Forecasting the Adoption of Emerging Energy Technologies: Managing Climate Change, Governance and Evolving Social Values

Tugrul Daim, Kelly Cowan, Wayne Wakeland, Hosein Fallah and Patricia Holahan

Abstract With the link between fossil fuel use and climate change now almost universally accepted, tackling greenhouse gas emissions (GHG) has become a subject of great social urgency and technological challenge. A variety of models exist, or are under development, for analyzing the role of more sustainable systems, such as renewable energy technologies, in mitigating climate change. However, the direct cost of these technologies is generally higher than that of fossil fuel systems. Methods are needed to more fully account for external factors, societal impacts, and social values associated with fossil fuels versus sustainable energy systems. This paper presents a conceptual model targeted at informing energy policy in order to bring about improvements to inform the management of energy resources so that they can be optimized for climate change. This would then yield a set of governance actions. The model builds on Linstone's multiple perspectives: technical, organizational, and personal, by attempting to forecast technology development along these perspectives. Thus, factors enabling faster and better adoption by consumers, and faster and more efficient development by organizations are evaluated by taking the potential technological improvements into account.

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1 Introduction

Addressing greenhouse gas emissions (GHG) has become a subject of great social urgency and technological challenge. A variety of models exist, or are under development, for analyzing the role of more sustainable systems—such as renewable energy technologies—in mitigating climate change. However, the costs associated with these technologies are generally higher than those of fossil fuel systems, at least in the short term. Methods are needed to more fully account for the societal impacts and social values related to fossil fuels versus sustainable energy systems. These methods can inform better energy policy and management of energy resources. Mitigation of climate change also presents significant opportunities in the emerging “Clean Technology” industries. Evolving values can lead to changes in customer preferences towards the adoption of new products, like hybrid and electric vehicles, or the purchase of “green” electricity from companies that generate it using wind power or solar energy Fig. 1.

Whilst there will be many policy and legislative actions establishing targets and directions, meeting the anticipated emission requirements in the U.S. will depend on advancements in energy generation and consumption technologies. Energy sources consist of primary sources, or “raw energy,” and secondary sources, which are created from the primary sources. The primary sources include fossil fuels, like natural gas, oil, and coal, as well as solar, wind, and geothermal. The secondary sources include energy carriers, like electricity, and refined fuels. These sources of energy in various forms and extents provide for the energy needs of industries, businesses, and residential communities. At national level, energy consumption consists of 28 % for transportation; 33 % for industrial use, and; 39 % for residential and commercial applications (2008). Electricity has become one of the most versatile and sought-after energy carriers in the modern economy, as it has potential uses in all of the above sectors. It can be produced readily through renewable and non-renewable technologies. However, approximately 50 % of U.S. electrical generation currently comes from coal-fired power plants, which produce the most GHG pollutants of any of the major generation options. The primary focus of this study will be on electrical power generation that has a minimum impact on the environment. The main objective is to identify the critical perspectives and a process to develop models to create technology roadmaps for better forecasting the evolution of new technologies to meet the challenges of climate change. In particular, the project is focused on technologies that are intended to:

1. reduce GHG emissions in electrical power generation;
2. improve efficiency in the management of transmission and distribution;
3. increase energy efficiency and conservation.

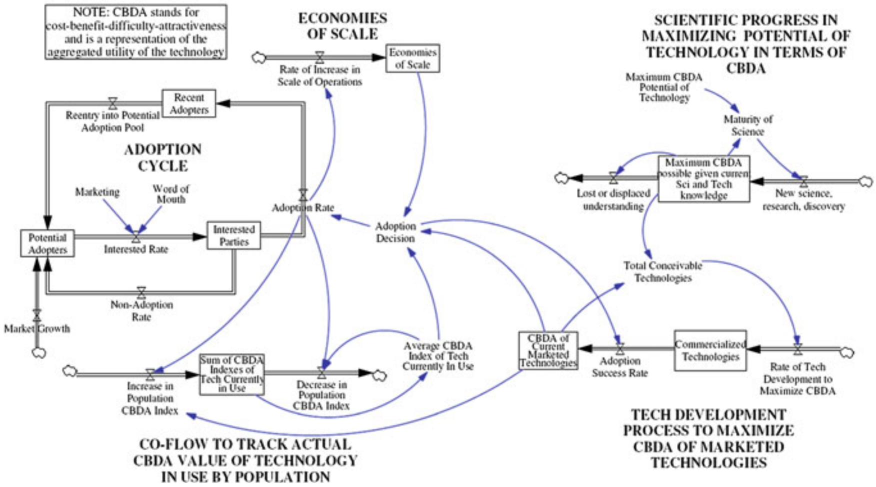

Fig. 1 A conceptual model demonstrating the basic concepts of the process (Ingle et al. 2009)

