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Article

Getting Smart? Climate Change and the Electric Grid

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Abstract: Interest in the potential of smart grid to transform the way societies generate, distribute, and use electricity has increased dramatically over the past decade. A smarter grid could contribute to both climate change mitigation and adaptation by increasing low-carbon electricity production and enhancing system reliability and resilience. However, climate goals are not necessarily essential for smart grid. Climate change is only one of many considerations motivating innovation in electricity systems, and depending on the path of grid modernization, a future smart grid might do little to reduce, or could even exacerbate, risks associated with climate change. This paper identifies tensions within a shared smart grid vision and illustrates how competing societal priorities are influencing electricity system innovation. Co-existing but divergent priorities among key actors' are mapped across two critical dimensions: centralized *versus* decentralized energy systems and radical *versus* incremental change. Understanding these tensions provides insights on how climate change objectives can be integrated to shape smart grid development. Electricity system change is context-specific and path-dependent, so specific strategies linking smart grid and climate change need to be developed at local, regional, and national levels. And while incremental improvements may bring short term gains, a radical transformation is needed to realize climate objectives.

Keywords: electricity; mitigation; adaptation; smart grid; grid modernization

1. Introduction

Transforming the electricity system is a crucial component of climate mitigation and adaptation [1]. Due to the high reliance on fossil fuels, electricity generation emits 26% of global greenhouse gas emissions and 41% of all carbon dioxide (CO_2) [2]. Although the Intergovernmental Panel on Climate Change (IPCC) suggests that an 80% reduction in greenhouse gas emissions by 2050 is required for stabilization of atmospheric CO_2 [3], electricity generation is projected to grow 70% by 2035 [4–6], and increasing societal reliance on electricity to provide energy services related to health, food, and communication requires more resilient and robust electricity systems. Smart grid (SG) could be a crucial component of adapting the electricity system to a changing climate, as well as mitigating emissions by reducing GHG releases from the existing electric sector and by allowing electricity to assume a greater share of total energy service provision (enhanced electrification). Over the last decade global interest in SG has grown [7–10], and a shared SG vision of a more efficient, reliable, resilient, and lower-carbon electricity system has gained broad appeal. As public policies encouraging and supporting SG have developed [11,12], conflicting motivations and priorities are emerging [13].

The term "smart grid" is used to represent a variety of interlinked social and technological changes to electricity systems, particularly modernizing networks that link electricity producers and consumers through advanced information and communication technologies (ICT) [14]. While the term has been criticized by some as too vague to be meaningful [14], its widespread use across the public and private sectors frames multiple underlying objectives. Recent SG-related research and public discussions tend to focus on specific technologies and their economic potential [15], but the term also encompasses social and technical change as electricity systems are socio-technical systems [16]. The social, behavioral and institutional dynamics accompanying SG technological shifts have received less attention although they are critical for both electric system function and meeting climate objectives [17].

Given the intimate link between climate and energy, a common assumption is that SG will contribute to climate mitigation and adaptation [18]. A U.S. study by the Electric Power Research Institute estimates a smarter grid could directly reduce electric sector emissions by 1.5–4% [19] and, more importantly, allow large-scale integration of variable renewable resources like wind and solar, manage electric demand and enable the electrification of transport [20], which could further decarbonize energy systems. SG offers additional climate mitigation benefits through enhanced monitoring and accounting of electricity generation and use which could result in social changes and improved efficiencies in how individuals and communities manage and relate to electricity. For climate adaptation, continuous system-wide monitoring and local islanding would make SGs more robust in the face of extreme and variable weather events [1]. In addition, SG could support the integration of environmental management of electric system pollutants and water-use into grid management, which could raise local awareness about environmental impacts of electricity production and thereby reduce environmental vulnerability and enhance climate resilience.

Yet it would be possible to roll out a SG infrastructure which did relatively little to address climate risks, or which in the worst case even exacerbated them. If insufficient attention is paid to climate dimensions, SG roll-out could lead to greater consumption of high carbon-emission electricity (if householders and commercial customers adopt novel electric devices, if electrification of transport increased transportation demand, and if efficiency gains are soaked up by the "rebound effect" [21]). SG could also lock-in new vulnerabilities (should the SG infrastructure and related electricity production/consumption patterns diminish system robustness and adaptive capacity in the face of an altered climate). While more extreme weather may directly stress transmission infrastructure (storms, floods, *etc*.), load management will also become more challenging because of potentially fluctuating demand (in cold snaps, heat waves, *etc*.) and production disruptions (for example, to hydro and thermal plants due to water shortages), even as societal dependence on the electricity system is growing. How much a future SG electricity system contributes to climate mitigation and adaptation will depend critically on which actors and public policy priorities shape the emerging system. And if climate change issues are not integrated adequately into SG investments going forward today, societies may find they have to rebuild these not-so-smart-in-retrospect systems in the future at great additional cost in order to address climate change more seriously.

