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Accelerating the Global Transformation to 21st Century Power Systems

Nations and regions need to share lessons about the best ways to create enabling policies, regulations, and markets that get the most social benefit out of power systems and incent the necessary investments.

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I. Introduction

Power systems around the world have begun a process of profound transformation, driven by the emergence of, *inter alia*, new technologies and the growing concerns for local and global environmental stewardship. This transformation will require trillions of dollars of investment (as detailed in Section II) and reshape the global landscape of opportunities and risks [1]. This article reflects on the challenges and opportunities ahead, and describes a framework for accelerating the transition to 21st century power systems.[1] The 21st Century Power Partnership, a year-old network for catalyzing action in this area among the world's major economies, aims to help facilitate the process of transformation.

Over the course of the 20th century, power delivery expanded from small and isolated grids developed to supply particular loads, to national and

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international power systems playing a vital role in supporting an ever-growing range of services [2]. In the process, power systems evolved into an elaborate socio-technical system, supported by complex ecosystems of technologies, private and public stakeholders, and financial, regulatory, and cultural regimes [3,4]. The socio-technical systems that comprise the electricity industry often evolve at a slower pace than other industrial sectors such as information technology or biotechnology.

Financial practices and business models in the power sector tend to emphasize least-cost, lowest-risk investments, often at the expense of innovation in technology. Deregulated markets (often more appropriately termed re-regulated) also face substantial challenges in encouraging investment in innovation as well as in energy efficiency measures. In both regulated and deregulated industries, structures are needed that encourage innovation and cost-effective investment in clean energy, end-use efficiency and resilient grids. In nations that are in the process of industrialization, where legacy assets are less of a barrier to system evolution, investment decisions must address a host of competing priorities for electricity generation. Governments face significant pressure to make fast, low-risk, and low-cost[2] investments that can quickly meet the rising demand for economic growth and expanded access to energy services, which can result in choices that give lower priority to environmental impacts or fuel-price volatility.

Despite these contextual differences, there is growing agreement by a diverse set of stakeholders on the need for accelerated power system transformation, including on many of the factors that influence the pace of transition or choice of pathways. These include: the state of existing infrastructure, demand growth profiles, availability and type of domestic energy sources, the state of capital markets, the type of regulatory and market structures, environmental impacts of current systems, and quality of supply. These elements often implicitly recognize the growing importance of social objectives beyond those that have historically driven the development of the sector. Most obviously, the health effects of air pollution, the emphasis on sustainable growth, and the threat of a changing climate are putting constraints on fossil fuel use and encouraging deployment of renewable energy sources. In response to these new social objectives, the adoption of novel technological systems have begun to disrupt the traditional model of electricity generation and distribution [5–7]. Integration of multiple sources of distributed generation will require better system planning, and tailored business models, which is particularly critical in developing economies where demand is growing rapidly. These forces present an opportunity for productive multilateral and public–private collaboration on aspects of power sector policies.

Despite contextual differences, there is growing agreement by a diverse set of stakeholders on the need for accelerated power system transformation.

The pathways to power system transformation, or even the ultimate characteristics of future power systems and markets,[3] still need further clarity. Both the theoretical and technology frameworks continue to evolve, and often faster than the regulatory structures. This article aims to provide a framework to advance new modes of international cooperation, thinking, collaborating, planning, and governing related to power system transformation. Section II paints a picture of what 21st century power systems might look like, and how they might operate. Section III discusses the scale of global power system transformation underway, as well as the diversity of starting points and approaches around the world. Section IV highlights specific actions that governments can take to accelerate the transformation of the power system, citing examples of

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progress in renewable energy (RE) integration, energy efficiency (EE), and Smart Grids. Section V describes the 21st Century Power Partnership, a multilateral initiative organized under the auspices of the Clean Energy Ministerial. Section VI concludes.

