Energy Systems Transformation*

CONFERENCE DRAFT

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Abstract

Successful climate policy requires the transformation of energy systems. This paper argues that those systems represent a unique technological, social, and political logic that has implications for the political economy of climate change mitigation and international economic competitiveness. In contrast to the dominant policy models for climate change, the logic of energy systems informs against depending solely on price to effect the adoption of low-emissions energy sources. Moreover, phenomena of learning-by-doing and large-scale systems optimization suggest that economies that begin their transformations earlier may capture long-term economic advantages in renewable energy technologies. Empirical evidence from earlier energy systems transformations supports both these observations. The paper closes with implications of both of these observations for technology policy.

1 Introduction

The search for solutions to global climate change has begun in earnest. The scale of the problem complicates the design of effective policy. The causal connection between greenhouse gas emissions from fossil fuels and climate change inextricably links climate solutions to the transformation of the energy system. But the central role of energy in all aspects of industrial societies means that climate policies touch almost every aspect of

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industrial production and social organization. In contrast to the systemic effects of such policy solutions, most policy proposals to date have emphasized one or another aspect of this system but not the whole. Emissions pricing, energy source replacement, renewable energy deployment, or energy efficiency all deal with components of the broader energy system, but not the system itself.

This paper will argue that these policy approaches miss the challenge at the heart of the climate-energy nexus. Effectively managing the transformation of a high-emissions, low-efficiency energy system to a low-emissions, high-efficiency alternative requires conceiving the problem as one of systems transformation. This paradigm is radically different from dominant policy approaches and poses very different challenges for technology policy, research and development, market regulation, and social policy. Success or failure in this environment depends on properly understanding both the systems nature of the problem and the implications of systems for political contestation.

Understanding this paradigm requires first elaborating on the systems logic of energy in modern industrial societies. With that understanding in hand, we can observe the implications of this logic in a series of energy systems transformations that each played critical roles in industrial transformation through history. Moreover, the idea that energy systems transformations can *enable* transformative, productive industrial change then suggests that energy-driven climate policy may not be merely about costs. Rather, as global competition for competitiveness in renewable energy technologies intensifies, states that capitalize on domestic energy systems transformation will find themselves well-positioned to compete globally in a wide range of new high-technology goods and services industries. This makes climate policy into not only an environmental concern, but a problem for international economic competitiveness as well.

2 Systems and Systems Transformation

Climate policy is predominately energy policy. Climate change results from the increased atmospheric concentration of greenhouse gasses, itself the consequence of emissions generated by the intensive use of fossil fuels in industrial economies. Most studies suggest that 50-80% reductions in absolute emissions levels will be required to avert the worst consequences of climate change. Climate change mitigation therefore becomes a problem of how to replace the energy foundations of the industrial and industrializing economies with lower-emissions substitutes, while leaving the prosperous, high-productivity superstructure in tact.

I argue that this policy challenge is best conceived as a problem of energy systems transformation. To make use of an energy source, an economy must have structures in place to produce that energy, move it to consumers, and employ it in economic production or social activity. These structures become a system on the basis of the implicit requirements of interoperability. *Technical* interoperability requires that technological evolution of any one part of the system complement the capabilities and evolution of the other parts. *Market* interoperability requires that the structure of supply match the structure of demand, such that changes to one match changes to the other. *Regulatory* interdependence requires that the market rules governing production, distribution, or use of energy reinforce the bias in favor of technical and market interoperability and deal adequately with market failures and imperfections that would frustrate either. This endogenously-determined set of technical, economic, and regulatory interactions across the domains of energy production, distribution, and use form these three tasks into systems.

2.1 Production, distribution, and use

Accomplishing the production, distribution, and use of energy in industrial economies requires complex subsystems for each task. These subsystems are themselves defined by the technologies they employ, the economic structures that embed these technologies in economic production, and the regulatory framework that structures the market in which the tasks occur. The requirements internal to each subsystem–compatibility and complementarity between the technological limitations, firm structures, and regulatory choices–match the requirement for interoperability across these subsystems. Absent this interoperability, the energy system loses its ability to supply energy in support of economic activity. This section considers each of the subsystems in turn before elaborating their implications for complementarity between subsystems.

2.1.1 Production

Energy production must respond to two very different sets of demands. Production requires the exploitation of a very small number of possible energy sources, each with its own physical and chemical advantages and disadvantages. Within these constraints, firms seeking to profitably exploit these energy sources and regulators attempting to secure the supply of energy both operate in the context of the broader economy. That economy generates energy demand, itself a function both of the processes of economic production that use energy and the systems that deliver that energy. The business and regulatory models that emerge from this twofold constraint thus reflect both the fundamental physical attributes of the energy source and the social and political demands of downstream structures of energy distribution and use.

Energy sources present a very specific set of constraints. Over the course of human history, only four categories of sources have been discovered:

1. Natural flows like sun or wind
2. Natural mechanisms to capture and store flows, such as photosynthesis
3. Chemical stocks of natural flows, like coal or oil
4. Non-chemical stocks, chiefly fissile materials

The most elemental of these, natural flows like sun or wind energy, are ubiquitous but intermittent and often unpredictable. Absent advanced technology, this forces economic activity into short-term equilibrium with the energy flux at the geographic location of production. This is problematic at both a very short timescale–consider factory shifts that turn on and off as clouds float past the sun–and at a medium timescale, such European winters where short days and bad weather might make energy unavailable for months.