The models developed in this study will inform industry practitioners and policy-makers on how to prioritize investment in new technologies based on their potential impact in both the short and long term and, as a result, yield a set of governance actions. Models are typically categorized as either *normative*, which create prescriptions for dealing with problems in theoretical optimum conditions, or *descriptive*, defining real-world problems in specific cases, but not necessarily being able to generalize solutions to other, additional cases. In the energy sector, there is a strong need for models which can bridge between the many complex criteria in both normative and descriptive models, dealing with situation-specific factors, but also offering general policy guidance, substantiated by a sound theoretical basis involving technological foresight and decision-making. The advent of modern computing has produced a variety of multi-criteria decision-making (MCDM) methods for consolidating and attempting to optimize the results of numerous inputs. However, in real-world technology management problems, conflicting or overlapping factors often prevent true optimization (Roy 1968; Figueira 2005). The concept of *satisficing*, or satisfying, one or more goals to the greatest extent possible, given the various constraints, must often be used instead (Simon 1976, 1991). But, if goals are only satisfied for short-term benefit, at the expense of long-term benefit, to the overall system, this leads to *suboptimization* (Baird 1989). Much of the current planning for fossil fuel energy systems has placed an emphasis on short-term economic gain for certain elements within the energy system, and this constitutes a suboptimization of the long-term benefits available under sustainable energy systems. In particular, social factors, values, and ethical concerns have been suboptimized. There is a need to develop better models which can deal with the complex, dynamic, and often overlapping factors involved with problems, like energy generation and climate change, and societal impacts. Fuzzy logic, data mining, and data visualization are just a few of the methods which could be used to create models appropriate for energy-climate-technology problems.

2 Literature Review

2.1 Technology Assessment and Governance

Technology Assessment (TA) is a key methodology for research in this area. TA has been in use for over 40 years. The concept was first formalized with the establishment of the Office of Technology Assessment in 1969. Its objective was to understand the social, economic, political, ethical, and other consequences of the introduction of a new technology into society. Thus, TA was conceived to assist in public policy decision-making, which is also a critical element of governance. The literature contains several definitions for TA. Coates (1973) defined it as “a term applied to a class of studies intended to illuminate and hence influence public policy decision-making in the Executive and Legislative Branches of the Government.” He then updated his definition as “a policy study designed to better understand the consequences across society of the extension of the existing technology or the introduction of a new technology with emphasis on the effects that would normally be unplanned and unanticipated” (Coates 2001). Another definition calls TA “an attempt to establish an early warning system to detect, control, and direct technological changes and developments so as to maximize the public good while minimizing the public risks” (Kiefer 1973).

Several frameworks to deal with different aspects of TA were developed and adopted over the years. Ethical Technology Assessment (eTA), a new form of TA, focused on the ethical implications of new technologies. Another major application of TA has been in the health care industry (Palm and Hansson 2006). Constructive Technology Assessment (cTA) is an emerging approach to TA, based on the assumption that technological development is driven by society. Those using this approach try to integrate many facets from society into their assessment processes. The underlying objective is to create a better technology for the betterment of society (Genus 2006). Participatory Technology Assessment (pTA) strives to include all participants who contribute to the innovation process through the use of workshops or meetings (Van den Ende et al. 1998). Real-time Technology Assessment (real-time TA), which integrates natural science and engineering analysis with social science and policy development, is an expanded version of cTA (Guston and Sarewitz 2002). The Multiple Perspectives framework (MP), put forward by Linstone et al. (1981, 1984, 1999), called for careful examination of the available technology from three perspectives, including an organizational/societal perspective, a personal/individual perspective, and the conventional technical perspective. The field of health Technology Assessment (hTA) is still relatively new, but has shown remarkable growth over the last decade. The initial focus of hTA was efficacy and cost-effectiveness of health care interventions. Recently, more attention has been paid to effective dissemination and implementation in order to influence administrators and clinicians (Banta 2003; McDaid 2003). Coates and Fabian (1982) found that many companies viewed TA solely in terms of trying to anticipate the effects of the outside world on their own activities, rather than anticipating the effects of their activities on external factors. They called this approach "inverted Technology Assessment".