II. Future Power Systems

While no single system configuration meets all the needs of all energy services demands, the following general trends and characteristics provide a sketch of power systems of the future:

- The pace of innovation is accelerating in electricity supply, delivery, control, storage, and the efficiency of end-use devices.
- Renewable energy costs have come down quickly, and variable supply is becoming a larger share of total generation.
- Distributed generation is gaining traction, partly motivated by the fact that it can contribute to power system resilience in the face of increasingly frequent extreme weather events.
- ''Deep'' end-use efficiency opportunities across residential, commercial, agricultural, and industrial sectors are delaying the need for continued investments in new, large-scale, baseload generation, while simultaneously creating new business opportunities.
- Electricity demand has leveled off in many industrialized nations, threatening utility business models, while emerging economies are seeing dramatic growth in demand from citizens who want reliable and affordable electricity.
- Grid operators are gaining the ability to control demand *via* ''demand response,'' making it easier to integrate variable generation through active approaches.
- Advances in information technology are resulting in new abilities for sensing, communicating, and controlling the power system, as well as vast increases in the ability to utilize and manage large volumes of data [64].
- New roles and tools have emerged for power system optimizers at every scale – from the building to the city to national and international systems.
- The possibility of increased electrification of the transportation sector will pose new challenges, and opportunities, for the power system.

The system boundary we consider must be much wider than the power sector itself, and include links to key related issues.

These trends have been extensively studied and described in academic journals, government cabinets, and corporate boardrooms. The evidence of their importance can be found in law books and the business models of hundreds of start-up companies, utilities, and major firms around the world. These converging trends promise to deliver substantial value to societies and economies, including:

- Rapid expansion of clean, affordable energy,
- Efficient use of resources, including fuel and water,
- Dramatic de-carbonization of power systems in industrialized countries,
- Improved health due to reductions in particulate pollution from the power sector,
- More empowered consumers,
- Reduced geopolitical tension from competition for conventional energy commodities,
- Greater resilience in the face of power system outages and extreme weather events, and
- Expanding opportunities for innovation and value creation in the power sector.

Still, the system boundary we consider must be much wider than the power sector itself, and include links to key related issues. As an example, the pollution-related burden of disease is epidemic in industrializing countries [8]. Energy-related economic vulnerability and political tension are persistent features of international relations [9,10]. Water-intensive energy generation competes with agriculture and direct

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consumption [11,12]. More than a billion people still lack access to electricity, and the global climate shift that threatens to impact peace and prosperity within our children's lifetimes. In addition, there are new challenges becoming central to power system transformation and the wider economy such as cyber security.

Although different systems will vary widely in their evolutionary pathways and final configurations, some common factors are already evident. Across all settings, the technological, political, financial, and social dimensions of energy are deeply intertwined (see the concept of energy systems integration as defined in [13]). For example, increasing shares of variable renewable energy will increase the need for system flexibility, which in turn will demand enabling regulatory, financing, and market structures. Distributed power generation and storage technologies will likewise create the need for new grid architectures, business models, and regulatory decision-making approaches. Smart Grid technologies and demand response programs allow for greater effective load balancing and overall system intelligence, but require dramatically different incentives and regulatory treatment in order to promote investment and ensure reliable performance. Greater efficiency of energy production and delivery is needed to reduce stress on water resources, and new technologies are needed.

In some of today's power systems, paradigms for matching demand and supply are changing from ''always meeting demand'' to more dynamic and interactive strategies. Demand reduction through energy management systems and increased end-use efficiency is often the most effective way to free needed supply. However, many energy efficiency opportunities currently go untapped, particularly those requiring systematic, coordinated action by multiple stakeholders and at various scales [13–15]. This market failure is caused or exacerbated by regulatory models that tie revenues directly to the level of energy sales, creating disincentives for utilities to invest in energy efficiency. Furthermore, energy efficiency measures are often legislated and implemented in isolation from supply and grid concerns. Addressing these areas comprehensively and simultaneously presents opportunities for unrealized synergies, as well as new challenges for planning, regulation, and market design.

The complexity of power system transformation requires agile decision-making and governance structures.

The complexity of power system transformation requires agile decision-making and governance structures, augmented by platforms for multilateral and public–private collaboration operating from local to global scales. The collaborative architecture of this new era should be driven not just by the idealized systems of the future, but also by a clear, rigorous analysis of the scale and diversity of the challenge. With that in mind, the next section explores the contours of power system transformation in more detail.

III. The Scale and Diversity of Power System Transformation

Globally, population growth, economic growth, and the need for dramatically improved access to energy services will help drive investments in 21st century power systems. The potential business opportunities, return on investment, and societal benefits are enormous [65]. This section provides a brief overview of the scale of this transformation, and then turns to a discussion of the diversity of contexts that will shape investment and policy pathways.