These shortcomings, which technology has only recently found ways of overcoming, led to an early preference for natural intermediaries for capturing flows. Trees, plants, and other photosynthetic organisms can store energy for future use. As such, they can relieve both the short-term energy budget constraint and the volatility of supply. But they must remain in medium-term energy equilibrium with the energy flux of the planet. While technology can be applied to increasing the rate of energy supply–by cutting down more trees faster, for instance–it cannot increase the rate of replacement of that supply. Moreover, as will be discussed in section 2.1.2, the point of exhaustion of the supply is contingent on the abilities of the distribution system.

These limitations led, at the dawn of industrialization, to the search for energy sources independent of natural flows.[1] Two were found. Fossil fuel energy sources like coal, oil, or natural gas stored millions of years' worth of solar flows and as such could be treated like

[1] See Sieferle (2001), who refers to the coal fields as a "subterranean forest" that created new possibilities for the energy system.

a stock resource. Technology could be applied to increase the rate of extraction without the medium-term energy budget constraint of photosynthetic sources. While the long-term energy budget remains, in the form of dry oil wells or exhausted coal mines, that constraint has always been far off. Alternatively, nuclear fuels offered a different path to escape the short-term energy budget, one which has only become available since 1945.

Each of these potential energy supplies requires very different technologies, business models, and modes of social and political organization. They also have very different physical and chemical characteristics, which impose downstream requirements on the subsystems that distribute and consume energy. As I will show, these characteristics influence what kinds of economic activity are possible, and thus the requirements imposed on the economic and political organization of that activity.

2.1.2 Distribution

Demand and supply for energy rarely locate at the same place for very long. Many energy sources are found in places inconvenient for other kinds of human activity. Societies may choose not to locate close to centers of energy production–next to the coal-fired power plant, for instance. Even when they do, the exhaustion of the energy source often does not lead to the relocation of society. The infrastructure of modern society is path-dependent and does not easily move. Thus, when making transitions between energy systems, societies often don't sacrifice social and physical infrastructures tied to earlier systems. The combination of the geographic distribution of energy production and the path-dependency of social decisions creates the need for energy distribution, and sets requirements on the gap between production and use that it must bridge.

Industrial history shows only three unique mechanisms for bridging these gaps:

1. Moving chemical energy carriers or fissile material via carts, trucks, trains, ships, or

other vehicles

2. Moving liquid or gaseous chemical energy carriers via pipes

3. Transmitting electrons over wires

Within these three, however, the possibilities of the distribution system vary widely by the physical and chemical characteristics of the energy carrier itself. Charcoal, wood, and coal are all solid chemical energy carriers; but until the arrival of smooth roads or effective suspension systems, charcoal was too friable to ship long distances over rough roads without disintegrating. Coal and wood were not. Thus the distribution systems for charcoal and wood differed in large part due to their different physical properties.

The specificity of the distribution system to an energy source and place may make its investments non-transferable. A pipeline to supply natural gas to a gas-fired power plant in the United States is of little use in supplying the coal-fired plant next door. Likewise, neither of these may be necessary for the solar plant to come. The system-specific nature of distribution assets both binds the assets to a given system and complications the transition to a new one. The consequences of this capital specificity will be discussed further below.

Finally, whatever the energy source, the distribution system supplies a complex set of economic and social energy uses. The structure of energy demand generated by those uses imposes specific requirements on the distribution subsystem. If distribution cannot adequately match the supply of energy to the demand of energy, it may create conditions for broader changes to the energy system: either to the distribution system itself, or to the systems of production and use that it serves to link.

Thus a distribution system at equilibrium with energy production and use will match the unique geographic, physical, and chemical characteristics of energy sources to the structure of energy demand. That demand structure, via both the geographic demands it places on distribution and the dynamics of the demand itself, imposes requirements on energy distribution. But, as the next section will show, the structure of energy use is itself determined by the possibilities created by the availability of energy, and the characteristics of that energy.

2.1.3 Use

Energy consumption is characterized by two sets of features: the economic activities undertaken with energy, and the structure of energy demand those activities generate. These features emerge from and depend on the capabilities of the system of energy production and distribution. Ultimately, this means that patterns of energy use are limited by the characteristics of the energy carrier itself: Iron can be smelted with charcoal, coal, or electricity; but not with wood, which cannot reach the necessary temperatures. It seems highly unlikely that air travel could exist in the absence of petroleum-based fuels. Information and communications technology cannot operate independent of electricity. Thus systems of economic production are determined, in part, by the forms of energy available to power them.

For a given energy carrier, however, the structure of energy use is further determined by the capabilities of the distribution system. Economic activity requiring constant inputs of energy cannot coexist with an energy distribution system incapable of supplying those inputs. This does not necessarily mean that some forms of economic production are impossible; one can imagine a factory shift structure in which production occurred contingent on the intermittent flows of solar energy, a kind of just-in-time organization of production. But that merely proves the point: the structure of energy-consuming economic activity is contingent on the capabilities of the distribution system, which in turn depends on the requirements and possibilities of energy production.

Moreover, while these examples have emphasized economic production, they apply equally well to patterns of social organization and behavior. The suburb is a perfect example of an entire form of social organization dependent on a transportation system made possible by gasoline and a gas distribution system that can service the personal automobile; and a highway infrastructure closely linked to the existence of that automobile and the energy system that makes it possible. Thus social as well as economic infrastructures evolve around the possibilities created by the subsystems of energy production and distribution.

Finally, the dependence of patterns of energy use on the capabilities of production and distribution feeds back up the energy system. Changing patterns of social and economic life place new demands on the upstream systems of production and use. Thus the systems of energy production and distribution, and their technological, business, and regulatory parameters, emerge from the patterns of energy use that they serve, even as their capabilities and limitations shape those patterns. Again, the highly integrated, interoperable nature of the energy system emerges from a set of endogenously evolved inter-dependencies based on technical, economic, and political factors.

