestic growth could fuel long-term international competitiveness. This latter argument was explicitly on display in the latter half of the 1990s, when Siemens and other firms made clear that the siting of new photovoltaic manufacturing plants was contingent on the renewal of the renewable energy feed-in tariffs.

The third government program offered guaranteed financing to home-

them at least plausible comparisons.

owners for installation of rooftop solar, first for 1,000 and then for 100,000 rooftops; excess power generated by these systems could be sold back to the public utilities at the feed-in tariff rate. This program proved extremely popular; the initial 1,000 rooftops were over-subscribed. The resulting demand for photovoltaic systems, coupled with the feed-in tariff, guaranteed a domestic market for German firms and fueled the expansion of a network of supporting companies providing ancillary electronics, installation and maintenance, and other affiliated services.

Finally, changing politics in civil society and the *Bundestag* altered the balance of power inside the federal ministries, increasing the weight of the renewable energy lobby and counteracting the traditional influence of the Ministry of Economic Affairs and its allies in the public utilities sector. This both increased the amount of funding available for research, development, and deployment of renewable energies, and forestalled attempts by the public utilities to dilute or eliminate the feed-in tariff and the deployment of alternative energy technologies.

Both the 1990 and 2000 renewable energy laws created a market for solar and other forms of renewable energy with incentives suitable for long-term investment. By providing guaranteed prices at remunerative rates, the first law encouraged the entry of solar at scale into the German electricity market. By then setting a sunset period for those subsidies, the 2000 update to that law has put in place conditions that will minimize renewables' long-term dependence on subsidies. Furthermore, as emissions pricing through the European Emissions trading scheme becomes more onerous, the remaining price gap between emissions-free and emitting sources will presumably disappear. Together, this combination of government policy and market-making, civil society advocacy, and technological innovation created what Jacobsson and Lauber (2006) and Jacobsson and Bergek (2004) argue is an innovation system leading to the transformation of the German energy system.

This paper disagrees with their assessment. The German policies, however successful at promoting technical innovation and industrial growth in the photovoltaics industry, have not for much of their active life done anything to directly confront the physical problems of solar or wind energy discussed in section 4.2.1. Because intermittency is a fundamental property of the energy source itself, controlling for it requires downstream changes capable of buffering energy consumption. The anticipated response to this problem requires the deployment of so-called "smart grid" technology capable of matching supply and demand based on continuously updated information about both, dynamic demand management through automated control of demand sources, and inter-temporal smoothing of the electricity supply though storage of surplus electrical power.[27] Because these requirements emerge from physical characteristics of energy production not shared by fossil fuels, the present power grid deployed in most advanced and emerging countries does not provide such services. As such, public policy intent on significant expansion of renewable sources of energy requires large-scale infrastructure investment and re-engineering of the power distribution network. This is not unlike the rather dramatic changes to the coal energy distribution system in 17th century England, though now at a much greater scale and complexity. The application of the innovation systems approach to the energy problem at the level of specific technologies mistakes success in one technology for success at the energy systems transition itself, and in so doing misses the larger and less promising picture of uneven development.

The German government appears to now recognize that a photovoltaic industry alone will not satisfy its energy and emissions goals. The *Bundesministerium für Wirtschaft und Technology* (BMWi, Federal Ministry for the Industry and Technology) has sponsored six regional pilot programs to test different versions of an enhanced smart grid.(Bundesministerium für Wirtschaft und Technologie, 2009) The regional distribution is shown in figure 4.2.2. The

[27]For a general discussion of this issue, see Katz (2008) and the longer description at `http://bnrg.eecs.berkeley.edu/~randy/`.

pilot projects represent different technological and market-design solutions to power management through enhanced grids, and deploy technologies from different firms and designed with different grid philosophies in mind. They also cover the geographic range from the city of Mannheim to the region of Harz in north-central Germany.

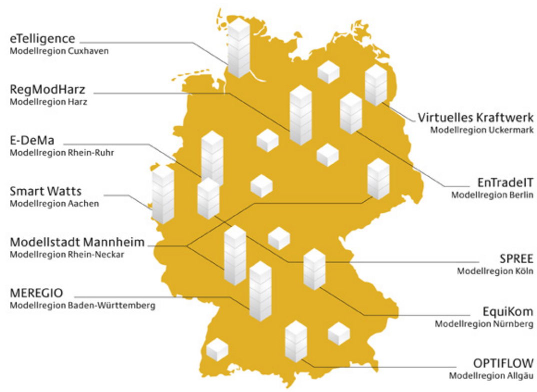

Figure 1: Geographic distribution of German smart grid pilot projects.

Nevertheless, the challenge remains the large-scale deployment of new grid technology coupled to renewable energy sources. Given that, the pace of German renewable energy policy may slow as these pilot projects are translated into wider deployments. Because solar and wind energy production have raced ahead of a complementary grid and demand infrastructure, their continued deployment may prove incompatible with the structure of downstream demand. This reality may slow the emissions reductions Germany has accomplished over the last two decades, as the period of East German economic retrenchment ends and the period renewables adoption slows in anticipation of future grid deployments. Whether policy can do anything to bridge this gap is unclear. The limitations imposed by the physical properties of the present energy system remain.