A. The scale of the transformation

The divergence between demand growth in non-OECD and OECD countries has major implications for future electricity

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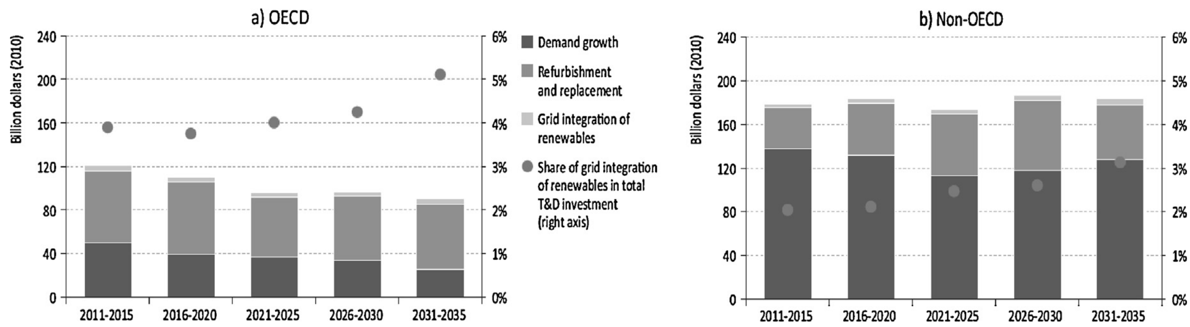

Figure 1: Annual T&D Investment [17]

industry development. The nature of the generation portfolio is changing from a heavy reliance on coal, nuclear, and natural gas to reliance on more renewable energy deployment. In 2011, global investment in renewable energy exceeded one-quarter of a trillion U.S. dollars, and renewables comprised more than one-third of all new capacity additions [16]. Over the next two decades, if announced policy commitments are met, half of all capacity additions will draw on renewable energy sources [17].

Investment requirements in the electric power sector are enormous and growing. In the IEA's ''New Policies Scenario'' (2011b), cumulative global investment in the power sector is forecast to be U.S.$16.9 trillion (2010 dollars) through 2035, or an average of U.S.$675 billion per year. New generating capacity accounts for 58 percent of the total investment, with transmission and distribution (T&D) making up the remaining 42 percent. The bulk of global T&D investment will take place in non-OECD countries, where the focus will be on meeting demand growth. The T&D investment landscape in OECD countries will be dominated by grid refurbishment, replacement, and modernization (**Figure 1**).

Power sector investments will have dramatic and lasting impact on social and environmental welfare through much of the 21st century. As large as these investment amounts are, however, similar or larger investments will occur in equipment and appliances, industrial uses, and buildings. Attention to appropriate end use is therefore critical [18]. Improved and integrated planning processes and market designs are needed to guide these trillion-dollar investments toward greater sustainability while ensuring affordability, reliability, and resiliency [19]. These trends increasingly encourage distributed generation, increased end-use efficiency, and third-party competition with conventional power systems. Government regulatory policy must be adjusted to support viable business models that recoup these types of investments, or the investments will not be made.

B. Diverse pathways to power system transformation

Future power systems will evolve from many thousands of local starting points, defined by the state of grid modernization, the value of potential stranded assets, the abundance or scarcity of domestic conventional and renewable resources, the political economy of national and sub-national power sectors, access to capital, and the pace of economic growth. Recognizing the heterogeneity of starting points can illuminate the modes of collaboration that will accelerate the transition. The bulk of power-system investment is expected to take place in industrializing (non-OECD) economies in sub-Saharan Africa, Asia, and Latin America. In many countries in sub-Saharan Africa, and in individual states of India, much of the electricity infrastructure of 2050 or even 2030 has yet to be built [10]. But how those investments are directed will depend heavily on each nation's distinct context.