2.1.4 Complementarity and the logic of the system

This discussion of production, distribution, and use has identified their core components and discussed how those components–the technologies, social structures, and economic actors–both shape and are shaped by them. It further argued that these subsystems create up- and down-stream requirements on each other that binds them together into an energy system. Those requirements are driven by technological interoperability, market compatibility, and regulatory consistency.

These overarching requirements create a tendency inside energy systems towards equilibrium. At equilibrium, a viable energy system will meet the requirements imposed by each of the core elements discussed above. The characteristics of the energy carrier will lead to technologies and firm structures capable of extracting it; a distribution system capable of carrying it to end users; and a set of uses that conform to the characteristics of the energy source. Likewise, the distribution system will provide the means to satisfy demand for a given energy carrier, and firms will choose structures and technologies best able to supply that distribution system with energy inputs. The resulting system comprises a set of complementary elements, the absence of any of which would undermine the others.

Note, however, that this *does not* result in technological determinacy. Even if we take Gerschekron's point that different technological forms place different demands on firms and states, we still get a range of diverse economies among the late-developers. Likewise, the dawn of electrification saw competition between two different visions of an electrical system–Edison's localized direct-current version and Tesla's centralized alternating-current version.(Hughes, 1979) Interoperability and complementarity generate the requirements that synthesize production, distribution, and use into a system. But they do not exclude the possibility of a diversity of different forms of a system to deliver the same energy carrier.

This diversity of forms emerges, in part, from the fact that energy systems are embedded in the social and political environment. We can identify three categories of linkages that tie the core functions of the energy system to the social and political system that exists around it:

1. Technological

   The characteristics of the energy supply must match those of energy demand. This somewhat trivial point leads to important conclusions. Replacement of the energy source in an energy system with some new source can occur under *ceteris paribus* conditions if and only if the new source can replace the old without changing the characteristics–physical, chemical, and economic–of energy supply. Likewise, the emergence of new forms of energy demand–new forms of economic activity–may prove difficult in the absence of supply structure that can support them.

2. Institutional

   The technological demands of energy production, distribution, and use exist within the context of a market whose rules are heavily dictated by regulation. Regulation occurs at a variety of levels: control over access to natural resources; control over access to dedicated rights-of-way for distribution; control over prices and standards of performance for public utilities; and regulation of operating standards to ensure compatibility between supply and demand (i.e., voltage standards for electrical power). Each of these institutional interventions in the market–whether by state control or industry associations–creates inter-dependencies among different aspects of both the technological–as in mutual compliance with standards–and the economic structure–as in the kinds of competition that firms face. In turn, decision-making on the part of different aspects of the system converges on equilibria supported by the institutions themselves.

3. Political

   A wide range of social systems grow up around and integrate with the energy system via use. Those systems in turn develop interests in the status quo energy system that inform against significant change that would disrupt them. Those interests can and do mobilize to influence changes to the system. For instance, American suburbanites have vested interests in perpetuating this social structure; this structure depends on the availability of cheap energy to power individual transportation; and so Americans may resist changes to the technological and institutional framework that would require them to change as well. The relative weight of these groups in maintaining versus changing the system will be contingent on their abilities to organize otherwise dispersed interest groups like suburbanites.

At equilibrium, the features of these subsystems are complementary to each other, in two senses: their features reinforce the features of the other subsystems; and their design makes up for the deficiencies in the other subsystems.[2] Out of equilibrium, such as during the oil shocks of the 1970s, this is not the case: a distribution and demand system optimized to a particular mode of energy production could not adapt fast enough to dramatic changes in the production system, leading to the breakdown of the system, market and non-market forms of rationing, and, in some instances, systems changes.

The automobile transportation industry provides a good illustration of an energy system at equilibrium. 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.[3] Firm decisions on how to allocate refinery time, purchase transport capacity, and franchise retail stations are driven by the presence of a large private motor vehicle fleet. That fleet is based on an internal combustion engine optimized to use a specific range of gasoline mixtures, and which cannot easily switch out of this range. The distribution of gas stations is determined in part by the range of the fleet, which structures the geographic distribution of demand for gasoline. Alteration of the fleet could, absent its

[2] The notion of complementarity has received significant attention in the political economy literature. Crouch et al. (2005) provides a good overview of this debate. I would argue that all of his forms of complementarity pertain here.

[3] 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.

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 compatible with the fleet's engines. These technologies have evolved a set of political and economic institutions–the supermajor oil firm, the national highway system, the international oil economy, and others–that regulate its markets and support its continuation. The highway system alone represents a massive ongoing investment in public goods provision that exerts a significant, if sometimes forgotton, influence on the automobile market. American consumers and firms have evolved a set of social and economic practices based on the continued ability of these technologies and institutions to supply transportation fuel at economical rates, and to provide them and their cars access to an ever-expanding set of locales. Suburban life and intermodel transport and long-haul trucking are but three examples of optimizations within this system that depend heavily on the availability of the system as a whole. At equilibrium, the production, distribution, and use of energy, in the context of the rules and regulations of the gasoline and transportation markets, displays complementarity across its technological, institutional, and social variation.

2.2 Energy systems transformation

With this idea of energy systems in mind, it becomes possible to discuss systems transformation in more detail. An energy systems transformation replaces the energy supply from one source with another. But as should by now be clear, this in no way marks the limits of the transformation. Absent subsequent, complementary changes to systems of energy production, distribution, and use, source replacement can have only a minor effect on the energy system as a whole. Thus an energy systems transformation involves complementary changes to production, distribution, and use. This implies, in turn, changes to technologies, the firms and business models that embed them in economic production, the regulatory frameworks that structure the markets in which that production occurs, the patterns of energy use and demand, and the social and economic sources of that demand. In other words, a systems change requires changes to each element of the system.

