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Article

Assessing Sustainability Transition in the US Electrical Power System

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Abstract: This paper examines sustainability transition dynamics in the US electricity system, drawing on the socio-technical systems approach. We view system change as unfolding along several critical dimensions and geographical scales, including dynamics in the environment, science, civil society, discourse, and state regulatory institutions, as well as in capital and technology formations. A particular emphasis is given to the interaction of discourses, policy networks, and institutions. We trace four distinct regimes which have characterized the evolution of this discourse-network-institutional nexus over the last century. The research examines dynamics that present a challenge to the incumbent energy regime based on fossil fuels, nuclear and hydropower, and demonstrates how the actor-network supporting renewables and energy efficiency has grown stronger and more capable of moving toward a sustainability transition than at any time since the sustainable energy movement began a generation ago.

Keywords: socio-technical systems; sustainability transition; technological change; electricity systems; energy policy

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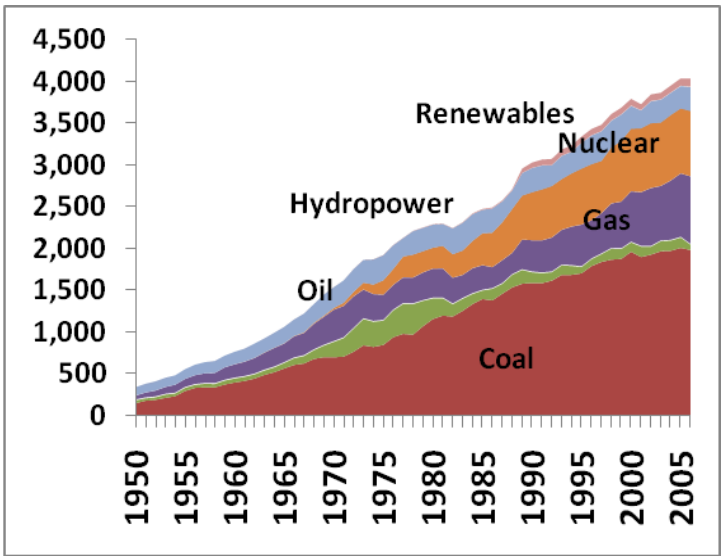
1. Introduction

In July of 2008, former Vice-President Al Gore [1] made a prominent and provocative call for the US to "commit to producing 100 percent of our electricity from renewable energy and truly clean carbon-free sources within 10 years", claiming that the goal was achievable and affordable and that "the future of human civilization is at stake". Some 31 years earlier, President Jimmy Carter, speaking from the energy crisis of the 1970s, had similarly framed energy system transformation as "the greatest challenge our country will face during our lifetimes", yet one that "we will not solve in the next few years, [instead] it is likely to get progressively worse through the rest of this century". Subsequent developments—geopolitical, economic and climate-related—have proven this last statement prescient. What then are the prospects for a "sustainability transition" in the US electricity system, understood as a restructuring that significantly steers this system, which presently accounts for approximately 40% of both primary energy use and greenhouse gas emissions, toward a far more renewable and energy efficient trajectory? Even before the extent of the current economic downturn became obvious, the Obama administration took office on a platform calling for investment in green energy technologies to promote economic growth and address climate concerns. Clean energy development now forms a central part of the country's economic recovery plan, reflecting the belief that a major rebuilding of the country's energy infrastructure is required and that the scope of such an effort would generate significant economic activity [2]. While these developments represent a major shift in the political discourse in the United States, the process of transitions in large socio-technical systems remains complex, fraught with competing interests, and heavily dependent on historical contingencies. This paper presents a long-term analysis of dynamics in this critical socio-technical system, exploring four distinct regimes that have characterized the system over the last century and that have conditioned the likelihood of a substantial near-term shift toward the sustainability transition Gore envisions. Should the system move substantially in this direction in the next decade, the genesis of this transition would lie in a broad range of social, environmental and technical processes that represent both continuity and disjuncture with these historic regimes and with the generation of sustainable energy innovation initiated in the 1970s.

A growing body of research on sustainability transitions emphasizes that shifts in socio-technical systems often embody a fundamental rupture in critical processes undergirding an incumbent socio-technical regime [3,4]. This incumbent regime in the energy sector, characterized by persistently increasing electricity demand and almost complete reliance on fossil fuel, nuclear and large hydropower generating plants, has shown great resiliency over the past half century. Since 1980, electricity and coal consumption in the US have both increased over 70%, while renewables have grown to just 2.4% of total net generation (Figure 1). Few analysts predict a sharp break with these trends, and most technical and economic analyses of climate change mitigation embrace scenarios far closer to the Energy Information Administration's [5] "business as usual" reference case scenario that shows electricity consumption and carbon emissions increasing more slowly than previously, but still by over one-quarter between 2006 and 2030, while renewables increase to just 6.8% of net generation. With annual revenues of some $500 billion, "business as usual" in the electrical power industry enjoys the support of powerful social, financial and political interests reinforced through public and private institutions that constitute and manage the electricity system. At the same time, we show below that an

increasingly effective sustainable energy actor-network has grown and attracted new actors to challenge conventional energy systems and, relative to their limited successes in the 1970s, is now achieving more broad-based changes in the laws, policies, and investment decisions affecting this industry.

Figure 1. Trends in electricity-generating fuels in the US (data source[6]).



Part and parcel of these energy sector developments are evolving, competing theories of how change in these systems can (and should) occur [7]. Academics no less than others debating the costs and consequences of climate change operate from complex sets of disciplinary and individual commitments and perspectives that are only partially bridgeable through recourse to empirical evidence [8,9]. Key insights informing our analysis are: that energy systems are central to human-environment relations due to their unique thermodynamic role in economic and ecological systems [10,11]; that very substantial and immediate changes toward low-carbon energy systems are required to mitigate climate change [12]; that while the resource base of fossil fuels is of diminishing quality, the flow of renewable energy resources—wind, sun, tidal flows, geothermal, *etc*.—vastly exceeds human demand [10]; that large "no net cost" energy efficiency and carbon emissions improvements are available through improved policy measures and concerted, though not heroic, effort [13]; and that sustained policy deliberation will be necessary but hardly sufficient to realize the potential for a renewables and efficiency transition. The analysis here includes, but extends beyond, questions of price and technical efficiency to explore how processes of innovation and system change unfold through complex social, environmental, and technological dynamics.