Power systems are rooted within their own historical, geographical, technical, political, and social circumstances, and

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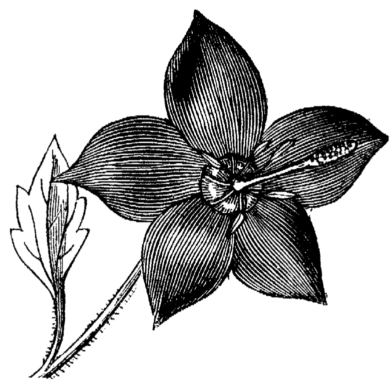
motivations for change. For many, the transformation could be driven by emerging local environmental and resource concerns, while for others it could be a security imperative, or a matter of economic and social development.[4] Still others may be motivated by the potential to create business value and individual wealth, whether by expanding access to electricity for those who do not have it or by increasing reliability of supply for those who do. Moreover, the motivations for transforming power systems often reflect concerns beyond solely the provision of energy services, such as water conservation and food production. The diversity of motivations and current system configuration is nowhere more critical than across emerging and developing countries. In these settings, acute planning challenges confront policymakers and regulators, as the interplay between new supply, grid extension, energy access, and energy efficiency adds complexity to the analysis of optimal power system investment pathways.

These are many examples of systemic shifts that are challenging legacy decision-making frameworks. However, while each nation (and many sub-national regions) starts from its own context, power system modernization raises common global technical and sociopolitical questions [40]. As power systems planners and investors around the globe strive to keep up with new technologies, business models, and infrastructure deployment, important lessons can be shared.

IV. Realizing a 21st Century Power System

Beyond physical infrastructure deployment and technological innovation, a handful of best practices can help accelerate



power system modernization. This section will provide initial suggestions for knowledge sharing, improved analysis and planning methods, and suggestions for power system management and governance.

A. Accelerated knowledge exchange

The following sub-sections offer some specific lessons from around the world, and identify important realms for enhanced knowledge exchange within and across national borders.

1. Energy efficiency

Despite the economic, energy security, and environmental benefits of energy efficiency, realization of its full potential has been impeded by market barriers, uncoordinated decision making, and lack of access to information. Innovative policies can help overcome these issues and put efficiency on a path to fast expansion in both industrializing and industrialized nations, such as:

- Japan's Top Runner program for appliances is an example of a self-tightening standard, whereby the most energy-efficient product in a given category becomes the baseline standard. This drives companies to compete on efficiency, as well as features and cost.
- California's Title 24 building code is also a self-tightening standard, making best available technology the minimum code on a seven year cycle.
- China's Utility-Based Energy Efficiency Finance Program "provides marketing, engineering, project development, and financing services to commercial, industrial, and multi-household residential sector energy users to support the implementation of EE projects" [20].
- Several regions within the United States are experimenting with how to allow demand reductions via energy efficiency or aggregated demand response to bid into power markets.
- In several jurisdictions, such as Australia and Italy, new market mechanisms (e.g. "white certificates") offer utilities and other market makers the impetus

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to participate directly in energy efficiency improvements for their customers.

These policies offer useful ''entry points'' for power sector reform, but new ideas and experiments are still needed to uncover the best way to deploy energy efficiency at scale, and to integrate demand response into modern power grid operations. Demand-side options are already critical system resources, and their importance is growing. For decades, electric water heaters in France have responded to price signals from the network operator [21]. Today, in U.S. power markets, more than 38 GW of demand-side resources are available to provide services to system operators [22]. Opportunities for innovation will grow as buildings become smarter (e.g. through increased use of energy management systems), new load types are added to the grid (especially electric vehicles), third-party providers of demand-response (''aggregators'') emerge, and the Smart Grid delivers better information and control of energy use. Taking advantage of demand-side resources to achieve their full potential as part of a system solution, however, will require energy efficiency and demand response to be better integrated into electricity industry decision-making and resource planning. Regulatory policies that encourage investment while reducing demand for electricity (e.g. decoupling) are likely important elements of the enabling environment. Comparing approaches from across multiple jurisdictions, regulatory structures and operating environments are important areas for international collaboration.

2. *Integration of renewable energy*

Integrating higher shares of renewable energy delivers

multiple benefits at the local and national scale, including reduced exposure to fuel price volatility, decreased dependence on fuel imports, and cleaner air. Some renewable energy technology prices are coming down faster than had been projected, and the declining prices are helping accelerate the deployment of renewables. Yet adoption of significant shares of variable renewable energy will require dramatically different modes of grid planning and operation. Case studies conducted by Cochran et al. [23] point to regulatory approaches for effective renewable energy integration, including:

- Engaging the public early, particularly for new transmission.
- Coordinating and integrating planning across supply and demand resources, and across centralized and distributed resources.
- Developing market rules that encourage system flexibility.
- Expanding access to diverse resources via expanded balancing areas.