The degree to which these changes must occur simultaneously may vary with the nature of the particular transformation under consideration. In cases where the new energy source is a proximate substitute for the old insofar as energy users are concerned–such as the substitution of natural gas for coal in electricity generation–switching sources may provoke few downstream changes. But in most cases, and certainly in the case of renewable energies under consideration for climate change mitigation, the possible sources are imperfect substitutes with very different properties, necessitating much wider changes to each element of the system before the adoption of the new energy source can proceed, and before the new system will converge on a sustainable equilibrium.

Moreover, there's no reason why we should expect that different elements in the system contain the capacity to change at the same rate. Consistent with Perez (1983), the technological, political, and market elements of the system may evolve at different rates, consequence of varying ability to manage change. This variability will prove particularly important with respect to the politics of energy systems transformation, as it suggests that the rate and nature of the transformation will depend in part on the capabilities of the political system to manage the adjustment process. Variation in these abilities within systems will create the "reverse salients" identified by Hughes (1983).

This brief discussion has concerned the *process* of transformation. Presently, it's not clear how the *outcome*, or "success" or "failure", should be judged. In some sectors, an energy systems transformation will mean a complete replacement of one energy source with another; transportation is a good example here, where oil has almost completely replaced coal. In others, though, the outcomes are less definitive. Jacobsson and Bergek (2004) suggest that transformation has occurred and continues to occur in Germany and Denmark, though renewable energy penetration in either case does not exceed 20% of electricity demand. Similarly, the source of energy for electricity production in the United States has changed from a universal reliance on coal at the start, to a diverse range of fuels at present–coal, oil, natural gas, hydropower, nuclear power, and now solar and wind. Is this a transformation in progress, or a set of complementary and parallel systems? The distinction between the process and outcomes of transformation will require additional clarification in the course of research.

2.3 Conclusions: concepts and systems at equilibrium

Thus the provision of energy in industrial society requires a system of technologies, firms, and regulators that structure the production, distribution, and use of energy. Those structures must complement each other if the system as a whole is to function. Moreover, they tend to converge on equilibria that create opportunities for innovation inside the existing system while forestalling opportunities for systems change. These conclusions generate questions about how systems change actually occurs. Given the technological, political, and social barriers to change present in systems at equilibrium, how can we explain the origins and processes of energy systems transformation? These questions, in the perspective of comparative political economy, form the core of this dissertation.

3 Energy systems transformation in practice: two vignettes

Empirical evaluation of the implications of this theory faces difficulties. Energy systems transformation at the scale implied by climate change mitigation is rare in human history. Most of the energy systems that dominate modern industrial economies have existed in more or less the same form since 1950 or so. Given these difficulties, historical evidence can provide empirical support. Three major energy systems transformations have occurred in parallel with industrial economic life: the move from wood to coal at the dawn of the industrial revolution; the switch from coal to oil at the end of the 19th century; and the move from primary energy to electricity through the first half of the 20th century. Each of these had profound implications for the demands on the energy system, and the implications of that system for the organization of social and economic life. Unsurprisingly, they also witnessed intense political contestation. While full consideration of each of these and all their national variation requires ongoing work, two vignettes can suggest the import of the energy systems paradigm.

3.1 England, coal, and the dawn of industrialization

From 1600 to 1800, the English economy shifted decisively from a wood-based energy system to a coal-based energy system. The transformation took place in two phases. Over the course of the 17th century, coal replaced wood in applications where it was a reasonably perfect substitute: home heating and cooking, lime burning, and salt boiling. Then, in the 18th century, a range of technological innovations only possible with coal emerged, most famously the blast furnace and the steam engine. The development of an industrial coal-fired economy emerged from the interaction of these technologies with a wide range of regulatory and industrial policies that brought forth the energy system that would power the industrial revolution.

For the purposes of this essay, three aspects of this transformation stand out. First, price played an important but not deterministic role in the timing and pace of the transformation. As figure 1 demonstrates, wood prices exceeded coal prices on a unit energy basis for most of this period. Nevertheless, even in applications where coal was a close substitute for wood, adoption occurred slowly. Huberty (2010) estimates that as of 1666, as much as 50% of the housing stock in the City of London had not adopted coal-fired hearths for heating and cooking. Figure 2 suggests that coal consumption in London grew slowly through the 17th century compared with the period after 1725. The innovations necessary to smelt iron with coal took nearly a century despite the iron industry's dependence on ever-more-expensive charcoal fuels.

The weak role played by prices is contrasted to the strong role played by the state in certain sectors. Glassmaking provides an important example. Glassworks were notorious consumers of wood for the glass kilns. A single works could consume 60-80 cords per year. This made the glassworks very unpopular among local communities, given their propensity to move into a well-forested region and consume firewood voraciously until local supplies were exhausted. The energy intensity of glass production, combined with low relative coal prices, should have made it a strong candidate for coal adoption. But the actual process of conversion was dictated by politics.

In 1612, the Crown granted Sir James Mansell a monopoly patent for the production of glass in England. Three years later, it forbade him from using wood to fire his kilns. This set two processes in motion. First, Mansell moved his works first to Wales, then to Newcastle, in search of a new fuel source. In the process, he invented the covered crucible, which kept sulphurous coal fumes from contaminating the molten glass. Second, he fought a series of challenges in the Star Chamber with legacy wood-fired glassworks, which he eventually won.(Hartshorne, 1897) State intervention in the glass market thus drove both the adoption of new technology and the elimination of old, in the face of relatively inelastic responses to energy prices.