Beyond climate mitigation and adaptation, many other issues motivate SG interest, and SG development is influenced by actors with diverse concerns and priorities. Reducing electricity costs and improving efficiency, increasing electricity access, minimizing electricity theft, and enhancing energy security are among the non-climate related objectives shaping SG development. The breadth of different priorities and potential social changes that can be integrated into the SG vision represents potential for synergistic alignment of interests among climate mitigation, climate adaptation, and other societal objectives, but also highlights the risk of climate priorities being neglected in SG development.

Many factors influence the evolution of electricity systems including their previous historical trajectory, demand growth, technological availability, reliability, cost, convenience, land-use preferences, laws and regulations, and environmental concerns [22]. Embedded within a loosely shared vision of SG are different social and technological architectures which represent both complimentary and oppositional societal priorities and objectives. Different perceptions of SG focus on different objectives that are directly linked to the societal position, priorities, and responsibilities of actors and organizations. Ensuring that climate objectives are incorporated into SG development requires improved understanding of this complexity and the emerging tensions influencing larger climate and energy public policy debates.

Recognizing the potential for SG to contribute to both climate mitigation and climate adaptation, this paper identifies tensions within a shared smart grid vision, illustrates how competing societal priorities influence the pace and orientation of socio-technological innovation, and suggests that effective climate change measures must be integrated synergistically and systematically with other economic, social and environmental objectives. This paper draws from comparative social science research conducted by the co-authors on the politics of SG innovation. Following a brief review of electricity systems, we explore co-existing but divergent SG priorities among key actors' and map them across two critical dimensions: expectations of centralized *versus* decentralized energy systems and radical *versus* incremental change. We conclude with suggestions for ways to integrate climate change objectives into both centralized and decentralized expectations of SG development and

emphasize the need for long-term planning that can lead ultimately to transformative rather than incremental change in electricity systems.

2. Electricity Systems in Society

Over the past century electricity systems in industrialized countries have undergone a complex evolution relevant to current SG innovation. Electricity distribution systems were not designed from "the top-down", but rather developed incrementally, from local systems (typically organized at the municipal level) into large interconnected networks, whose basic units now operate at regional or national scales [23,24]. For most of the twentieth century, the electricity industry was dominated by the pursuit of economies of scale and an active quest to increase electricity penetration. Generation technologies (primarily hydro, coal and nuclear) were deployed in large centralized plants that required substantial capital outlay (millions to hundreds of millions of dollars) with 40–80 years anticipated lifetimes. Power producers actively cultivated industrial, commercial and residential markets (for example, in the 1950s and 1960s encouraging the development of electric-based consumer durables). The result was centralized generation systems adapted to supplying electricity to millions of end users. With the oil crises of the 1970s this expansionary model came under pressure, prompting a turn towards energy efficiency, interest in which has waxed and waned according to circumstances in different jurisdictions.

Electricity systems have for the most part operated under two basic regulatory models: either as public utilities (owned by municipal, state/province, or national governments) or privately owned monopolies with a public regulator (overseeing investment, prices, system reliability, *etc.*). But since the mid-1980s many jurisdictions introduced competition into the sector by privatizing state-owned utilities and splitting generation, transmission and local distribution. The result has been an increasingly complex and fragmented electricity regulatory system with very different business models. Government involvement has meant that electricity supply has always been politicized and investments scrutinized through multiple lenses. Electricity system politics are driven by public sensitivity to price changes and service interruptions, public concern over the choice of generation technologies and environmental impacts, problems of siting generation and transmission facilities, and the propensity to view electricity as critical to regional and national development strategies.