Applying these best practices, several important new policies are being tested around the world:

- Various renewable energy-related Directives from the European Commission have enabled progress on issues ranging from priority dispatch to market power and asset ownership.
- Market design enhancements in the Australian National Electricity Market have facilitated wind penetration, for example a new category of semi-scheduled generation, supported through measures including centralized wind forecasting for each wind farm and market region [24].
- A weather forecasting and demand prediction system has been deployed by network operators in China, generating U.S.$60 million of additional annual energy sales from increased use of power from wind and solar sources. Using sensing technologies and mathematical algorithms, analytics software predicts the wind and solar conditions on an intra-hour basis and the subsequent power

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generation from the plant to balance this against the demand stack of the network.

Developing next-generation power systems will mean moving beyond specific renewable support policies and toward more general market-based solutions. Electricity market rules play an increasingly central role in delivering sufficiently attractive returns for investors and may need to be reformed as the sector moves to technologies with higher capital costs and lower operating costs.[5] As grids around the world integrate new levels of variable renewables, emerging demands, such as vehicle electrification, new best practices and exemplary policies will need to be identified.

3. *Smart Grids*

The technical advances in electrical grid architecture that fall under the general umbrella of ''Smart Grids'' enable flexible and intelligent operation of power systems in support of reliability, energy efficiency, and integration of variable renewable energy resources. Examples of Smart Grids are widespread[6]:

- China is coordinating an 11-year ''Strong and Smart Grid'' plan, which comprises demonstration projects that integrate intelligent transmission and distribution systems, smart meters, home energy management systems, and advanced communications infrastructure [43].
- Under the European Commission Framework Programme, European utilities, technology providers, and academics have deployed advanced grid demonstration projects across the continent, ranging from inter-active distribution networks to regional and pan-European electricity monitoring and control systems.
- The South Africa Smart Grid Initiative (SASGI), a new initiative of the South African National Energy Development Institute, coordinates Smart Grid activities of the electricity supply industry, evaluates options, and makes recommendations. Eskom, the state-owned utility and stakeholder of SASGI, aims to demonstrate the business case for Smart Grids, with a goal of also improving the overall reliability and safety of the South African electrical grid [25].

- The South Korean government has announced significant Smart Grid efforts, focusing on developing cutting-edge system integration technology and business models for export markets. The Jeju Island Smart Grid Testbed is a keystone project for these efforts.
- The U.S. Department of Energy, in partnership with major utilities and technology providers, has invested several billion dollars on more than 130 unique Smart Grid deployment and advanced system demonstration projects since 2009 [41].

A growing number of studies have highlighted the potential environmental and economic benefits of Smart Grid deployment [26,27]. Importantly, complementary policy and regulation can dramatically increase the benefits of Smart Grid technology. Observers estimate that the widespread adoption of dynamic pricing would unlock an additional €53 billion of benefit from European smart meter deployments [28]. This is one example of the ways in which Smart Grids, coupled with smart regulation and policy, can act as key enablers. Much of their long-run value will be determined by the innovations that they facilitate. Governments, regulators, and policymakers might usefully maintain a broad and long-term view of Smart Grid costs and benefits, as they may require a different business model or significant social and behavioral changes to be fully realized. A strong vision of how consumers can directly participate in the energy system will help achieve the desired goals. Part of gaining consumer buy-in also requires effective management of expectations, and delivery on promises about the tangible and intangible benefits of

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the Smart Grid (SmartGrid.gov, 2013).

International policy and standards collaborations in this area are increasingly common. For several years, Smart Grid interoperability standards have been a topic of collaboration in various multilateral contexts, such as the Asia-Pacific Economic Cooperation (APEC) and the European Union. Standards for Smart Grids have also been the focus of specific multilateral efforts such as the Smart Grid Interoperability Panel established by the United States through the National Institute of Standards and Technology.

B. Improved analysis and planning methods

Power system planning tools are evolving to handle many more inputs and produce more robust scenarios. New tools can optimize for a broader set of constraints and link to other sectors of the economy. In particular, highly predictive data analytics and high-performance computing are already changing the way we think about and plan for the future. These advances are already helping to lower risk and uncertainty in planning for, investing in, and understanding the impacts of new infrastructure.