TA has been a key part of Science, Technology and Society (STS) research. The approaches discussed above have been used to evaluate the impacts of numerous technologies. Brooks (1976) and Shrader-Frechette (1980) provided some of the initial building blocks for this research stream in STS. Others evaluated the use of different approaches. Hildebrandt and Gutwirth (2008); Marris et al. (2008); Guston and Sarewitz (2002) and Lengwiler (2008) explored different uses and perspectives of pTA. Stirling (2008) explored "appraisal" and "commitment" in technology choice, and concluded that greater appreciation is required—in both analytic and participatory appraisal—to facilitate the opening up (rather than the closing down) of governance commitments in science and technology. Other STS researchers explored policy implications. Grin and van de Graaf (1996) explored how policy-makers could influence the processes of technology development. Herrick and Sarewitz (2000) proposed a more effective role for scientific assessments in environmental policy formulation.

There has also been specific interest in STS research regarding the assessment of energy-related technologies. Schot (1992) used cTA to evaluate clean energy technologies. However, the study was limited to the demonstration of a methodology. Climate change has also been of interest to the STS field. Shackley and Wynne (1996) explored uncertainty in climate change science and its impact on related policy-making. Grundmann (2006) explored the role of expert opinion on cases such as climate change. Agrawala et al. (2001) explored impacts of climate predictions on societal decisions.

By studying technological development, societal perceptions, and consequential adoption or non-adoption concurrently, this research will identify how these factors interact with governance. Linstone's MP framework, discussed above, has proved to be a very successful technique for dealing with complex techno-social problems, decisions, and business cases. Coates et al. evaluated the future of technology forecasting and assessment using MP (Coates et al. 2001). One conclusion from this work is that an MP approach is particularly useful for addressing complex issues, such as the energy crisis. A number of recent case studies have focused on the growth of green energy programs from a government policy, or organizational (O), point of view (van Rooijen and van Wees 2006; Coates et al. 2001; Ek 2005), as well as from a technical (T) point of view (Stadler et al. 2007). These studies explored the impact of regulations and incentives in national and regional green energy programs in Europe. Due to situation-specific factors, it is unclear how generalizable European case studies will be for North America or elsewhere. Other studies have addressed government policy (O) efforts in the United States to develop green energy programs at the national, state, and local levels (Vachon and Menz 2006; Menz and Vachon 2006; Menz 2005). These studies highlight a complex and confusing mass of policy differences in various jurisdictions, and have largely ignored market-based initiatives. Attempts have been made to tie together various aspects of the TOP viewpoints with energy issues. A study by Harmon and Cowan examined the market for green energy using an MP framework (Harmon and Cowan 2009). Daim et al. have shown that TOP factors can be used for forecasting the emergence of new technologies ranging from fuel cells to optical storage (Daim et al. 2006). Astrand and Neij used a “socio-technical systems approach” (O and T) to evaluate green energy technologies (Astrand and Neij 2006). This case documents how early insistence by the Swedish government on a two-bladed wind turbine design, and the decision to limit supplier choice to only the country’s largest energy providers, may have severely stunted the growth of the country’s wind power program. Although Sweden had set aggressive goals for wind power development, they were far less successful in terms of investment returns from deploying wind power than in nearby Denmark and Germany (Richey and Grinnell 2004).