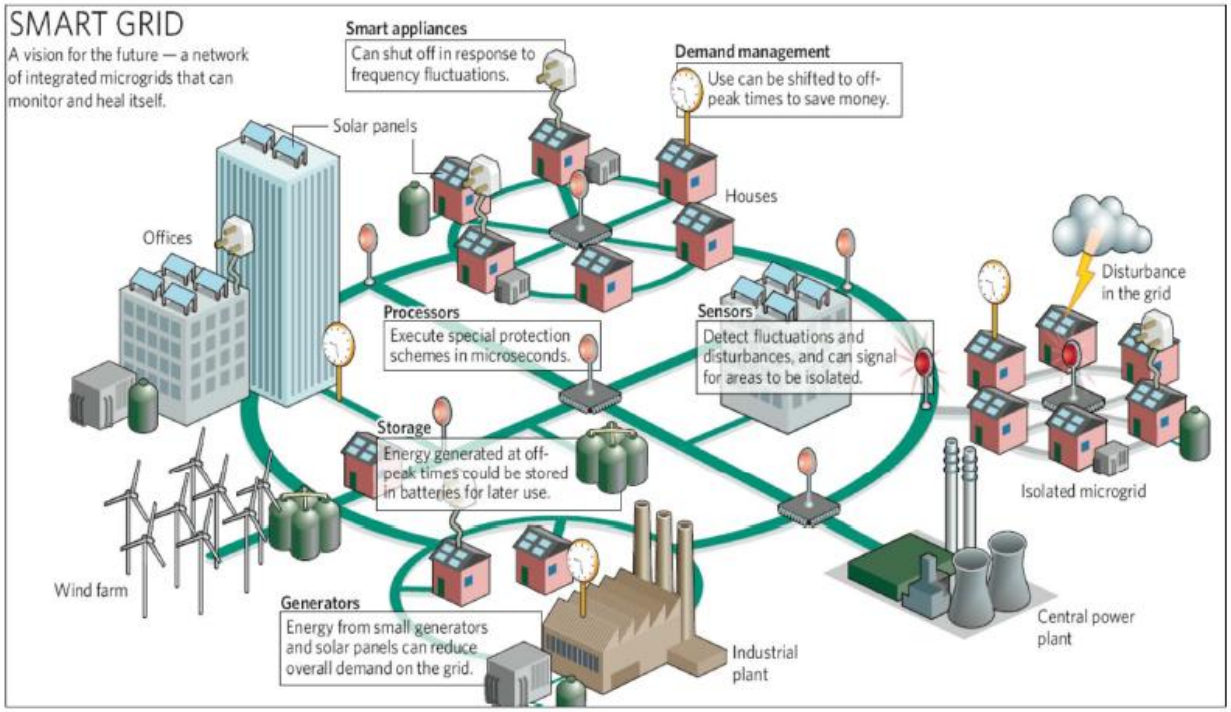
In technological terms, the transmission system has been a relatively stable artifact, characterized by incremental progress (e.g., the development of long-distance transmission in 1960s). But in recent years the pace of innovation has increased as the potential of the ICT revolution to transform the power industry (e.g., through smart meters, increased sensors, two-way communication) has begun to be recognized, and policy pressure to incorporate more variable renewables and demand management into the system has begun to grow [25].

3. Smart Grid as an Inspiring Vision of the Future Electricity System

The currently dominant vision of SG (represented in Figure 1) consists of a network of technologies including ICTs that facilitate system monitoring to optimize efficiency and enable self-repair [26]. The SG vision includes renewable and distributed generation and is often imagined to reduce reliance on fossil fuels, lower pollutant emissions and support renewable generation including wind, solar, and geothermal. The vision includes storage that enables integration of variable renewable sources, with

electricity generated at off-peak hours to be stored for later use, potentially enhancing system-wide efficiency and reducing total generation need because stored electricity can be used during periods of peak-demand. Advanced sensors, which detect fluctuations in power flows and identify system irregularities, are a critical part of the SG vision enabling enhanced management, minimized blackouts, and rapid system recovery. These sensors can facilitate distributed generation with two-way communication on grids, linking local electricity supply and demand response with new demand management tools and smart meters in homes and businesses, and smart household appliances that automatically adjust electricity consumption.

Figure 1. An illustration of an idealized vision of the "smart grid" future reproduced from Nature [27] with permission.