Still, model results must be used with caution [29]. Transparency is a foundational element for enhancing trust in model results. Even when models results are transparently articulated, there is often a disconnect between the questions policymakers want answered and the results that models can provide. Balancing the perspective that quantitative analysis can provide with appropriate caution about over-reliance or irrelevance, policymakers and the research community would benefit from

expanding on several promising areas of progress:

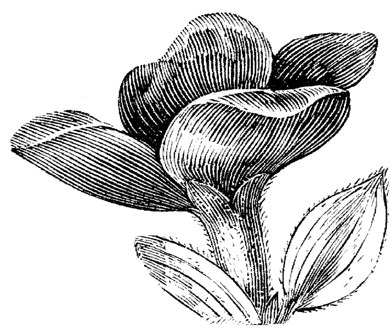
- A systems approach will continue to be important in order to capture the interaction between the energy sector and other closely related factors, such as fuel availability, water and food, and national security [10,12]. Current models and policies sometimes ignore these interactions, which can lead to short-sighted solutions or costly consequences.
- Model uncertainty can be attenuated by a careful characterization of risk using analytical tools borrowed from financial literature [30]. Risk (both perceived and real) affects the way decisions are made throughout the economy; it fundamentally affects technology choice as well as the strength of policy signals required to influence the evolution of the infrastructure-heavy power sector.[7] However, the power sector is exposed to many unexpected circumstances that may arise entirely outside the prior realm of recognized possibilities.[8] One way to deal with this deep level of uncertainty is to take advantage of increased computing power to inform new types of robust decision-making and stochastic optimization [31,32].
- Important analytical progress is under way to enhance the ability of models to represent real world outcomes. Increased data availability and computational power have accelerated model fidelity, resulting in techno-economic models with unprecedented resolution on both time and spatial scales. Examples include: ReEDS [33], SWITCH [34], and USREP [35].

Power systems modeling and research is becoming ever more robust as it takes into account more factors, builds on traditional power flow equations that examine the physical electricity grid, and moves toward true energy services optimization that can inform policy-making. Increasing the real-world utilization of these new capabilities is emerging as a key area of focus.

C. Improved power system governance and multilateral collaboration

Power system governance reflects a tension between the need to reliably meet current demand and simultaneously prepare for an uncertain future. Any proposed reforms to the architecture of power system governance must strike a ''tenuous balance between the determination and efficiency needed to drive energy transitions with the flexibility and innovation necessary to deal with complexity and uncertainty'' [36]. Short-term operational challenges must be balanced with long-term power system dynamics, as well as interaction with other critical infrastructure, information systems, and social considerations. International, national, and sub-national coordination platforms may need re-thinking. At the multi-lateral level, existing energy organizations such as the International Energy Agency do not include China, India, and other major industrializing economies as full members.[9] There is not currently a clear pathway to reach consensus on international energy governance [42].

At the national and sub-national level, transformations like Germany's *Energiewende* require well-managed coordination between energy efficiency, renewable generation, transmission, and distribution grids, as well as regulatory and policy reforms at both the state and federal levels. Coordination across smaller jurisdictions can help align local solutions to power system challenges of national and global scale. Decentralizing some decision-making can also help achieve energy access for all in emerging economies. Power system governance must also be closely tied to the physical system and the rapid technological evolution that drives it. If electric vehicles become a significant source of electrical demand (and system flexibility), for example, policies will need to be coordinated across heretofore unconnected domains: transportation, fuel subsidization, and power system operation (for an overview see [37]).



V. A New Partnership

Transitioning to 21st century power systems will require technical excellence, targeted innovation, and smart regulations, supported by sustained financial and political investment and ambitious public–private sector collaboration. A number of challenges are limiting the pace and scale of this transition, including legal, market, and institutional barriers, lack of coordination, reliance on tools developed for 20th century grids, and the need for customized solutions. The Clean Energy Ministerial (CEM) is a high-level global forum created to promote policies and programs that tackle these challenges. CEM Initiatives are based on areas of common interest among participating governments and other stakeholders. In April 2012, a new initiative was launched under the auspices of the CEM to leverage synergies across these various efforts: the 21st Century Power Partnership.