We situate our work in relationship to the literatures on socio-technical systems [14], policy networks and discourses [15-17], and sustainability transitions [3,4,18]. As it has become more evident that radical restructuring of critical societal systems is required to achieve sustainability [3,19], research on innovation and socio-technical system change has focused on steering systems toward more sustainable configurations. Energy systems, though not the only systems of interest in this research (see [4,20]), have received considerable attention. Much of this work examines dynamics in European electricity systems (e.g., [7,21,22]), as surprisingly little research has analyzed from a

socio-technical systems perspective the major shifts that have occurred in the US electricity sector and their potential impacts on a system-level sustainability transition (though see [23]). Essential literature informing this study includes Hughes' [24,25] account of the early evolution of the US electrical system that introduced core concepts that continue to shape socio-technical analysis, including the essential broadening of the concept of "technological system" to include alongside technical components—power plants, transmission lines and the like—a panoply of social actors, including inventers, entrepreneurs, financiers, politicians, and others driving system evolution through a "seamless web" of economic, political, institutional and technical processes. Hirsh [26] carries the story forward to the late 1990s, through two major changes in the institutional landscape and emphasizing more the role of elite groups in shaping the industry's evolution. While we draw on these sources theoretically and empirically they, like Sine & David's [27] useful account of the effect of institutional change on electrical sector entrepreneurial activity during 1935–1978, do not forefront in their analyses implications for sustainability, nor take into account more recent, large changes in the industry and energy-environment landscape. We also extend the socio-technical systems literature, which generally focuses on lessons from past system changes, whereas our question, while historically grounded, also concerns prospects for future change. Finally, the work contributes to a growing body of work [28,29] which centers the concept of discourse formation in the analysis of socio-technical system change.

In the next section, we discuss theory informing our analysis. The remaining sections present an empirical analysis of developments in the US electricity system, organized around major themes identified in the theory section, including sections on environment and science; civil society; discourse, state action and institutions; and a look at changes in related capital and technology development decisions. We conclude by highlighting key themes revealed in the analysis. The research is based upon analysis of secondary sources, including previous studies of sectoral change and reports of recent electrical sector innovation investments. The lead author participated in a study [30] of sustainable energy advocacy efforts in the 1990s that involved 50 interviews and a focus group with a wide range of informants from academia, industry, utilities, advocacy groups, and state officials. All information contained herein, however, is sourced to publicly available records.

2. Theory

Unlike analyses focused more narrowly on market dynamics, policy outcomes, or the behavior of firms, socio-technical systems analysis seeks to illuminate the complex interactions among a broad and diverse range of factors that influence system change. At the core of the approach is the notion that large technical systems are comprised by a complex configuration of social dynamics, including legal, institutional, regulatory, educational, and cultural processes, which co-evolve with the material and technical artifacts in a system. This perspective is particularly useful for revealing the dynamics of system transition. The embeddedness of electricity generation, transmission, and distribution technologies within complex social networks lends such systems a strong path dependence. While resistant to change, research on historical shifts in entrenched socio-technical systems has shown that, where alternative system configurations achieve sufficient strength, even large technical systems can

shift quite rapidly toward an alternative system as the configuration of interacting social and technical factors re-aligns around the alternative [4,31,32].

In the case of energy systems, new technologies typically augment rather than replace existing systems. For example, today the US burns thirteen times more coal for power production than in 1950 (Figure 1), and uses more coal for all purposes than in the 1920s, when coal was the dominant energy resource. This particularly strong path dependence is partly explained by the political economy of energy. The large capital flows commanded by energy industries and the centrality of energy for economic production lead to close alliances between energy producers, utilities and states, and to institutions, relationships, market rules and complementary industries strongly supportive of the entrenched energy regime [33,34]. Unruh [35] explains how such "techno-institutional complexes" defined as "large technological systems embedded in a powerful conditioning social context" have systematically advantaged fossil fuels and led to "carbon lock-in" in the industrialized world. Fossil fuel lock-in has to date been a major barrier to carbon-saving technologies and the rise of alternative energy systems. Thus analyzing the prospects of an energy system transition requires a focus not only on technological change and innovation, but on the social structures and processes that maintain the incumbent regime and those that might destabilize it [14]. We conduct this analysis with a view toward assessing whether the current sustainable electricity movement, building on the efforts begun in earnest in the 1970s, can realize the significant system shift that was envisioned at that time but not yet realized.

An important conceptual model in the socio-technical systems literature is the multi-level perspective (MLP) model. The model, which Geels [20,36] organized and which many others have advanced [4,37,38], identifies three conceptual levels involved in the process of socio-technical system change: the niche, the socio-technical regime, and the socio-technical landscape. The meso-level comprises the socio-technical regime—the deeply-entrenched, "conventional" configuration of social groups and actor networks, routines and rules, and material and technical artifacts that dominate a technological system. Path dependence and lock-in are the norm, as structural barriers to change maintain and protect incumbent actors, social networks, and technologies [35]. At the micro-level, small-market or technological niches act as incubation spaces, shielding potentially disruptive new technologies from mainstream market selection and allowing novel technologies to develop. The macro-level is the socio-technical landscape, the political economic and environmental context that shapes the dominant regimes over long time spans. System transition occurs when the incumbent regime is challenged or stressed, either by its own contradictions or by external pressures, and the niche technology advances enough to compete with and eventually replace the existing regime [38].

The MLP has proved a useful model for organizing analysis of socio-technical regime change, and numerous case studies, on energy systems [38] and other large technical systems [39] have utilized the approach. Current work is enriching the MLP model in useful ways by either elaborating the mechanics of the model [4] or by developing important dimensions of the transition process which are not well captured by the MLP model [29]. We add to this latter body of work by exploring transition dynamics in an important empirical case—the large and complex US electricity system. The MLP provides a useful heuristic for understanding the contours of historic system transitions, yet analysis of ongoing transitions requires a richly empirical approach which highlights the multidirectional and complicated dynamics through which system change unfolds. In analyzing the contestation between

entrenched incumbent regimes and more sustainable alternatives, we follow Laird [15] and others [29] in asserting the importance of ideas and discourses, and the ways in which ideas transform the terrain on which the transition process occurs.

Our analysis focuses particularly on the nexus between discourses, political networks, and institutions. Discourses are narratives used to contest or enforce power and decision-making by explaining (and obfuscating) dynamics of change, and there is a rich body of literature describing the role of discourse in shaping environmental policy [40,41]. Policy networks refer to the broad range of actors, spanning civil society and advocacy groups, government, industry, and investors, among others, who engage in the practice of generating discourses and linking discourse with policy prescriptions. Networks have become particularly crucial in policy formation with the shift from government to governance [42]. Institutions refer to the routinized practices and bodies which carry out policy and governance [43]. Discourses, policy networks, and institutions interact dynamically with each other, yet we follow Lovell and colleagues [29] in asserting that discursive shifts, supported and promoted by policy networks, precede institutional changes. Institutions, by definition, enforce stasis and therefore change only slowly and incrementally in response to shifting discourses. Where Lovell and colleagues [29] emphasize the embeddedness of discourses in physical and material realities, we emphasize the articulation of discourses with existing institutions and the ways in which institutions and policies formations are transformed through discursive shifts.