The SG vision has been presented as a progressive, modernistic, future offering a broad array of societal benefits (efficiency, utility, security) across different societal spheres (economic, environmental and social). While building SG will be expensive, the economic benefits include lowering the costs of electricity generation by increasing efficiency, limiting electricity theft, and enhancing management of consumer demand (though some studies show consumers paying more for electricity with SG [28]). US-based cost estimates for building a SG over the next 20 years range from $338 billion to $476 billion, but the associated economic value is estimated at $1.3 to $2 trillion [28]. Other potential economic benefits include an expanded high-tech industry, a growing renewable energy sector, fewer costly power outages, and a higher quality of power. Environmental benefits associated with the SG vision include lower air pollution, reduced water pollution and lower CO_2 emissions resulting from integration of more renewable generation and lower electricity demand. Social benefits of the SG future include the potential for more equitable access to electricity, improved reliability and resilience of electricity services, and enhanced public health. Electricity production adversely affects human health through local air pollution; contrarily, the lack of electricity adversely

affects human health through energy poverty, undercutting basic health care (water, refrigeration, *etc*.), linking multiple direct and indirect welfare gains to the SG vision.

The breadth of societal benefits associated with SG is so encompassing that SG has emerged as an iconic representation of technological optimism [29,30]. SG has been characterized as a technological utopia [31], an energy technology nirvana, and an idealistic set of socio-technical changes that can solve almost all of society's problems. At this point, however, questions regarding who benefits and who bears the costs from smart grid remain unanswered.

4. Tensions and Struggles in Smart Grid Innovation

This inspiring SG vision has been invoked widely, particularly in industrialized countries, to encourage investment and mobilize action for electricity system change. Yet multiple challenges to advancing SG have emerged, across jurisdictions and among key players. Actors involved in SG development have a broad range of divergent interests (see Table 1), with incumbent power producers, local distribution companies, SG equipment manufacturers, different government agencies and regulating bodies, consumer and environmental organizations all pulling in slightly different directions. Tensions among these actors have been evident in the deployment of smart meters, devices located in consumers' residences that allow utilities to control and manage electricity consumption. For many residential consumers, their interface with SG is limited to smart meter rollouts. In some cases, this has been problematic with no obvious direct benefits for consumers [32]. While some countries and localities have witnessed relatively smooth smart meter rollouts (e.g., Italy, the state of Texas in the U.S., and the Canadian province of Ontario), others have experienced challenges (the U.K., the Netherlands, the U.S. state of California, and the Canadian provinces of British Columbia and Quebec). The relative power of key actors to advance their interests and shape SG development varies across jurisdictions. Based on our analysis of the complex emerging SG landscape, we have identified two fundamental tensions that provide a framework to map divergent SG priorities: (1) whether SG should advance a more centralized or a more decentralized electricity system and (2) whether SG should involve incremental or radical change (Figure 2).

Table 1. Priorities, perspectives, and tensions associated with key actors involved in creating a smarter grid.

Key Actors	Priorities and Perspectives	Smart Grid Concerns and Tensions
Consumers Industrial, commercial and residential. Each have different energy use patterns and different abilities to use SG capabilities	Desire access to low-cost, reliable electricity. Some demand electricity with lower environmental impacts. Difficult for non-experts to shape SG design, but their behavior is crucial for system operation.	Consumers have raised concerns about the fairness of cost allocation. Some areas have seen electricity price increases and errors in billing after SG investments. A small but vocal group is concerned about health issues.

Table 1. *Cont.*

Key Actors	Priorities and Perspectives	Smart Grid Concerns and Tensions
	Customer classes differ in their abilities to capture SG benefits. While large energy using industrial customers may respond to economic incentives and pricing policies (e.g.,time of use rates), it may be harder for residential customers to react. Such policies have different levels of acceptance across customer classes and remain politically unpopular in many jurisdictions.	As SG collects more information on electricity use, tensions between information ownership and privacy concerns have come to the forefront. SG data could potentially give suppliers vast knowledge of consumer habits and, if not restricted, could be sold to third parties.
Companies Incumbent and new entrants to the electricity field span multiple sectors (including ICT) and disparate interests.	Electricity companies must make a reasonable rate of return to survive and are obliged to follow laws and regulations. Incumbents have legacy infrastructure and investments and SG could allow them to better optimize their evolving systems and market share. SG may provide new entrants with new business opportunities in, for example, distributed generation technologies or demand management.	SG presents new opportunities to create more efficient, reliable and resilient power systems, and to improve management of the system, but simultaneously creates new risks and uncertainties which challenge existing business models. Incumbents face concerns on recovery of SG investments and potential problems with customer acceptance. To seize the new opportunities created by SG, new entrants may require shifts in laws and regulations governing the electricity system, but may not have the necessary political capital.
Government National, regional, state/provincial, and local, jurisdictionally complex and varied in responsibilities	Different levels of government create policies to promote SG and also have the responsibility to uphold and enforce laws and mandates affecting SG. This includes consumer and environmental protection, economic development, health and safety, and tax collection. Utility regulators have a mandate to ensure low-cost service and reliability and to advance government policy priorities. May have difficulty approving SG investments by utilities.	Political risks and opportunities in promoting and approving new technologies exist which could simultaneously allow for new economic development or could raise electricity prices. Larger policy interest in SG stems from increasing system reliability and efficiency, and in some quarters integrating low-carbon electricity.