Third, the completion of the transformation to a coal-based energy system required a whole range of complementary changes in addition to the adoption of the energy source itself. Overland distribution of coal was prohibitively expensive until the advent of the railroad in 1830.[4] Thus the expansion of a coal energy system required the buildout of a water-based transportation network capable of long-distance movement of coal to the industrial cities of the Midlands. Royal chartering of canal and turnpike road companies significant improved the quality of transport within England beginning in about 1700. (Temple-Patterson, 1951; Turnbull, 1987; Cox, 1986) Coal dominated the traffic on these new canals, particularly around Birmingham and Manchester. Infrastructure buildout was complemented by a range of regulatory interventions. The Crown intervened in the coal shippers' monopoly, the Vend, to police price collusion(Hausman, 1984); and set standards for the content and unit of sale of coal, to prevent price gouging.

Thus the English wood-to-coal transition, despite having occurred in a proto-industrial economy, illuminates several important factors for energy systems transformation. Prices were a weak signal for both energy source substitution and technological innovation. Direct state intervention, albeit of a form that modern industries wouldn't tolerate, worked much faster. Finally, the complementary changes energy distribution and use that had to occur before coal could fully replace wood all came with the assistance of the state.

Last, but not least, we should note that the adoption of coal did not merely forestall an energy crisis. Rather, it also enabled new forms of industrial production that wood alone could not have supported. The energy budget imposed by wood could not have supported the scope of economic activity that the English industrial revolution would come to represent. Thus energy systems transformation generated opportunities even as it imposed costs.

[4] Estimates suggest that the price of coal doubled for every 7-15km of overland travel.(Sieferle, 2001) Canal shipping was much less expensive.

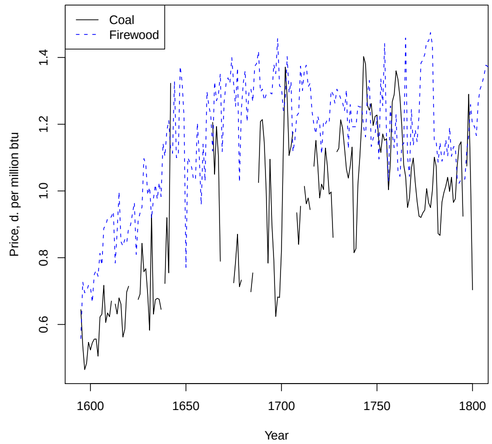

Figure 1: Energy prices in London, 1600-1800. Coal price data from Flinn (1984). Firewood price index from Clark (2004).

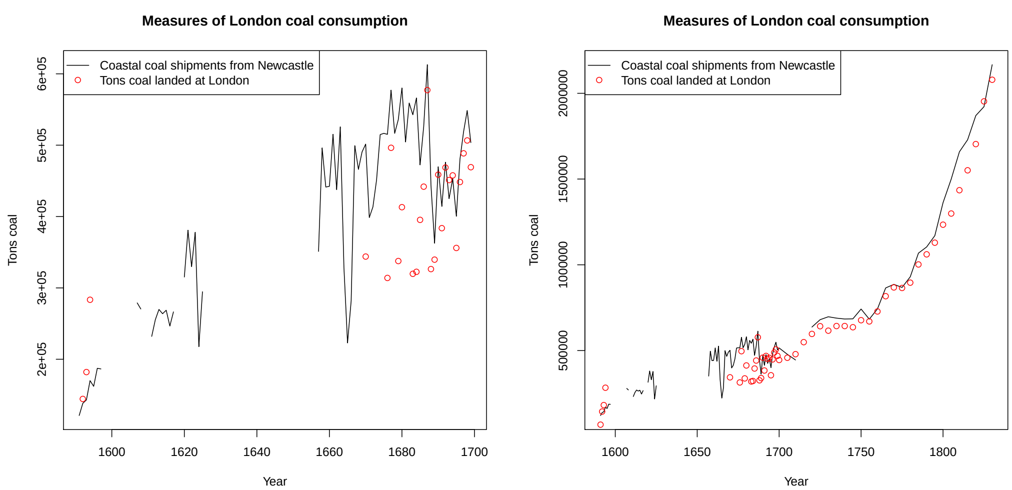

Figure 2: Measures of coal consumption in London in the 17th century. All data from Flinn (1984).

3.2 Electrification and the politics of standards

In 1882, Thomas Edison built the first electric power generation station in the United States, at 225 Pearl Street in Manhattan. It lit 1300 light bulbs. A year later, demand had grown to 11,000 light bulbs. By 1900, there were 25 million light bulbs and a range of other domestic appliances.(Energy Information Administration, 2010) On the shop floor, electrification had a transformative effect on mass production. Whereas steam-driven production lines had to be organized around access to shafts that connected belt-driven tools to the central steam engine, electric motors were small and powerful enough to permit each tool to contain its own motor. Production lines were now as flexible as the engineers who designed them, leading to radical changes in the organization of production.(Perez, 1983) All told, the adoption of an electricity-based energy system proved perhaps the single most transformative change of the second Industrial Revolution, one that radically altered the possibilities for social and economic life.

The history of electrification demonstrates three important aspects of the political economy of energy systems transformation. First, the role of the state as standards-setter in large networked systems is inescapable. Early on in the process of electrification, New York State faced a choice between Edison's DC system and Tesla's AC alternative. The choice of technical standards had huge implications for the organization of electricity production and distribution. DC stations were smaller and more geographically distributed than AC stations, and implied different firm and regulatory structures. AC stations permitted centralization of power production long distances from consumers, but were potentially much more dangerous. The technical tradeoffs were transformed into political arguments as the state legislature debated. Edison went so far as to invent the electric chair to demonstrate to the public the dangers of alternating current.(Hughes, 1979, 1983)

The eventual choice in favor of AC, well before any large-scale system had been deployed, set the terms of innovation and competition in the industry for a century. Whatever the problems implicit in non-market selection of standards, it is clear that the electrical network could not have tolerated mixed systems for very long. Downstream users would have faced uncertainty as to what standard to comply with when making major purchases for plants, production lines, or home appliances. Perpetuated uncertainty might have forestalled investment and slowed the expansion of electrification. Moreover, the private firms were apparently unable to resolve the standards decision amongst themselves.