Our analysis of socio-technical change in the US electrical power sector thus focuses on shifts in the discursive and regulatory regime which are potentially supportive of moving the system toward a broader sustainability transition. We identify four distinct phases in this regime over the last century, and we examine in detail how shifts from one regime to another embody both new opportunities and legacies from prior regimes. The extent to which discourses become embedded in institutions and policy formations to a large extent depends upon the strength, skill, and strategies of policy networks supporting those discourses and transforming them into particular policy approaches. These networks are described by Richard and Jordan's [44] policy communities, Sabatier's [45] advocacy coalitions, and Hajer's [41] discourse coalitions. Each in some way reveals how substantial changes in policy require the dominance of new discourse coalitions and the institutionalizing of new ideas. We emphasize, however, that remnants of past discourses remain institutionalized even as new discourses ascend, and the result—the actual policy and institutional formation in which electricity management, governance, and innovation occurs—is often a messy hybrid of past and new discourses shaped by political negotiations. Our study shows that the particular form this discursive and institutional hybrid takes results in unique barriers, but also opportunities, for system change, with distinct implications for sustainability.

The emphasis on discursive regimes and their institutional articulation reveals the shifting concerns and values which have supported the US electricity system over the last century. In some ways these concerns have passed through the three major elements of sustainability—economic, social, and environmental—at different moments highlighting different domains of social interest. The rise of the climate change discourse and its convergence with electricity policy discourses [29], suggests that the environment can no longer be subordinated to economic or social interests in electricity policy. Nature can now be seen as an agent in the broad electricity system. Nature does not speak for itself, however, and science has been critical in identifying and interpreting environmental change and its strong

connections to fossil-fueled energy systems [12]. We describe below how the contemporary impetus toward a sustainability transition in the electricity system has been stimulated by the ascendance of nature into the electricity discourse.

Our account also highlights political networks which have not been treated extensively by other transition studies. Much of the existing research on electricity system transitions has focused on national level dynamics, often in Europe [22,38,46], but also in the US [15], while other accounts focus on urban scale dynamics [47]. Our study of the US electricity sector highlights the unique role of state level dynamics, and particularly the role of civil society networks working through state governments and creating linkages at the national scale. As such, we demonstrate the importance of bottom-up transition dynamics, which are critical in adding pressure on the incumbent regime and in formulating new discourses and policy options, as opposed to the top-down dynamics described in many transition studies, which emphasize the role of governments in "steering" systems toward more sustainable configurations.

The stimulus to change presented by nature and science has been significantly amplified in the US case by the rapidly growing civil society advocacy network. This "alternative energy" network had for many years been limited largely to a handful of large environmental organizations and allied philanthropies, politicians, regulators, academics, renewable energy businesses and others. Recently, however, new actors representing a wider array of interests have brought new resources and perspectives to the advocacy effort. These actors have contributed to envisioning and executing a loosely coordinated, yet sophisticated strategy based on creating new policies and institutions to support sustainable energy initiatives in states like California, Massachusetts and New York [48]. The challenge has then been to diffuse these innovations "down" to localities, "across" to other states, and eventually "up" to the federal government. Central to this strategy are efforts to contest the discourse through which relationships between energy, the environment and society are explained so as to make the embrace of sustainable energy policy both "thinkable" and politically tenable [41]. The new discourses and institutions of energy policy advocacy create very different paradigms for the industry and the innovation environment.

3. Nature in the Electricity System Discourse

As argued by actor-network theorists like Latour [49], "nature" has agency, and in the case of electrical power systems, it is easy to see that nature has been and will remain a critical force for change. At numerous nodes in the network linking energy and ecological systems, environmental stress creates pressure for a sustainability transition. "Conventional" energy system problems are significant: large hydropower plants alter the ecological functioning of river systems; nuclear power presents unresolved waste processing challenges and potentially catastrophic system failures; and coal use involves landscape-altering "mountain-top removal" and strip mining as well as emissions that contribute significantly to acid rain, smog, ozone depletion and other hazards [50]. Electricity production also causes 24,000 premature deaths annually in the US and over a half million asthma attacks [51], and exposes some 600,000 babies prenatally to dangerous levels of mercury [52]. Such comparatively direct impacts have led to reform (e.g., pollution reductions under the federal Clean Air and Clean Water acts) but not transformation nor displacement of the existing energy regime. It is

perhaps surprising, then, that climate change has emerged as a potentially disruptive force in the industry, given that many impacts are likely to be most severe decades in the future and outside the US. It is also ironic that carbon dioxide—the greenhouse gas most responsible for global warming yet otherwise a non-toxic gas essential to life processes—should have become a major force in the sustainable energy transition. And while climate change is emblematic of the problems of too much fossil fuel use, peak oil theorists suggest that, barring a prolonged worldwide recession, global oil demand will soon outstrip production capacity growth, leading to persistently high prices and economic stresses until alternatives to oil are widely deployed [53].

Most socio-technical analysts locate nature outside the system, in the socio-technical landscape, where along with many other exogenous factors, perturbations can sometimes produce "environmental jolts" that trigger "search processes that can both delegitimate existing institutional structures and uncover alternative arrangements" ([27] citing, [54] p. 515). Although the concept of the environmental jolt is quite broad (at the organizational level, "transient perturbations whose occurrences are difficult to foresee and whose impact on organizations are disruptive and often inimical")*, the electrical power industry has clearly experienced a series of jolts triggering searches for new institutional and technological arrangements in recent years (discussed further below). These jolts often arise directly from contradictions within the system itself—for example, the mammoth scale of operations and reliance on depletable fossil fuels leading the system to be "jolted" by climate change and energy price volatility concerns—that may appear to many actors to be exogenous "surprises", but that analytically are better understood as manifestations of crisis in a dialectical process of negotiation and reconfiguration of relations between "environment" and other system actors [55].

While nature is thus a critical actor instigating energy system change, nature's agency is mediated by those who speak for it, most authoritatively scientists who represent and interpret environmental processes. Advances in earth system science over the last three decades have significantly increased confidence in assessments that anthropogenic climate change is occurring and presenting potentially grave challenges to humans and ecosystem functioning at multiple scales. We cannot review here the vast literature on the complex role of science in the politics of climate and energy policy (e.g., [56]), but clearly climate change science has helped reinvigorate the sustainable energy network of the 1970s and 1980s and stimulated public concern about the implications of what nature and science are "saying" about the hazards of conventional energy systems. Climate change thus appears to present a long-term threat that will remain a stimulus to energy system transformation, regardless of how other factors like energy pricing ebb and flow.