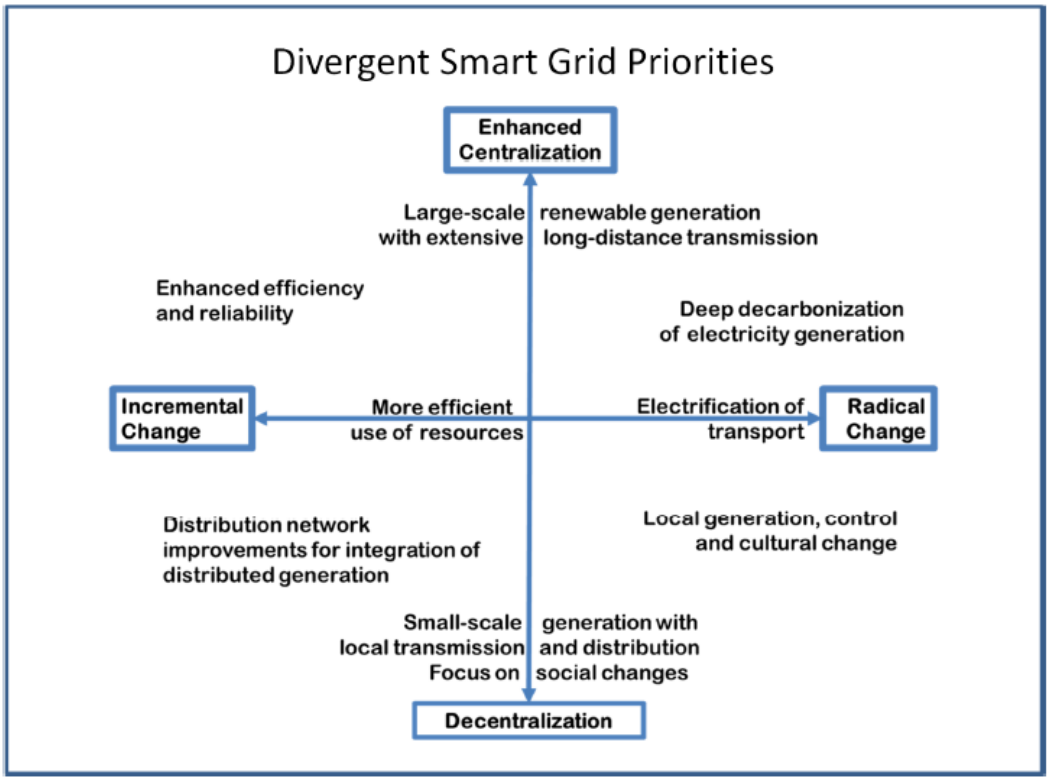
Table 1. *Cont.*

Key Actors	Priorities and Perspectives	Smart Grid Concerns and Tensions
	Municipally owned utilities either producing and/or purchasing power have taken many different positions on SG, with some promoting it heavily and others showing less enthusiasm. Natural resource and environment departments interested in climate, air quality and water-use may experience tensions between mandates to protect local landscapes and efforts to develop large-scale renewable energy projects or transmission lines. Those involved in planning and managing the bulk power system could see SG investments in transmission grid technologies as ways to improve electricity market function, management of power flows and system reliability.	Some municipal utilities believe that SG offers advantages in promoting integrated distributed generation like solar, while others worry about disadvantages in raising costs and risk of investing in technologies which will become rapidly obsolete. For those involved in the bulk power market, SG technologies like synchrophasors could allow for more data and better system monitoring and control, market rules will determine how renewables, demand response, and storage, are used and priced. Minimal direct interaction with consumers, so generally less directly affected by public acceptance issues.
Civil Society Consumer advocacy organizations, environmental organizations	Civil society actors engage at different levels across the electricity system intervening in multiple venues at many levels of government to advance a broad range of goals (environmental, consumer protection, health, etc). Consumer advocacy organizations push for access to electricity and low electric rates for all classes of customer. Environmental organizations often promote low-carbon electricity systems, local energy systems, and environmental conservation, yet with SG some of these could be at odds with one another.	Consumer focused organizations are often concerned that utility investments in SG might raise electric rates and that SG benefits will not help consumers. Environmental organizations are often SG advocates to increase penetration of renewables, distributed generation, and lower carbon electricity sources. Tension between advocates promoting large-scale centralized renewables (with transmission) and environmentalists focused on land conservation and local community electric systems.
Energy System Researchers Government laboratories and academic researchers, think tanks	Often motivated by new technology development, deployment, evaluation and modeling, as well as accompanying policies. May be directly/indirectly supported by industry or government May publish papers, reports, or policy briefs shaping expectations about the opportunities and challenges.	Generally technologically optimistic. SG researchers have generally focused on engineering and economic perspectives, and the large societal potential of SG to enhance and improve the electric system, *i.e.* lots of studies on electric vehicles or future emissions scenarios.

4.1. Centralization versus Decentralization