This pattern of technological development suggests that the notion of an "energy systems transformation" in the sense described by Jacobsson and

Lauber (2006) bears little resemblance to either the nature of the technological challenge or the structure of policy initiatives currently underway in Germany. They describe the innovation system at the level of the photovoltaic device. But for reasons explained here, such a system would be incapable of delivering the kinds of innovation required to deliver much higher rates of solar power penetration in the German energy system. By choosing their level of analysis at the single technology level, they have misconstrued both the nature of the energy problem and the structure of the policy response. Moreover, they have missed certain technological and political challenges that may in the near future frustrate what they have regarded as a well-functioning innovation system. Climate policy, and the design of research and development for climate change mitigation, requires an innovation system at the level of the energy system, not the narrow technological system. Within this, of course, will exist multiple subsystems for the development of innovation across different energy sources. But the successful exploitation of these sources will depend on their ability to plug into a wider system that is adapted to their particular physical and technological properties.

5 Conclusions: Energy Transitions and the Implications for Technologists

The energy systems transition required for effective climate change mitigation will require significant technological innovation. Replacing the current system, largely based on energy stocks, with a future one, based on renewable energy flows, will challenge the capacities for innovation across production, distribution, and use of energy. However, these technological innovations will arrive in systems of political economy that presently are highly adapted to a stock-based energy system. Left unchanged, the new technologies will attain much less than promised, or needed.

The evolution of the political economy of energy production, distribution, and use will be a complex process driven by myriad forces beyond what technologists have direct control over or expertise in. Nevertheless, the pace, smoothness, and effectiveness of this energy transition in moving advanced and emerging industrial economies to an emissions-sustainable infrastructure will improve greatly if technologists can take the nature of the energy system and its evolution into account. In particular, three recommendations emerge from this study of past and ongoing energy transitions. Each touch on the specific role that researchers, engineers, and scientists have to play in bringing their expertise in energy technology to bear on the climate problem.

- **Systems integration should be a requirement, not an afterthought**

  In both the English and German cases, the critical link for a fully-fledged energy system to emerge proved to be the distribution system. Whether waterways or smart wires, these links provided the integration mechanisms that could tie production and use in ways that enabled the full exploitation of the potential of the energy source. While new technology development at its earliest stages necessarily focuses on the specifics of production or distribution or use, the long-term success of these technologies is clearly predicated on the role they fulfill as elements in an integrated system. Thus, to the extent possible, the technologist should look for opportunities to begin pilot programs that expose and address the engineering challenges implicit in systems integration.

- **Standards will play a vital role in facilitating innovation across the system**

  Technologists are not strangers to the importance of open standards. The phenomenal success of the Internet and modern electronics owes a great deal to the creation of and adherence to a set of open standards for interoperabiltiy that firms could design to. Likewise, the creation of a dynamic set of innovation systems around the energy systems transition can be facilitated by sets of open standards. Establishing standards for, among other things, power delivery and intermittency, and protocols for how the grid would switch between active generation and storage discharge, canl contribute to the ability of technologists and firms to innovate with some reassurance of interoperability with other developments. Again, these issues also emerge from the German and English cases. Canals, and later railroads, had to standardize dimensions, track gauges, and other aspects of the infrastructure to enable smooth travel through the distribution system. Germany's smart grid experiments suggest a range of possibilities for the future; national integration will eventually require standardization across alternatives to ensure interoperability and market openness.

- **Nonlinear energy transitions should be expected and planned for**

  The English adoption of coal went through two phases in part because rapid developments in production and use outstripped the capabilities of the distribution system. The German case looks to experience a similar lull in development as grid technology and end-use demand catch up to the rapid deployment of renewable energy sources. This nonlinearity should be expected and, to the extent possible, proactively dealt with. This will require both consideration of what technologies need to go into the pipeline in order to be ready at different points in the transition; and what advice technologists need to provide to policymakers about the evolution of technology and its consequences for markets and market regulation.

In closing, to provide both industrial competitiveness and emissions reduction, energy policy must effect the transformation, not the marginal modification, of the fossil fuel energy system. In contrast to technology or industrial policy in pursuit only of prosperity, a narrow focus on single technologies will not produce the series of innovations, both technological and otherwise, required to achieve dramatic emissions reduction. As this examination of both past and present energy transitions has suggested, such parallel innovation across the energy system does not occur by default. Successful government policy therefore cannot be as hands-off as an abstract tax on emissions, nor as hands-on as sponsorship of particular technologies. Rather, as with transportation in the 17th century or grids in the 20th, government must both help set the market conditions in which renewable energies can succeed, and identify the major technological barriers to the emergence of a new energy system. On more theoretical grounds, I've suggested that, given the sparse recent evidence on the patterns and complexity of energy systems transitions, the past can provide useful insights into how we approach technology and market policy in preparation for the next energy systems transformation. The marked parallels between the English and German cases, despite three centuries of separation, indicate that greater exploration of similar cases in other countries and time periods will provide more information as this complex task begins.

A Median wage and energy price data for the postwar United States

Series	CAGR, 1953*-2008
Median family wage	1.3%
Electricity, kwh	-0.15%
Coal, retail	-0.30%
Gasoline, gallon retail	0.83%

Table 3: Compounded annual price and wage changes, 1953-2008. Sources: Wages, United States Census Bureau, Current Population Survey 2009, table F-6; energy prices, Energy Information Administration, Annual Energy Review database, 2009. All price series begin in 1953 except for electricity, which begins in 1960. For gasoline, 1949-1975 refer to leaded only; 1975-1990 average the leaded and unleaded price; and 1991+ refer only to unleaded.

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