4. Civil Society as a Key Political Network

Whether climate change can be used to mobilize sufficient political will and entrepreneurial innovation to undermine entrenched power systems in a way that earlier "conventional" threats have not remains to be seen. In recent years, however, the green energy movement in the US has grown deeper and broader, and has contested conventional energy in a more diversified and sophisticated manner. The multilayered "climate action network" that has emerged from within and alongside the environmental movement is far more diverse than earlier advocacy efforts. For one, the groups

aligning themselves with significant aspects of the climate change agenda have grown to include new actors such as the religiously-based Interfaith Power and Light, the Business Environmental Leadership Council, hundreds of state and local governments and grassroots climate action groups, a sustainable campus movement, international collaborations such as ICLEI-Local Governments for Sustainability, the international climate science and policy process, and increasingly, entrepreneurs and venture capitalists from high tech industry. All of these groups bring a richer set of perspectives and resources with which to pursue a sustainability-oriented agenda for the electrical power sector. This growth in resources and advocacy, whether supporting particular sustainable technologies or focused more broadly on raising climate awareness, is critical for establishing an alternative regime capable of displacing conventional energy interests.

Climate change concerns have become increasingly evident in popular culture, notably through Gore's *An Inconvenient Truth* film and book [57] and the Gore-affiliated Alliance for Climate Protection's [58] "unprecedented mass persuasion exercise" that includes TV ads pairing unlikely political figures from the left and right who find common cause on the subject of climate change. The widening consensus on the need to address climate change was reflected, for example, in the 2008 request by the Ceres Investor Network on Climate Risk, which comprises more than 50 major institutional investors then managing over $2 trillion in assets, for Congress to impose climate change regulations to reduce GHG emissions 60% to 90% below 1990 levels by 2050. Ceres [59] argued that "[s]trong and decisive action from Washington will open the floodgates on large-scale clean technology investments, enabling US investors and businesses to lead instead of lag on climate change solutions". This plea for federal action by some of the world's largest institutional and financial investors reflects, in part, the success of a spatially sophisticated advocacy strategy initiated in the 1980s to encourage key states to enact policies and generate sustainable energy momentum that could be diffused to other states and form the basis for national policy (see discussion below). The aim of this movement is to promote change in both the normative and regulatory rules affecting the energy sector.

Entrenched energy regime actors have likewise sought to influence public opinion and the gains made by sustainability advocacy groups have been achieved against some of the best-funded and most powerful lobbies in the world. Peabody Energy, for example, the country's largest coal company, has spent 0.5% of its profits on political contributions, and electrical utilities altogether spent $800 million on lobbying from 1998 to 2006, an investment that, among other returns, secured billions in coal subsidies in the federal 2005 Energy Act and $18 billion dollars in new subsidies for nuclear power [60]. The US electrical power system is thus fraught with competing interests and conflicting policy claims. To understand if and how advances in broadening the network of actors expressing concern about climate change and other problems of conventional energy might be leveraged to instigate a sustainability transition, we explore below the evolution of energy-related discourse, state policy and institutions governing the electric power sector over the last three decades.

5. Discourse, State Action and Institutions

Environmental discourses structure how issues are framed—What is the problem? Who is responsible? What are the solutions?—and thus help shape policy and institutions [40]. In the case of

energy system evolution, competing interests have long sought to control policy development by influencing public understanding of the nexus between energy, environment, economy and society [41]. Energy conservation and efficiency, for example, has been negatively associated over the years with shivering in the cold in a sweater or being un-American, unmanly, or a "personal virtue" but not a basis for policy, and positively associated with a return to virtues of frugality and environmental stewardship and an enormous market opportunity. Science is an important resource in constructing energy-environment-economy discourses, both as a source of insight into underlying processes and as a signifier of objectivity and credibility. Discourse is also a process—neither nature nor "facts" speak for themselves—and discourse is the process of binding always partial facts together into a more-or-less compelling narrative arguing for particular kinds of understandings, institutions, actions and inaction. Discourse *per se* is an often overlooked force shaping innovation (though see [61]), yet the history of the US electrical industry suggests that discursive shifts have impacted energy policy and infrastructure developments, with important social and environmental consequences. What follows is a brief overview of this history, with particular attention to how elements in each era continue to shape the prospects for sustainability today.

5.1. "Natural Monopolies" ERA: 1900s–1980s

By the 1930s, the early era of innovation in the US electricity industry had led to a policy coalescence around the notion that electricity supply represented a "natural monopoly", that economies of scale and the costly nature of electrical power supply infrastructure made it inefficient to have competing firms operating in the same area [25]. Instead, electricity service would be provided largely by private investor-owned utilities (IOUs) granted exclusive rights to operate in regional service areas regulated by state public utility commissions (PUCs). Federal involvement was largely limited to regulating interstate transmission and to developing a few massive hydropower projects providing wholesale power. The IOUs were vertically integrated companies responsible for generation, transmission, and distribution of power to essentially all residential, commercial and industrial customers in their service area (some areas developed publicly owned utilities, but the IOUs until recently controlled about three quarters of the retail market and most of the wholesale market). In return for reliably providing power, the IOUs were guaranteed a modest rate of return on capital invested in service provision. An underlying assumption of this regulatory model was that electricity was an essential ingredient for economic growth and that there was a 1:1 coupling between the two. The essence of system planning was, therefore, to project how fast the economy would grow over a several-year planning horizon and require that utilities build generating capacity to match. The exercise was technocratic and conducted largely through rate cases, quasi-legal proceedings initiated by utilities and governed by state PUCs [26].

The system had many strengths: with the completion of rural electrification, the social sustainability goal of near-universal access to electrical power of high quality and reliability was achieved, and for decades economic growth was sustained through power supplies that grew exponentially as costs steadily declined. The guaranteed rate of return meant that the industry could readily meet its vast capital needs, with utilities serving as a secure form of retirement investment for millions of Americans. Incentives for innovation were weak, but "cost per kilowatt-hour" declined as economies

of scale led to ever-larger power plants. This in turn led to a grid architecture featuring large, remotely sited plants regionally interconnected through high voltage transmission lines that then supplied local distribution networks in cities and elsewhere. The industry grew to become the single largest recipient of sunk capital investment in the economy and currently has annual operating revenues of equal to approximately 4% of national GDP [6].