One of the tensions embedded within the SG vision is whether to enhance centralization through larger interconnected electricity systems by expanding long-distance transmission and supporting distant large-scale electricity generation far from demand centers, or rather to support decentralization by encouraging distributed and local electricity generation coupled with community control. An increasingly centralized electricity system using efficient long-distance transmission lines to move power from sites hundreds of kilometers away may enable large-scale renewable generation in specific areas and will empower those private sector actors that manage and maintain the systems. For example the proposed (and now deserted) DesertTec project anticipated powering much of Europe with electricity generated from concentrated solar power in North Africa. Some North American proposals envision an extensive high-voltage transmission grid to move large-scale inexpensive Midwestern U.S. wind to the more populated coasts. Such systems could benefit some incumbent energy sector actors, though regional differences and context-specific factors would determine which local actors gain or lose.

Figure 2. Actors' vision of the potential of Smart Grid can be characterized by perceptions of the possibility and need for radical *versus* incremental change and perceptions of a future with enhanced centralization or decentralization.



An increasingly decentralized electricity system is a priority for other actors who support more local generation and community control to encourage electricity production and economic development close to demand centers [33,34]. The Danish Energy Association, for example, integrates SG into its goals for national energy independence, replacement of fossil fuels, and integration of massive amounts of renewable energy, often generated and distributed at residential- or municipal-levels [35,36].

Decentralization, including micro-grids and local renewable production like rooftop solar is heralded as providing customer and community empowerment and potentially lessening centralized corporate control of electricity systems.

Investment focused on re-orienting the grid toward either of these endpoints reduces the likelihood of achieving the other: if investments are made in local electricity generation, the demand for long-distance transmission lines and centralized generation will be reduced. On the other hand, major investment in long-distance transmission lines and concentrated electricity generation at sites far from demand centers could reduce the need for distributed local generation. Decentralization collides with existing patterns of ownership and control, and given the power and expertise embedded in established institutions that rely on a centralized system [24], a widespread shift to decentralization may be difficult to secure [34,37]. The current controversy in Boulder, Colorado highlights this tension: Xcel Energy, the large utility that serves Boulder initiated a SG demonstration project in response to community demands, but cost overruns and the utility's inability to provide low-carbon sourced electricity frustrated residents, and the city is currently attempting to municipalize electricity services.

From a climate change perspective, various combinations of centralization and decentralization could contribute to deep GHG emission reductions for climate mitigation and/or to enhanced resilience for climate adaptation. In some places, decentralization could empower communities to move to a lower-carbon and/or less vulnerable local system, while other regions may embrace large-scale movement of low carbon energy distributed through a more centralized system. But, of course, actors have reasons for favoring centralization or decentralization besides concern with climate change. The heterogeneity in the geographic scale and scope of electricity system development means that actors typically approach SG priorities based on what appears optimal from a narrow jurisdictional context, with few considering the implications for larger or smaller physical/administrative scales. Government roles in the electricity sector vary across countries and also shape smart grid advances.