Second, policy models themselves really mattered. As Hughes (1962) points out, Britain lagged the US in electrical adoption despite having access to the same technologies, the same firms, and, in many cases, the same firm engineers and managers. The difference came down to municipal utility regulation. The British decision to extend the successful Victorian municipal ownership model from waterworks to electrical power was perhaps a natural conclusion, but had disastrous results. It gave municipalities the option to buy the entire installed capital stock from electrical firms after 21 years of private operation, for the cost of the bricks and mortar alone. This effectively killed off investment until the repeal of the law. Note that the British decision was not superficially stupid: this kind of soft "municipal socialism" had very effectively improved the quality and reliability of water services in London; and water networks looked superficially like electrical networks. But in practice the policy model proved non-transferable.

Third, government regulation proved critical to the creation of market incentives for innovation. *Contra* Demsetz (1968), Troesken (1996) notes that public utilities regulation was demanded by both firms and municipalities to stabilize the investment conditions for capital-intensive infrastructure. The firms found that the immense non-transferable capital commitments required to enter the electricity market gave them few exit options when faced with expropriation by municipalities. The municipalities in turn found that they had little power over private firms to compel investments or service improvements once they had granted contracts for service rights. Municipal utility regulation that guaranteed rates while enforcing performance standards solved the commitment problems that both faced. Absent market regulation, under-investment appeared to be the dominant alternative.

Thus the most recent energy systems transformation required, consistent with the theoretical arguments posed in section 2, more than just price advantages. Capital intensity, standards uncertainty, and natural monopoly all posed barriers to progress whose resolution occurred at the juncture of private firms and public regulators. Moreover, the regulatory model was hugely important, and required a range of regulatory innovations rather than the extension of older models.

4 An alternative theory: the marginalist school of transformative change

This evidence of complementarity between market and non-market incentives for energy systems transformation stands in contrast to the dominant models in the climate policy debate. The marginalist pricing framework views transformation as a problem of two externalities: underinvestment in innovation consequence of the inability to privatize all gains from innovation, and over-production of pollution consequence of the market's failure to properly price its costs. In that context, transformation becomes a problem of fixing relative prices such that consumers and producers of energy make the right investments to initiate and sustain energy systems transformation.(Popp et al., 2009) To date, the latter externality has received more attention than the former. The preferred, "optimal" solution regardless of political context has been emissions pricing–either via a carbon tax or a system of costly permits–which treats transformation as a problem of relative energy prices.(Baumol, 1972) In theory, changes to the relative price of different energy sources should generate the upstream incentives for innovation required to complete a transformation from one source to another.

Despite this dominance, Popp (2010) suggests that more recent research has found that pricing alone may fail to provide for either the adoption of known substitutes or the investments in innovation required to provide new substitutes for the now-disfavored energy system. Consumers already under-invest in benefit-positive energy alternatives with very short payoff periods. Firms could save significant amounts on energy bills with relatively little investment but do not.[5] Enkvist et al. (2007) find a range of efficiency investments with immediate cost savings as large as €50/ton CO_2 abated, which as of now are not widely adopted.

These observations concern market imperfections among energy users, a diverse set of actors making decisions in markets with lots of substitutes and reasonably high turnover rates. What of production and distribution, which display much higher levels of market concentration and imperfection? Monopolist actors in markets with relatively inelastic demand may be even less price-responsive than energy users. Moreover, the threat of market entry by lower-cost competitors may be insufficient: Stiglitz et al. (1987) present a model of a monopolist industry in which entry requires some sunk cost due to non-transferable capital investments. He finds that the monopolist may innovate to keep these sunk costs and their barriers to entry high, and not for other purposes. Troesken (1996) argues that non-market regulation of public utilities may increase the level of innovation and tech-

[5] Retailing giant Walmart and computing giant Google are two outliers here. Both have invested significant time and money in energy efficiency. But these two firms operate at a scale far removed from most firms or consumers. Moreover, Walmart only became interested in energy efficiency in the last several years, despite having operated at massive scale for over a decade.

nology adoption by guaranteeing future profits in markets that otherwise generate hard-to-capture public goods. Finally, power distribution infrastructure is a very expensive para-public good for which there are almost no reasonable substitutes. These market imperfections and inelasticities should inform against purely price-based approaches that assume market perfection.

Additionally, pricing may fail to solve the problem of providing for compatible innovations across energy production, distribution, and use that would lead to an energy system that can satisfy the endogenously determined requirements discussed in section 2.1. This finding is unsurprising in view of the understanding of innovation as a quasi-public good. Interoperability in technical standards is one aspect of public goods creation, which private firms tend to support *ex post* but fail to create *ex ante*. Standards enable many different firms to enter markets on equal footing, and ensure interoperability between different solutions to a given problem. But this implies that the innovations in the standard itself are public goods, leading to under-investment.

Hanemann (2009) argues that these issues present real difficulties for energy pricing as a comprehensive solution. In an environment where present substitutes for the offending energy source are imperfect and future substitutes are uncertain–conditions not present in the successful case of acid rain mitigation–price alone may not deliver on the rapid development of technology and its deployment at scale. Instead, these problems can create a collective action problem that rewards firms for waiting for greater technological and regulatory certainty, a problem that results in stasis.