The resulting system achieved great technological momentum, but its increasingly massive scale of operations also embodied contradictions that periodically led to social activism and landmark reforms in areas such as labor and occupational safety rights (think coal mine union activism), antitrust protection (most notably depression-era laws limiting market power), and environmental protection. These factors added pressure for reform in the incumbent, and by now deeply entrenched, regime, yet they did not sufficiently destabilize the regime to give rise to serious alternatives. In the early 1970s, however, several factors threw the industry into crisis. OPEC succeeded in raising oil prices, leading to price increases across energy sectors and a decade of global economic instability that reduced demand. Economies of scale in steam generation plants reached a thermodynamic limit, nuclear power plant costs skyrocketed, and federal legislation imposed new pollution controls on power plants. Suddenly, it became apparent that economic growth and electricity consumption *could* be decoupled, and many new nuclear plants turned out to be unneeded when demand fell far short of projections. The social contract underlying the industry began to unravel—ratepayers saw rapidly rising rates and utilities faced economic stress and sometimes bankruptcy [26]. Analysts and activists called for institutional change, arguing that utilities had "captured" regulators—and sometimes legislatures and governors—and thus rendered state oversight ineffective [62].

5.2. Integrated Resource Planning (1980s–mid-1990s)

The tumult of the 1970s created openings for experimentation with new institutional arrangements in some states, legitimated by a discourse arguing that, given the manifest implications of power sector "mismanagement" in a process controlled largely by utilities and state regulators, it was imperative that a wider range of stakeholders be admitted to the planning process. Beginning in California and New York in the early 1980s, representatives of environmentalists, consumers, industry, low income consumers and others began "intervening" in rate cases. A new regulatory paradigm emerged called Integrated Resource Planning (IRP) (or Least Cost Planning) based on the argument that, given how expensive, risky and ultimately unsustainable the endless expansion of electricity supply was proving, it made sense to develop programs to promote energy conservation and efficiency [63]. Accordingly, under IRP, utilities were given incentives to pursue demand-side management (DSM) programs that could be shown to cost no more than new supply options. The IRP paradigm engendered much experimentation in how to deliver, monitor and evaluate DSM programs [64], and along with related legislative initiatives, gave birth to a wide range of now familiar programs such as residential and commercial energy audits, lighting and insulation incentives, appliance energy standards and labeling requirements, and enhanced building energy codes. IRP advocates developed a sophisticated spatio-political strategy to develop IRP and DSM models in lead states that could then be diffused to other states and eventually lead to a national program [65-68]. By the early 1990s, IRP had been

adopted in a dozen states, utility DSM spending exceeded $3 billion annually, and IRP was clearly gaining institutional traction [69].

The success of IRP as a sustainable energy strategy lay in its ability to tap into the large capital flows traditionally controlled by utilities and directed to building the new electricity supply to which their profits were tied. IRP also institutionalized the ideas that diverse stakeholders had a right to participate in setting the development pathway for this critical industry and that the state had a legitimate role in promoting efficiency as a regulatory and social goal. Although the driving force behind IRP was clearly the sustainable energy network, the regulatory regime, still reflecting to a large extent entrenched regime interests, enforced discursive boundaries limiting the rationale for IRP exclusively to cost reduction [65]. Environmental considerations were excluded, which while not particularly problematic for promoting DSM, did inhibit PUCs from considering supply-side, renewable energy initiatives to spur niche technologies. A brief burst of renewable energy development in the 1980s was largely a function of federal tax incentives that dried up, along with other federal support for renewables and efficiency with the return of low fossil fuel prices in the mid to late 1980s [70].

Although IRP grew rapidly and enjoyed support among some influential utilities like Pacific Gas and Electric (PG&E), IRP was often contentious, litigious, and opposed by utilities, regulators and others [71]. Large industrial energy users lobbied hard against IRP because many resented sharing in DSM costs that primarily benefitted residential and commercial customers, and many were also eager to free themselves from their local utility to instead purchase power in developing wholesale markets. Wholesale prices were dropping because non-utility power producers could supply power with new, more efficient natural gas-fired turbine technology and without the burden of servicing nuclear power debt and other full system costs.

5.3. Neoliberal Restructuring: (mid-1990s–2001)

In 1994, as the IRP model of industry regulation was growing rapidly, predicated on an ecological modernist discourse of the state as a convener and mediator of stakeholder interests, the California PUC announced its intention to restructure the industry in accordance with an entirely different set of principles embedded in neoliberal discourse. The plan was to substitute market mechanisms for state-led IRP, and to apply to US electrical power systems the "Washington Consensus" principles that had guided restructuring of energy systems elsewhere, mainly in the developing world, but also in the United Kingdom [72]. While facilitated by federal legislation [27], restructuring played out as a networked, state-level process. As eventually enacted in 1998, California's plan ended the fully-integrated, territorial, exclusive rights franchise that IOUs had held as natural monopolies, and instead required utilities to "unbundle" their generation, transmission, and distribution functions. Power generation was to be an open market, with buyers free to purchase power from any of the competitive generators now given open access to consumers through the transmission grid managed by an Independent System Operator (ISO). Local distribution and billing would remain a regulated monopoly function, but IOUs were not to be in both the generation and distribution businesses. A transition period of some 5–10 years was envisioned, during which time rate increases would be limited, but consumers would be charged fees for "stranded costs" (so utilities could continue servicing

past debt obligations, mainly for nuclear power plants), and for "stranded benefits", mainly state-mandated DSM programs that were to be phased out as energy services companies came on line to provide only those efficiency services consumers might choose to buy. Other states began to follow suit, and the conventional wisdom was that California-style restructuring would soon become the national norm.

Although environmental NGOs were divided in their view [73], many believed that restructuring was inevitable and offered an opportunity to step beyond IRP, which required an expensive, ongoing advocacy effort that, while successful on demand-side policy, did little to promote renewable energy supply. The political negotiations over restructuring in California and other early adopter states led to a menu of environmental provisions that would be debated in many other states, not only those considering restructuring. These policies included continued, though less robust, DSM support, market and state-based incentives for renewable energy, and retail surcharges to fund public benefit programs [74]. Thus, as restructuring went into effect in 19 states in the late 1990s [75], the neoliberal discourse of reducing rates, limiting government interference and letting markets determine resource allocation was driving the policy agenda, yet the political horse-trading that ushered in restructuring also opened the door to new state incentives for niche technologies for renewable energy production.