4.2. Incremental versus Radical Change

Beyond the centralization *versus* decentralization tension, a second major fissure relates to the extent to which SG implies incremental improvements to the existing system or dramatic system transformation. Is SG about a gradual process of modernization to optimize current ways of providing electricity, or does it imply a more radical shake-up that includes novel technologies, new operating procedures, and establishment of new norms, expectations, and business models? For many actors, SG offers an idealized long term vision, but in *practical operational* terms it comes down to a steady "smartening" of existing power systems, involving recurring investment and infrastructure upgrades as particular technologies mature and their deployment makes sense within the logic of existing institutional, market and regulatory frameworks. Other actors—especially those interested in climate goals—emphasize the disruptive potential of SG technologies dramatically to transform the way we make and use electricity, achieving a step-change to address multiple energy-related problems.

Unsurprisingly, established electricity system actors (especially utilities and associated regulators) may define SG in terms of incremental rather than radical change. These actors tend to be suspicious of grandiose schemes with uncertain risks and benefits and are often wary of upsetting customers with increased bills. Incumbents also have the most at risk from rapid innovation associated with the entry

of new actors into the electricity system. Moreover, electricity system engineers focused on maintaining day-to-day operations are cautious about innovations that might compromise system reliability. Environmental and climate advocates and energy researchers, on the other hand, often focus on long-term issues and tend to emphasize the potential for radical change, sometimes seemingly oblivious to the social and institutional obstacles to technological change. For example, although the development of off-shore wind in Nantucket Sound seemed like a climate-friendly way to provide carbon-free electricity to eastern Massachusetts, the scale of the long, expensive, and jurisdictionally complex controversy that has slowed down the Cape Wind project was not widely anticipated within energy and climate communities. These tensions are typical of socio-technical transitions where change is resisted by multiple actors for an array of reasons.

Just as both centralization and decentralization could contribute to climate mitigation or climate adaptation in different places, both radical and incremental change could support climate goals across different contexts.

5. Linking Climate Change to a Smarter Grid

So how is it possible to negotiate these tensions and ensure that SG development enables climate change mitigation and adaptation? While climate objectives can be integrated into both centralized and decentralized systems, climate goals cannot ultimately be achieved without radical changes in the ways electric power is produced and consumed. Given the scale of the climate problem, social as well as technical changes in energy systems will be required. When considering such transformative change a fundamental challenge is the extent to which incremental improvement and broader system transformation can be reconciled. While incremental adjustments can bring immediate gains, and contribute to broader patterns of system change, in certain circumstances they can also defer more radical innovation, and even enhance lock-in to a sub-optimal development trajectory. In large, complex, and interconnected systems like the electric power sector, poorly conceived incremental changes can work against long term goals. For SG to be effectively linked to climate change objectives, short term implementation priorities must be established with a clear eye on the long term and more fundamental goal of transforming electricity systems to a low carbon-emission configuration.

Specific strategies to ensure climate priorities are integrated into SG deployment must be tailored to fit region-specific contexts. Coal-heavy systems like the U.S. Midwest, Poland, or the Canadian province of Alberta present different challenges and opportunities for SG than hydro-dominated systems like Norway, the Canadian province of Quebec, or the U.S. Pacific Northwest. Restructured electricity markets, traditionally regulated systems and government-owned power companies, present different business opportunities and logics. And local or national political constraints may favor particular sets of SG configurations. The context of electricity system innovation is thus critically important; leverage points which could link SG and climate in one set of circumstances could have the opposite effect in another and unintentionally subvert climate objectives.

Still, common leverage points across diverse contexts can be identified. First, all SG investments should be *assessed* for potential contributions to climate change mitigation and adaptation in the short and long term. This accounting for the climate implications of electricity system investments could be a government requirement integrated into financing and regulation to guide a long term trajectory of

SG roll-out that places value on both climate mitigation and adaptation. High discount rates favor near-term benefits, and additional evaluation to assess longer term impacts is warranted.

Second, SG initiatives that contribute to energy efficiency and electricity conservation should be a priority, as controlling demand is often the cheapest and most effective way to reduce emissions and costs. But managing demand is not just about novel technology, but also about the interactions between technology and electricity consumers, so appreciating the needs and concerns of end-users and integrating them into decisions about SG deployment is essential.