The Power Partnership focuses on creating enabling environments for power system transformation. It was designed to enhance the large-scale deployment of energy efficiency and variable renewable energy through smart policies and programs that leverage Smart Grid solutions and clean energy technologies, and by improving system operations and long-term planning practices. Specifically, the Partnership has four goals:

- Develop and share knowledge and research on key topics related to the transformation of the electric power sector,
- Strengthen and disseminate relevant technical, legal, financial, and regulatory tools,

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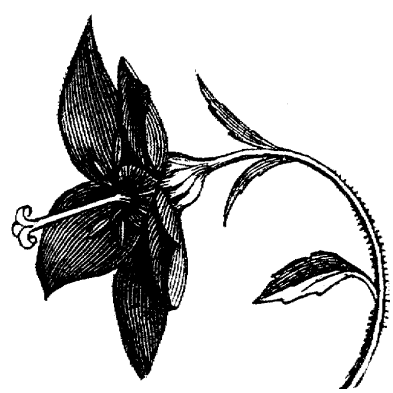
• Bolster the capacity of experts and institutions needed to advance related policies, programs, and practices, and

• Apply the knowledge, tools, and capacity developed to refine and augment regional, national, and sub-national policies and regulations.

The Power Partnership includes an actively growing network of experts developing and enhancing a cross-cutting set of tools to support integrated power sector transformation. These tools in turn will be used to inform and support a series of peer-to-peer engagements. The Power Partnership will influence operations and planning efforts at the policy and regulatory levels, by working directly with systems operators and planners.

VI. Conclusions

The century-old framework for planning, building, regulating, and operating electric power systems is at a critical juncture. No longer able to base their decisions solely on inputs (demand, cost, and fuel), power system decision-makers face an increasingly complex dynamic focused on outputs (affordability, reliability, sustainability, resilience, environmental, and socio-political goals). At the same time that power generation is becoming more variable through the large-scale integration of renewables, power demand is becoming more dispatchable via demand response. Additionally, many are seeing the value in fostering comprehensive energy efficiency, challenging the traditional utility revenue model of steady growth in demand. This fundamental transformation requires a re-thinking of power system policies, business models, and operations. It also requires



maintaining a vibrant global dialogue about policy design and governance mechanisms, and the deep engagement of the finance and investment community. To this end, international public-private partnerships, like the nascent 21st Century Power Partnership, will help to accelerate critical knowledge sharing and adaptation of best practices – helping to make the transition more viable and successful.■

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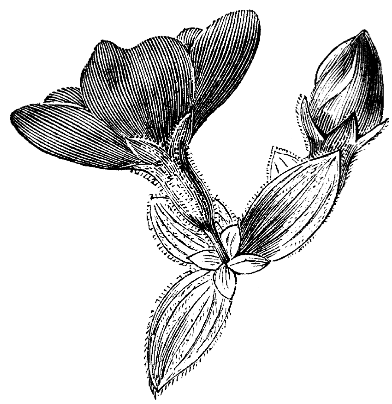

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Endnotes:

1. It does not consider in any depth the wider energy system transformations that are, of course, closely related (see e.g. [44,45]).

2. Upfront capital expenses of conventional generating technologies are typically lower than renewable sources, although long-run costs may be higher.

3. On markets, see Pollitt [46].

4. The literature associated with these various motivations is large and eclectic (see e.g. [10,47–53]).

5. See also for example Sàenz de Miera et al. [54], Sensfuß et al. [55], Poyry [56], Oberstianer and Saguan [57], Green and Vasilakos [58], Gowrisankaran et al. [59], Blyth and Bunn [60] and Hirth [61].

6. Also see, for example, DNV KEMA [62].

7. Blyth and Bunn [60] reports on recent work investigating the impact of different sources of risk on the investment case for wholesale power generators.

8. Stirling [63] distinguishes three basic states of incertitude:
Risk: ''a probability density function may meaningfully be defined for a range of possible outcomes''
Uncertainty: ''there exists no basis for the assignment of probabilities''
Ignorance: ''there exists no basis for the assignment of probabilities to outcomes, nor knowledge about many of the possible outcomes themselves''

9. Although there are signs of this changing, albeit slowl y.

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