5.4. Emergent State Climate Leadership and Institutional Heterogeneity (2001–Present)

Just as the neoliberal paradigm was taking shape, California's restructuring experiment turned into a debacle that brought the entire Western region into a protracted energy and economic crisis. Due to a combination of factors including poor market design and gaming of the system by power producers and brokers, by 2001 electricity costs were surging, rolling blackouts were common, and some utilities and heavy electricity using industries were going bankrupt [76]. As an ironic result, California suspended restructuring and state government became more involved in the electricity business than ever before, entering into expensive long-term power agreements to assure supply and shore up utilities. The diffusion of restructuring to other states stalled, and the institutional landscape today remains quite heterogeneous, with some states hewing largely to the original model of state-regulated, vertically integrated monopoly utilities, others using an IRP model, others restructuring along neoliberal lines, and California, the largest and most critical state for establishing institutional policy and precedent, remaining a unique institutional amalgam. This institutional variety and fluidity has created new opportunities for sustainability experimentation. The stark "leave it to the market" discourse has been discredited, yet there has been no rush to public ownership to suggest that a "leave it to the state" paradigm has traction. Instead, a new discourse has emerged situating the state as "leader" catalyzing clean energy entrepreneurship [77,78].

The crux of this new argument is an inversion of the traditional syllogism that electricity use → economic growth → social (and environmental) progress. The new logic is that states that promote clean energy innovations will be positioned to exploit a vast new global market for economic growth; that is, environmental protection and sustainable energy innovation → economic growth → social progress. The discursive shift has destabilized the dominant narrative that an energy transition would be exorbitantly expensive and risky, costing jobs and curtailing economic growth, the core argument

made by politicians of both parties for declining to enact carbon reduction policies that would seriously challenge the entrenched fossil fuel regime.

Recently, however, politicians in a number of states (e.g., California, New York, Massachusetts) have embraced the leadership discourse and invested political, financial and regulatory capital in the proposition that nurturing clean energy can be a responsible and popular platform. As a result, states have adopted hundreds of sustainable energy policies in recent years [79], and leading states are in fact seeing sustainable energy entrepreneurship rapidly expanding [80]. States are also becoming the first polities in the nation to directly regulate greenhouse gases. As of June 2008, 24 states were members and another eight were official observers in one of the three regional climate change accords covering the Northeast, upper Mid-West and Western regions.

Supporting these sub-national developments is a broader transition landscape more conducive to sustainability. The discursive impetus to change rests not only on threats (e.g., of climate change, high energy costs, geopolitical instability), but on opportunities to capitalize on new, "clean tech" markets. While the debate is hardly over, arguments such as that offered by New York Times columnist Thomas Friedman [81] that "Green is the new red, white and blue" are increasingly salient in popular culture and political discourse alike.

5.5. From States to Nation: Critical Federal-Level Issues Going Forward

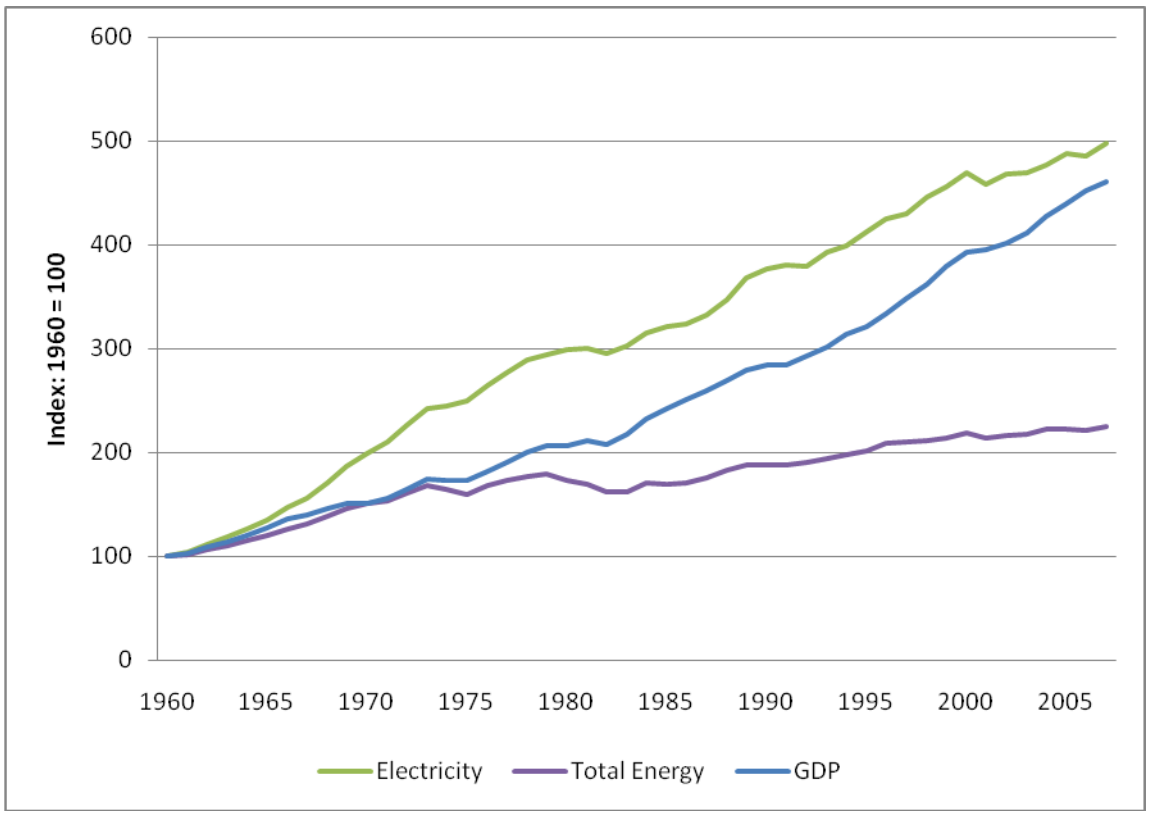
Recent developments suggest that the strategy to push a sustainability transition from the "bottom up", begun in key states in the 1980s, is gaining traction at the federal level, but significant uncertainties remain regarding how strongly policy will support energy system transformation. The Obama administration has made energy innovation a top priority and proposed or initiated several actions modeled on state policy, including binding emissions targets, a carbon cap and trade system, a national renewable portfolio standard and other major energy efficiency and renewables policy innovations. A national GHG emissions cap and trade program is central to the Obama plan for slowing emissions and funding clean energy innovation, but Congressional approval is uncertain. The administration is proposing a federal clean energy R&D budget of $15 billion dollars annually over the coming decade, far more than the total energy R&D budget of under $2 billion and the combined public and private R&D investment of less than 1% of US retail energy sales that has been standard in years past [82]. Congressional bills adopted or debated in 2009, however, dedicate less than 2% of projected carbon permit credit revenues to clean energy R&D, or about one tenth that proposed by the Obama Administration [83].