Third, SG initiatives that facilitate the incorporation of low-carbon generation should be encouraged. Given the climate mitigation priority of reducing fossil-fuel dependence, SG investments that contribute to displacing reliance on carbon emitting electricity generation are critically important.

Fourth, SG measures that support the emergence of local microgrids and enhance local and community-based energy systems are generally positive. Bringing generation close to the point of use reduces transmission losses, and allows the development of integrated energy solutions (multiple fuels, heat and power, and so on) in buildings, and local communities. Localization also allows for more modular and, therefore, more adaptable systems.

Fifth, particular attention should be paid to ways in which SG can enhance system flexibility and redundancy. Climate uncertainty, and the unpredictability of future energy needs point to the importance of adaptive management approaches (that can make rapid adjustments in response to fuel price changes, resource shortages, or technical disruptions)—and SG innovations can be helpful here.

Sixth, SG initiatives that promote further societal electrification also have potential. Electrification of transport (even if fossil fuels initially remain part of the generation mix) is beneficial: it increases end-use efficiency, opens the possibility for carbon reduction strategies at large generation facilities (for example, CCS on power plants), and increases pressure on the remaining petroleum based transport sector to further reduce vehicle emissions.

Seventh is the issue of maintaining public trust and support, and here a critical factor is the appropriate distribution of costs and benefits. SG proponents need to make a clear case for the specific economic, social and environmental benefits particular investments will secure. They should avoid cycles of hype and disappointment, and shun schemes which allow particular interests to monopolize gains, while socializing the SG costs.

Finally, the regulatory focus on developing electricity markets (as pursued by many North American jurisdictions and by the European Commission over the past decade and a half) must be tempered by the need for greater coordination and longer term planning than private actors typically provide. The regulatory and planning focus needs to include visions out to at least 2050. The private sector and short-term political cycles alone are incapable of integrating this time-frame into their strategic decisions. So restructuring the regulatory framework of electricity systems to coordinate more actors over a longer time frame will be critical to integrating climate priorities in SG innovation.

6. Discussion and Conclusions

Despite their centrality to human well-being, electricity systems are invisible to most, noticed only during power outages which disrupt access. Development of SG offers the potential of transformative socio-technical change in electricity systems. Yet this critical restructuring is going largely unnoticed; opportunities for a larger public debate are being squandered, and developments are for the most part being orchestrated by incumbent interests who are making incremental adjustments to maximize current economic returns.

The complexity of SG illustrates both the challenges and opportunities of integrating climate change priorities into broader societal goals. The SG story highlights how those advocating for climate policy should connect their priorities with other societal objectives. As climate priorities are not part of the dominant decision making logic of many electric system actors, they must be explicitly woven into initiatives and policies that are simultaneously advancing other economic, social and environmental objectives. The vague inclusiveness of the SG term appeals to a diversity of supporters, but also obscures divergent actors' values and system endpoints. General SG debates often omit the critical details of how future electricity systems will develop; yet these details remain essential if SG is to help societies confront and adapt to climate change.

Within the SG space, the diversity of actors' interests and perspectives creates tensions that are difficult to reconcile. Some traditional allies are finding themselves at odds with each other. For example, in the U.S. national-level environmental groups like the Sierra Club are more focused on the need for large amounts of low-carbon electric power than their local chapters who concentrate on local priorities including habitat protection. Large wind, solar, or transmission projects which alter landscapes also put environmental organizations at odds with one another [38].

SG offers multiple potential benefits, yet effective capturing of the climate benefits will be context-specific and dependent on particular socio-political energy system landscapes. There will be no "one-size-fits all": the optimization of SG configurations to maximize climate objectives will differ greatly across regions. In this context it is worth emphasizing the role social science can play in helping to understand the interests, institutions and ideas that are currently shaping societal practices around SG. Over the past two decades an impressive body of scholarship has been built up on socio-economic paradigm shifts [25,39], innovation systems [40–42], and large scale socio technical transitions [43–46]. We know much more than we did about how to promote the integration of economic, social and environmental goals, and build coalitions to promote movement towards more sustainable and climate friendly social practices.

Until climate goals are explicitly embedded within formal electricity system decision-making structures, SG development may perpetuate growing greenhouse gas emissions by strengthening the dominant growth paradigm of sustained increasing electricity generation and use. Getting smart about linking electricity system change and climate change objectives is an urgent societal priority.

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Conflicts of Interests

The authors declare no conflicts of interests.

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