2.2 Forecasting Technology Diffusion and Adoption

Technology forecasting experts generally agree that models should be used in combination (Millett and Honton 1991; Martino 1983). With complex consumer technologies there are usually several organizational factors—political, cultural, etc.—that influence the rate of diffusion for a commercial technology. Technical trend analyses alone cannot incorporate the organizational and political scenarios that will influence future technologies. Systems Dynamics (SD) is an integrating methodology for incorporating many variables into a single numerical model that represents complex feedback loops and generates projected “S-curves,” which show anticipated trends in market penetration. It is an approach to modeling complex systems that was developed in the early 1960s by Forrester (1961). Traditional SD models used in technology forecasting incorporate historical data for calibration and validation. Models here also integrate the use of scenarios, bibliometrics, and patent trend analysis. SD models have typically not been viewed as appropriate forecasting tools, but are used primarily to uncover feedback loops to show how factors interrelate for strategic analysis (Millett and Honton 1991). Patents are used for competitive analysis and technology trend analysis (Abraham and Moitra 2001; Liu and Shyu 1997). Patents are analyzed in R&D project management to assess competitive position and to avoid infringement. Patent analysis is also a valuable approach for deriving information about the growth of an industry and/or diffusion of a particular technology. Patent growth generally follows a similar trend that can resemble an S-shaped growth curve. In the early stages of a technology, the number of patents issued is very limited. A period of rapid growth then follows when the number of patents filed and issued increases, until a plateau is reached (Abraham and Moitra 2001). Because the patent process is costly, and can take several years, filing a patent generally means there is optimism in the economic or technical contribution (Basberg 1987). Several indices have been introduced to measure technological strength as a function of patent quantity or quality. Some examples include patent citation indices and regression models (Abraham and Moitra 2001; Wang et al. 1998). Because the total number of patents over time for a technology has a saturation point, growth curves can also be used (Bengisu and Nekhili 2006). Other models aim to describe the relationship between patents using citation networks (Brinn 2003). Patent analysis has been shown to be valuable in planning technology development from analysis of strategy at national level (Liu and Shyu 1997) to modeling specific emerging technologies (Ashton and Sen 1988; Bengisu and Nekhili 2006) (Abraham and Moitra 2001). Patent data is usually freely accessible in most countries, and several guidelines have been introduced to enhance the technique using keywords and categorization. Much like text and journal information, very few patents actually develop into something of commercial value. However, most are technically significant because they encourage or lead to follow-on developments in technology (Ashton and Sen 1988). Understanding growth in an area of technology and measuring the use of keywords or phrases can provide insights into developing an overall technology forecasting model.

Bibliometrics is defined by Norton (2000) as the measurement of texts and information. Historically, bibliometric methods have been used to trace back academic journal citations. However, today, bibliometrics can be used to understand the past and even potentially to forecast the future (Morris et al. 2002). Bibliometrics help us to explore, organize, and analyze large amounts of historical data, allowing researchers to identify "hidden patterns" that may provide insights into the decision-making process. Some common tools that have been used in bibliometrics include the study of authors, affiliations, conceptual maps, cluster and factor analysis, and citation and co-citation analysis, to mention but a few. Important works have been presented by Morris (Morris et al. 2002) using the Database Information Visualization and Analysis system (DIVA), where documents are visualized as clusters on a two-dimensional map. Kostoff et al. (2001) have presented database tomography for textual database analysis, extracting multiword phrase frequencies and determining phrase proximities using the Science Citation Index (SCI) and the Engineering Compendex (EC) databases. Bibliometric analysis helps to identify: (1) the most prolific topical area authors; (2) the journals that contain numerous topical area papers; (3) the institutions that produce numerous topical area papers; (4) the keywords specified most frequently by the topical area authors and the authors whose work is cited most frequently. Also, (Porter and Watts 2003, 2005; Porter 2003) have presented relevant papers in data mining using a proprietary software called VantagePoint. Porter developed a technique called Innovation Forecasting, which combines bibliometrics with other forms of technological evidence. Porter and Watts (2005, 2003) and (Pilkington

2003; Pilkington and Teichert 2005) have demonstrated significant bibliometric applications for the management fields of engineering and technology. Both study how bibliometrics help to identify and classify patterns of innovation.

SD is another well-established methodology for dealing with complex problems, strategy and policy decisions, models with unintended side-effects, delay times, and problems for which prior attempts to solve them have failed (Wakeland 2006; Sterman 2000). Much of the SD method relies upon concepts such as feedback loops, time delays, and non-linearity effects, which determine the dynamics of a system. Dynamics arise from the multiple interactions of two types of feedback loops: (1) positive, or reinforcing loops; and (2) negative, or balancing loops. Positive loops amplify the behavior of the system, while negative loops counteract and oppose change. Growth curves represent growth in performance over time. They were created making an analogy to the growth of a living organism (Warr and Ayres 2006; Carrillo and González 2002; Young 1993). Growth curves are frequently used to forecast the substitution of one technology for another (Martino 1983). In the Gompertz model, however, assumptions are different. This model is often referred to in technology forecasting as the "*mortality model*." The Gompertz model produces an S-curve which rises more sharply, but begins to taper off earlier than the Fisher-Pry model (Porter 1991). The Fisher-Pry model predicts characteristics very similar to those of biological system growth. For this reason, it is commonly referred to as the "*substitution model*," due to its application in forecasting the rate at which a new technology will replace an existent technology. Fisher-Pry presents a slow beginning, a rapid slope, and tapers off at the end.