With most prior energy R&D and other government support going principally to nuclear power and fossil fuels, expectations about the "realm of the possible" have been shaped by an innovation environment tilted sharply against renewables and efficiency. Government RD&D is particularly critical to both basic research and to helping entrepreneurs bridge the "valley of death" between promising ideas and technologies sufficiently developed to attract support from venture capitalists [82]. While major federal program elements remain to be worked out, regulations emerging at the state and regional level, and the expectation of federal action to come, are already impacting the marketplace, encouraging investment in renewables and slowing investment in coal, as discussed below.

6. Capital and Technology

Despite federal policy tilted in favor of entrenched energy regimes, how are the foregoing macro and meso-level developments influencing movement toward a sustainability energy system transition? With respect to reducing energy demand, **Error! Reference source not found.** shows that, as in the period 1973–1983 when GDP grew by one quarter without an increase in total energy consumption (or carbon emissions, not shown), GDP and total energy consumption once again decoupled between 2000 to 2006, with annual GDP growth of 2.4% and energy consumption growth of just 0.1% [6]. Despite strong historical trends towards electrification of the economy, the annual rate of growth in electricity consumption has also declined sharply: from 4.9% from 1960 to 1973, to 2.6% from 1973 to 2000, to just 0.6% from 2000 to 2006. These declines have occurred despite little federal support for efficiency improvements, utilities generally incentivized to sell more rather than less electricity, and many system benefits of efficiency (and distributed renewables) left unaccounted for in market rules and system planning [84]. Significant opportunities thus remain for reducing electricity use and GHG emissions at "no net cost" [13].

Figure 2. Gradual decoupling of GDP and energy and electricity consumption? (data source [6]).



Even prior to the recent recession, uncertain demand growth was impacting supply-side investment. From 2000 to 2006, only a handful of new coal plants opened and coal-fired generation grew just 0.2% annually, while no new nuclear power or large hydropower plants have been ordered and built in over two decades. Natural gas-fired generation grew by over one-third during the period as the move to open generation to competitive pressures has led investors to favor smaller, cheaper, cleaner, and more

distributed and efficient power plants, preferences that have reduced the average size of new power plants from about 1,000 MW (an average coal or small nuclear plant) in the 1970s to just 21 MW in 1998 [85]. Renewables generally share these attributes and US solar and wind industry revenues grew over 30% annually for the past decade, comparable to the personal computer industry during its most expansive periods [86], yet total renewable resources—wood, wind, waste, geothermal, and solar—still accounted for just 2.4% of total US net generation in 2006, growing a moderate but hardly revolutionary 19.5% from 2000 to 2006 [87], although state-level performance continues to vary considerably [88,89]. By contrast, among leading European nations, Denmark has a renewables share of 29.4%, the Netherlands 9.2% and Spain 8.6%, with the latter experiencing a 256% growth rate between 2000 and 2005. From a socio-technical perspective, the key question in the next decade will be whether a sustainable energy actor-network can succeed in further curtailing both demand growth and major new investment in coal and nuclear power, and instead direct resources toward bringing renewables to a point of technology take-off. Below we sketch important developments in supply-side niches that make such developments more probable than previously.

6.1. Status of Conventional Energy Regime

While the coal power industry remains politically and financially potent, adding to the ~600 plants that now supply half of all US electricity has grown increasingly difficult. As recently as June, 2006, 150 new coal-fired plants were proposed, representing an estimated proposed investment of $137 billion and a potential 25% increase in sectoral carbon emissions [90]. In the following two years, however, shifts in the innovation environment undermined these plans: plant construction and fuel costs rose sharply [60]; the US Supreme Court ordered the EPA to treat GHGs as pollutants under the Clean Air Act; Wall Street investment banks began including costs of carbon regulation in plant financing decisions [91]; states, including traditionally coal-friendly Kansas, began denying permits for new coal power plants due to climate change concerns [92]; and diverse coalitions of local communities, farmers, environmentalists, health advocates and others began more aggressively challenging proposed plants in court [93]. As a result, over 100 proposed plants were canceled or blocked [92], though a few plants are moving toward completion [94].

The coal industry has responded discursively and politically by expanding its "clean coal" campaign to highlight carbon capture and storage (CCS) as a solution to its carbon emissions Achilles heel [95]. While the industry and others (e.g., [96]) argue that CCS is essential given the inevitable exploitation of "cheap and plentiful" coal around the world, its feasibility is highly uncertain and will remain so for the 15–20 years proponents estimate will be required to design, finance, build, monitor and prove CCS economically viable. Private capital is unlikely to finance CCS development unless government assumes most financial risk. Though the Department of Energy in 2008 cancelled its ~75% stake in the nearly $2 billion "FutureGen" project to build the first US commercial scale CCS facility due to cost escalation, federal CCS support remains robust under the Clean Coal Power Initiative. It remains to be seen whether the promise of CCS in the future will be sufficient to legitimate new coal plant development in the coming decade [28].

While climate change concerns threaten to undermine the coal energy regime, they are being used to reinvigorate interest in nuclear power. The industry relies on public subsidies for all phases of

operation from uranium mining to waste disposal, and private investors generally require government guarantees that ratepayers or taxpayers will assume the capital risk for new plants, each estimated to cost over $5 billion and require decades to repay [97]. The financial model underpinning both nuclear and coal power is thus increasingly at odds with the move to competitive power generation markets. Nuclear power also remains beset by a uniquely daunting range of problems, including non-competitive costs, radioactive waste disposal and weapons proliferation hazards, reactor safety risks, and a "human capital crisis" impacting both the industry and the Nuclear Regulatory Commission overseeing it [98]. The argument among scholars is not whether these problems remain daunting despite a half century of unprecedented public investment [99], but whether they can be resolved through further additional public spending [see contrasting views in 97,100]. As a response to climate change, however, nuclear power costs 1.4 to over 11 times more per unit of GHG reduction than alternatives like windpower, cogeneration, and end-use efficiency [97]. New plants would also not be operational for at least a decade, during which time multiple innovation cycles in other energy generation and efficiency technologies are apt to change market conditions and assumptions—dynamics similar to those that undermined nuclear power in the 1970s and 1980s. Thus, each of the very large incumbent technologies—coal, nuclear and hydropower—all face significant obstacles to further expansion and thus remain vulnerable to competition from natural gas (especially given recent expansions in proven reserves due to new drilling technology) and renewables.

6.2. Status of Sustainable Energy Options Development

Against the potent actor-network supporting coal and nuclear power expansion, the sustainable energy network is expanding rapidly, bringing new players with new perspectives, influence and resources to the challenge of enrolling more of nature's vast renewable energy flows into the electrical power grid. Large conventional energy firms are investing in renewables and adding political-economic clout to the traditional network of small and medium-sized renewable sector firms. Nuclear power developer General Electric had $4.5 billion in wind division sales in 2007, and the leading US nuclear power utility, Florida Power and Light, is now second in global wind power operations and in 2006 completed the world's largest wind farm, the 735 MW, 421 turbine Horse Hollow Wind Energy Center in Texas. In all, wind power is now price competitive with conventional power resources in many contexts and is growing rapidly. Wind capacity increased 6-fold from 2000 to 2007 and accounted for 30% of all new US power generation capacity in 2007 [101].