We may add other market failures or imperfections to the set of barriers to a purely price-driven energy systems transformation. Energy production and distribution networks are capital-intensive, non-transferable infrastructures. Both require access to very limited resources–land and mineral rights and rights-of-way–which combine with capital intensity to favor market concentration. For consumers, the choice of technologies compatible with a new energy system requires that system be available at scale; electric cars are of little use without places to recharge them. Whether relative prices that anticipate fully-functioning markets can deliver transformative investment and change amidst these myriad market imperfections remains unclear. In any event, it suggests the need for a much closer understanding of the relationship between policy in a variety of different domains of the energy system, and the prospects for energy systems transformation.

Finally, emissions pricing pays relatively little attention to problems of political economy. Given that policy-induced changes to relative prices will create serious, credible opposition among a range of powerful interests across the energy system, any approach reliant solely on prices should generate serious doubts as to its long-term credibility. Absent the ability to make credible commitments, policymakers and policy advocates should doubt whether the emissions pricing approach alone can generate and sustain energy systems transformations.

5 Technology policy in a systems context

Returning to the motivation for this paper: if arms-length price-based policies will not accomplish the systemic changes required of effective climate policy, then what options should states consider instead? Can states choose policies with an eye towards both environmental sustainability and the creation of durable comparative advantages in a range of new high-technology, capital-intensive industries? This paper will argue that states can and will pursue renewable energy-based transformations motivated by both environmental and economic concerns. Moreover, done properly, this pursuit can yield substantial benefits for industrial development. But achieving these ends will require novel approaches to technology policy.

First, however, states must decide what end policy should serve. Energy, like any other technological domain, provides tremendous opportunity for industrial competiveness. But competitiveness and climate change mitigation are not the same thing. Industrial policy that serves the development and deployment of a range of new energy technologies may have no impact on domestic economies absent a corresponding commitment to domestic energy systems transformation. Likewise, that transformation could occur solely on the basis of imported technology that did little for the competitiveness of domestic firms.[6]

Reconciling climate change mitigation to economic growth requires embracing both objectives with the proper policy instruments. That means supporting both the development of the new technologies that will underpin a high-efficiency, low-emissions energy system, and structuring domestic markets for their deployment and use. The learning effects of the latter will prove vital to continued progress in the former. Unlike Edison, who could model the entire Pearl Street generating system in his laboratory, no single firm can hope to grasp the entire complexity of the energy system. The optimization of the system and its components thus requires laboratories on the scale of the system itself. Domestic energy systems transformation, and not just technological development, will provide that laboratory.

Where should these technologies come from? As in the case of English electrification, the novelty of the energy systems challenge informs against recycling old models of technological innovation. As Zysman and Huberty (2010) and Shellenberger and Nordhaus (2010) have pointed out, energy systems transformation looks nothing like the technology problems that motivated the Apollo moon missions or the Manhattan projects. Both

[6]Indeed, the vaunted "green" investments undertaken with US stimulus money apparently bought lots of Chinese solar power units. Chinese solar power firms captured a third of the California solar market in 2009.(Woody, 2010)

were successful examples of what government-directed intensive technology development could do when faced with a price-insensitive mission requiring technically sophisticated solutions to narrow problems. Successful energy policy looks nothing like this: it is a price-sensitive problem that affects a vast range of integrated solutions to problems spanning the full spectrum of economic production. Calls for "big science" solutions to the energy challenge are thus misguided.[7]

The other signature technology success of the late 20th century, venture capital, will likewise face difficulties. Venture capital produced extraordinary innovation for the application and diffusion of microelectronics, semiconductors, and the Internet. But it did so after the core technologies–the transistor, the Internet communications protocols, and the web browser–had already stabilized around common standards. The Internet could not have become what it is today without venture capital support for massive experimentation in business models and technology deployment in the 1990s. But the VCs neither invented the internet nor managed the standardization of the communications protocols on which it depends.

Neither did they build the telecommunciations networks on which the Internet depends. Venture capital has been most successful in industries where the products face low capital overhead, high turnover rates and short product lifecycles. Internet and computer components companies operated in sectors where these qualities enable diverse experimentation and provide relatively constant, high demand for new products. They could do so initially because policy in other areas, such as antitrust investigation of IBM or AT&T, ensured unimpeded access to both the core technologies and the networks on

[7]Capital-intensive, high-risk technology ventures like clean coal, carbon sequestration, or nuclear fusion may be exceptions here. Note that each of these projects has attracted significant skepticism from the scientific community. Practical fusion-based power generation, for one, has been "twenty years out" since the 1960s. Nevertheless, to the extent that solutions might become available, these big-ticket items more closely resemble the kinds of problems that Apollo-style technology programs excel at.

which they ran.[8](Borrus and Zysman, 1997) Other venture capital sectors, such as biotechnology, have proven much less successful in part due to their very different structure of risk, reward, and market competition.

This history suggests that venture capital will face difficulties in two of the three technological domains implicated in energy systems transformation. Energy production and distribution require massive investment in capital-intensive technology that turns over on 50-100 year lifecycles. Both are undertaken by highly regulated industries in which technological sophistication and innovation are balanced against service provision, reliability, and safety. Meeting these terms of service has required continual optimization of complex systems around specific factors. All these features mean that the creation of a new energy system will require a technology paradigm very different from the one that drove the rapid development, deployment, and diffusion of the internet.

This is not to say that a venture capital model of technology development and deployment will have no role in the coming energy systems transformation. But it does suggest that the role they play will emphasize markets for components rather than systems solutions.[9] Those components, in turn, will emerge if and only if the highly regulated networks on which they operate can converge on a set of workable standards, deploy a new network compliant with those standards, and operate within a regulatory regime flexible enough to permit innovation atop those standards.