There are also several diffusion theories that could be used for understanding the adoption of new technologies. Diffusion of Innovations (DoI) is defined as "the process by which an innovation is communicated through certain channels over time among the members of a social system" (Rogers 1962). Rogers (1995) defines an innovation as "an idea, practice, or object that is perceived as new by an individual or other unit of adoption." According to Rogers, communication is "the process by which participants create and share information with one another in order to reach a mutual understanding," and communication channels are "the means by which messages get from one individual to another." Bass (2004) proposed and tested an epidemiological model for the diffusion of consumer durables and other innovations. The Bass Model shows how a new product or idea spreads through the user community by quantifying the introduction of new technologies depending on the take-up by innovators and imitators. The model is used to predict technology introduction rates from a set of estimated values for the innovation and imitation factors. According to the Theory of Reasoned Action (TRA) developed by Fishbein and Ajzen (1975), the main determinant of an individual's behavior is the individual's intention, which is influenced jointly by the individual's attitude and subjective social norms. In TRA, attitude towards the behavior is defined as "the individual's positive or negative feelings about performing a behavior." It is determined through an assessment of one's beliefs regarding the consequences arising from a behavior and an evaluation of the desirability of these consequences. The Technology Acceptance Model (TAM) developed by Davis (1985) can be accepted as an adaptation of TRA. This model defines the perceived ease of use and perceived usefulness as two determinants of attitude towards behavioral intention and usage. In TAM, perceived ease of use is defined as "the degree to which a person believes that using the system will be free of effort," whereas perceived usefulness is defined as "the degree to which a person believes that use of the system will enhance his or her performance" (Davis 1985). The Theory of Planned Behavior (TPB) developed by Ajzen (1991) is another variant of TRA that also takes into account the perceived behavioral control as a third determinant of an individual's behavioral intention to use a new system. In TPB, perceived behavioral control is defined as "one's perception of the difficulty of performing a behavior." TPB views the control that people have over their behavior as a continuum ranging from behaviors that are easily performed to those requiring considerable effort, resources, and so on.

To advance the understanding of emerging energy technologies, both in terms of their adoption by individuals in society, and management strategies for their adoption by industries, new models must combine behavioral theory and strategic problem-solving methods. The Unified Theory of Technology Acceptance and Use (UTTAU) (Venkatesh et al. 2003) builds upon DoI, TRA, and TPB. However, it lacks a high-level organizing framework that would categorize its many disparate factors into coherent perspectives.

2.3 *Case Analysis: Climate Change and Electric Power Generation*

With the 141-nation Kyoto Protocol entering into force in February 2005 and the updated Bali Roadmap on climate change in 2007, fossil fuel-based power systems face a worldwide trend toward GHG restrictions (Clemencon 2008). The expectation of emissions restrictions is already making it difficult for companies to obtain permits for the development of conventional power plants, such as coal plants, even though legislation has yet to outlaw them. Available low-emission power generation technologies, like wind power and hydroelectric, will likely meet only a portion of future power demand. Therefore, development of new low-emission generation technologies is necessary to meet future requirements. There is a need for improved load management in electrical systems operations, additional energy efficiency measures, and technologies for smart grid applications. Many of the long-term solutions proposed to fill gaps between low-carbon power supply and demand are in their early stages of development or adoption. Emerging generation options that are "carbon-free,[1]" meaning they do not directly add

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[1] Using full life cycle analysis, most forms of power generation are responsible for some amount of energy expenditure, such as fossil fuels used in the creation of parts or components of the

emissions of CO_2 to the atmosphere, include: biomass, geothermal and enhanced geothermal technologies (EGT), solar photovoltaic (PV), concentrating solar power (CSP), hydrokinetic energy (including wave power and tidal power), wind power, as well as next-generation nuclear power (Gen-IV). For low-carbon power generation, technologies such as coal gasification, integrated gasification combined cycle (IGCC), and natural gas combined cycle with carbon storage, or "sequestration," are also under development. Increased efficiency in power transmission, demand sensing, and load management are additional demand-side options. Each of the above-mentioned technologies must also be evaluated in specific national and regional contexts to be consistent with local needs and goals (Gerdsri and Kocaoglu 2007). Further research on societal impacts is also essential to determine where and how these technologies would be best implemented.