New entrants are bringing new resources and different perspectives to risks, rewards and speed of innovation than was characteristic of the historically conservative utility industry. Venture capitalists in 2006 invested $2.9 billion in North American "cleantech" (mainly renewable energy) companies, up 78% from 2005, making cleantech the third largest venture capital category and fastest growing since 2000 [80]. Similarly, Silicon Valley entrepreneurs are moving into renewable energy, epitomized by Google's decision to "invest hundreds of millions of dollars in breakthrough renewable energy projects" and to produce "in years, not decades" one gigawatt of renewable energy capacity that is cheaper than coal and enough to power a city the size of San Francisco [102]. Renewable energy developments in the US are, of course, shaped by the global clean-tech marketplace and international

policy decisions. China, for example, has become increasingly attractive to multinational energy technology companies and now leads the world in wind turbine and photovoltaic cell production [103].

The modularity of many renewable technologies allows scaling projects to fit available opportunities, and announcements of large new projects are becoming routine: the largest US solar photovoltaic (PV) system completed in 2007 at Nellis Air Force Base; a fifty times larger PV project to be built with PG&E backing to help it meet its California mandate of 20% renewables by 2010 [104]; another PG&E-backed project, a 300 MW concentrating solar power facility in California being built by Australian firm Ausra, whose innovative water thermal storage process will allow generation to continue overnight and during cloudy periods, reducing intermittency of generation that is a key limitation of solar and wind power. Ausra claims to produce power competitively in today's market ($0.08 per kilowatt-hour for large facilities) [105].

The potential for truly revolutionary, breakthrough technologies to emerge from this creative ferment is symbolized by Nanosolar, Inc. The company recently opened the world's largest solar cell manufacturing plant in California and claims that its new thin-film PV printing press-like process can achieve 100-fold improvements in production speed, annual output, materials use (*versus* silicon-based PV), and most importantly, cost. While these claims are unproven, they are not dismissed out of hand by leading experts [106], and the firm's dozen financial backers include major venture and investment capital firms, the Skoll Foundation formed by eBay's founding President, Stanford University, OnPoint Technologies, the US Army's private equity fund, and Electricité de France, the world's largest utility and largest owner/operator of nuclear power plants [107]. Intriguingly, Nanosolar's aim is to launch a revolution in power generation through very modestly sized, 2MW–10MW municipal solar power plants built on marginal land around urban areas, feeding directly into the local distribution grid and thereby avoiding both the transmission costs and line losses of large systems and the comparatively high unit costs of small systems. Whether or not these claims materialize, they hint at the potential for radical socio-technical transformation characteristic of high tech sectors. In addition, entrepreneurs are exploring a wide range of alternative technologies beyond solar and wind power.

There is thus strong divergence in the character of the innovation investments being made in conventional and alternative energy technologies. On the one hand, a sustainability pathway predicated on coal or nuclear power would require large public investments in technologies embedded in a relative handful of highly capitalized, massive plants requiring long-term protection from market forces. Both technologies present significant socio-ecological hazards, and their costs, benefits and feasibility will not be discernable for many years. During that time, renewable and energy efficiency innovation can be expected to stimulate numerous competitors to explore a wide range of fundamentally safer, far more varied alternative technologies, the most promising of which are likely to advance comparatively quickly through fast cycles of commercialization and improvement. This is not to suggest that substantial barriers no longer remain to a transition to a far more renewable and efficient electrical energy system—they do, and the incumbent technologies have proven remarkably adept at maintaining a dominant position in the industry for decades. We do suggest, however, that synergies across a range of socio-technical domains appear to be hindering coal, nuclear and large hydropower and simultaneously opening new potential for sustainable technologies to emerge.

7. Conclusion

In this paper, we have presented a long-term analysis of changes in the US electrical power sector and their implications for a sustainability transition. We analyzed four distinct regulatory paradigms animated by different discourses, actor networks, institutions and policy actions, each with different implications for sustainability. The study adds a US energy system analysis to a socio-technical literature focused more often on European experiences, and highlights dynamics at the state-level, a scale of analysis often overlooked in favor of national or urban studies. The paper also examines how change in this large socio-technical system has often been driven by actor-networks using spatially-explicit strategies aimed at creating system-wide change by developing in key states a compelling discourse and set of institutions and policies that then can be diffused "across" to other states and regions and "up" to the national level.

An important, if implicit, component of our analysis has been the question of whether the current wave of interest in a sustainable electricity system differs fundamentally from the alternative energy movement that sprang up in response to the energy crisis of the 1970s, and the implications of any similarity or difference for the potential of a major system change in this generation. Most importantly, we note a tremendous enriching of the actor-network engaged in creating a sustainability transition, including advocacy groups operating at scales from the neighborhood to the national, renewable energy entrepreneurs as well as utilities, conventional energy companies, venture capitalists and high tech companies, media, state governments, research institutions, and increasingly the US national government.

This richer, deeper, and wider actor network in fact grows out of the movement of the 1970s and the successive waves of institutional restructuring of the electricity system in the 1980s and 1990s that have created a heterogeneous institutional landscape that, while complicating system management and integration, has also introduced new possibilities for sustainability. IRP opened electricity system management to a wider range of stakeholders and social and environmental concerns. Neoliberal restructuring, while sometimes disastrous, opened up the electricity market to a wider set of profit-oriented interests, and ironically, helped pave the way for states to become much more involved in regulating carbon emissions and promoting renewable energy, in contrast to how liberalization in the more top-down EU may be narrowing options [7]. The advocacy efforts initiated in the 1970s were critical in highlighting the scope of the long-term energy challenge to which President Carter referred, and in maintaining continuity and policy learning even as declining energy prices in the 1980s drew attention away from renewables and efficiency. Some elements of an innovation environment conducive for a sustainability transition were present in the 1970s, but many others were missing or inadequately developed. The actor-network today appears to be reaching more deeply into the range of social and technical domains that make for socio-technical system change, and the attention of earth science to the problem of climate change has made the environment an important and unavoidable actor. Clearly, these underlying drivers and the richer social network committed to energy system transformation have advanced renewable energy and efficiency technologies to a more mature stage in the transition process. Whether these gains will be consolidated and translated into national policies strongly supportive of a sustainability transition, or be attenuated by the strength of the incumbent regime, remains to be seen.

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