Such an approach would have much in common with earlier instances of energy systems transformation. Both the English adoption of coal and the electrification of the

[8]Note that the US also ensured firm coordination in semiconductors in order to generate ongoing innovation in pursuit of Moore's Law. Sematech's success started as a parapublic organization with governmental leadership, and turned fully public only later.

[9]Indeed, there is evidence that this pattern is already taking shape. Conversations with venture capitalists at a 2009 New England Venture Capital Association visit to UC Berkeley suggest that they are investing in firms that produce components of solar cell units but not the units themselves. Alternatively, capital-intensive projects like the Better Place electric car have attempted to define the standards for a wholly new industry. Whether that model will be successful has yet to be seen.

United States depended on the extension of the distribution networks–canals or transmission lines–that operated on common standards and for which access was governed by rules. The system of turnpike and canal trusts in England gave operators incentives to maintain service quality and permit a wide range of goods to travel their networks. The utility regulation of power grids in the US did the same for electricity generators. In both cases, the network became a multiplier for the development of industries on each end–the Midlands coal fields and industrial cities in the first case, and the widespread and exponential adoption of electricity in the second.

Managing the coordination problems presented by the grid constitutes the greatest novel challenge to industrial policy. The technological challenges of the grid alone are substantial. In its most extreme form, a new, "smarter" power grid is projected to allow real-time dynamic demand and supply management. This would require managing an intermittent supply of renewable energies against a fluctuating electrical demand profile though the use of both demand management and electrical storage. The paradigmatic case of this problem is the integration of solar power and air conditioning: just as everyone comes home from the office and turns on their air conditioner, the sun goes down. How should supply and demand in this case be reconciled?

Technologically, this implies a grid that maintains real-time contact with nodes of energy production, storage, and use; and that could, within some parameters, adjust the demands on each to ensure the stability of the power supply. The technological issues are complex. They imply that all major point demand and storage sources would have communications intelligence embedded, which could talk to and be controlled by a power grid intent on maintaining reliability within certain parameters. Such a system by default anticipates the convergence of a huge range of industrial and commercial sectors on a single interoperable set of standards. The scope of the problem is visible in the *e-Energie* trial projects currently operating in Germany: major electric generators, IT companies, regional electric utilities, storage operators, and appliance makers all collaborating on county-scale "smart grid programs."

The regulatory issues may make the technical issues look trivial. Real-time demand management implies that users give up their presently absolute control over patterns and levels of energy use. This raises a hose of thorny problems: What privacy problems apply to real-time management of household-level energy consumption? Which kinds of critical infrastructure (hospitals, police stations, etc) are excluded from demand management? Does that excluded population change with changing supply and demand conditions? Should homeowners who accede to demand management receive compensation, or is it even a choice? How is storage paid for, in a system that now only considers production, distribution, and consumption? Can anyone provide production or storage solutions to the grid, so long as they comply with the right technical protocols–that is, can my rooftop solar cells feed into the grid, and can I get compensated? In other words, achieving the technological capability to engaged in dynamic demand-supply management to support widespread adoption of renewables will force a wide range of choices on the state that will determine how the energy system will evolve and optimize. These choices are as important a part of energy systems transformation as the rapid development and deployment of technology.

In this context, the state will face choices about how best to support the development of technology and its deployment in a complementary regulatory structure. The complexity of this problem make the lessons of Rodrik (2004) all the more relevant. Unlike the Apollo or Manhattan projects, the state cannot hope to achieve the diversity of technological innovations required for energy systems transformation through top-down policy programs. Likewise, the hands-off approach promoted by advocates of emissions pricing will not solve the myriad regulatory and coordination problems posed by major changes to the energy system.

Such a policy model would also point ht way to reconciling the problem of emissions and economic growth. The policy approach outlined here does not anticipate that an economy must create for itself the entire range of technologies required for the systems transformation. Rather, consistent with Breznitz (2007), states can find competitive advantage in complex technological systems through niche specialization that draws on their unique national comparative advantages. But the terms on which this occurs are closely tied to the policy choices

Finally, these choices are heavily contingent on the decision to pursue both emissions reduction and industrial competitiveness. When Edison built the Pearl Street plant, he could model the entire energy system in his Menlo Park laboratory beforehand. The scale and complexity of the modern energy system permits no similar experimentation. Rather, learning by doing, at scale, will provide critical information to firms and regulators about how to adapt and innovate in the new energy system. Many states have already realized this: the *E-Energie* project in Germany[10] and the rapidly expanding grid in China are but two examples of public-private partnerships in pursuit of both renewable energy deployment and learning-by-doing. They can provide a model of incentives for the development, deployment, and optimization of new energy sources in service of energy systems transformation.

6 Conclusions

Few challenges today are as technologically or politically vexing as climate change. The energy systems transformation required to achieve meaningful climate change mitigation

[10] See http://www.e-energie.info/

will require a parallel set of technological, economic, and social changes to how we produce, distribute, and use energy. Policy models suitable for the scale of this challenge must reflect its novelty and complexity. Evidence from past energy systems transformations reinforces the lesson that attention to the distribution system on the one hand, and to the structure of market regulation on the other, constitute important parts of any policy program. Moreover, they also suggest the limits of policy programs imported from other areas of the economy–whether purely price-based approaches on the one hand, or command-and-control programs on the other. Finally, there's at least some reason to believe that a properly structured approach to energy systems transformation today will generate the same kinds of transformative econoimc change that earlier transformations did. Just as England benefited from being the first to coal, and the US from being the first to electrification, so too will the leading economies of today benefit from the transformative innovation required to achieve meaningful emissions reductions.

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