In order to reduce CO_2 emissions for the utility industry while maintaining economic growth, work will need to be done to identify and deploy solutions for efficient use of energy. In all likelihood, loads will eventually be added to the system beyond that which can be attributed to economic or population growth. For instance, loads from the transportation sector may begin to switch to electric power: plug-in hybrid electric vehicles (PHEVs) are being used and General Motors has announced that it is investigating the commercial release of its extended range electric vehicle, the Dodge Volt, by 2012. As the industrial sector moves to more sustainable business practices, the reliance on electricity could rise dramatically, further increasing system load. 'Smart Grid' technologies will be necessary to ensure proper grid operations into the next few decades. Several factors are contributing to the dramatic increase in system complexity: increasing amounts of wind power and other renewable energy generation with intermittent generation profiles, increases in system demand, increasing distance between generation sites and loads, and demand response schemes that require bi-directional, real-time communications between end-use equipment and the control system. In order to handle this additional complexity, electronic switches, bi-directional communication capabilities, and both centralized and decentralized control schemes are needed. It is anticipated that these web-enabled, digitally controlled, intelligent delivery systems will allow power systems to operate with more stability and be able to self-correct before problems arise (Blankinship 2006). This can allow grid operators to take advantage of system capacity that is currently forfeited in order to allow the current system to respond to unanticipated issues. To create a roadmap to optimize integration of these many evolving technologies in ways that maximize efficiency and result in an effective transition plan to meet the challenges of climate change, development and enhancement of technology forecasting models is needed.

(Footnote 1 continued)
system. The PV manufacturing process, for example, typically emits an amount of carbon equivalent to about 25 g of CO_2 per kilowatt hour of electricity produced (25 gCO_2/kWh). By contrast, coal emits about 950 gCO_2/kWh.

3 Conceptual Process

The following four-level method of analysis is proposed:

3.1 *Identification of Factors and Relationships in Multiple Perspectives*

Scientific understanding of the technologies necessary to address global warming has progressed to the point where the barriers to solving the problem of climate change are no longer technically insurmountable, but questions remain about their feasibility in financial, political, and social terms. While certain technologies may not be suitable simply from one point of view, considering them from several perspectives may make them, in fact, some of the only acceptable solutions to the urgent and potentially catastrophic problem of climate change. Also, as mentioned in previous sections, when technologies like fossil fuels are understood in a full systems context, it becomes clear that they suboptimize the solution to the energy problem by focusing only on what is economically expedient at the expense of damage to human health, ecosystems, and climate (Baird 1989). They also result in strategic energy dependency to fossil fuel-exporting nations. Thus, more comprehensive models are necessary which specifically consider issues like human values and do not simply solve one small part of the energy problem at the expense of the overall social system. Although no model can consider an infinite chain of causal factors, which are in turn related to other factors, technology research has shown that methodologies like SD and the MP framework can aid decision-makers.

3.2 *Identification of Alternative and Complementary Technologies*

The growth in electric power demand and the need to reduce GHG from electric power generation will create challenges for new and enhanced technologies, and will fuel the drive for innovation. We need to leverage existing knowledge and develop new knowledge on embryonic and emerging technologies to characterize and baseline the technology landscape. This process may follow these steps:

Firstly, identify known and evolving technologies from sources such as government and industry studies, association reports, technical and trade publications, product prototypes and demonstrations. Secondly, identify embryonic and emerging technologies from university research programs, analysis of patent applications, starting with the US and Europe, and characterize major innovation networks and technology clusters. Patent analysis can provide information about emerging technologies in several ways:

- Patent applications and their forward citations will be studied as a source of information on new technologies. Given that it takes at least 18 months before a patent is published, knowledge of the new discovery does not emerge for a few years. As the new technology evolves, new patent applications are filed citing the original patent. Forward citations will be examined to provide information about the speed of the evolution of the new inventions, as well as spillovers into other technology classes. Such information will help in forecasting growth, enhancement, and adoption of the new technologies.
- Patent data will also be used to examine information about the networks of inventors and relationships among the R&D organizations, as well as the emergence of technology clusters, in particular, technological areas. Applying social network theory to such patent data can provide insight into technology forecasting models.

The data can be augmented with information gathered through interviewing leading inventors and experts (T). To create a structure for the baseline data, the technologies can be grouped according to life cycle stage: embryonic, emergent, growing, mature, and declining. Embryonic technologies are targeted for longer-term (10 years or more) deployment. Mature and declining technologies, such as current coal- or gas-fired power plants, may need to be significantly refurbished in order to reduce GHG emissions and power generation efficiency, or be earmarked for replacement. Furthermore, one can organize technologies by: (1) type of application, such as electric power generation, transmission, and load management; (2) risk of development and deployment; (3) current cost per kWh, and potential for cost reduction; (4) contribution to electric supply in 10 and 20 years; and (5) the effect on reduction of GHG emissions.

To incorporate the MP framework, methods such as Delphi can be used to convene a panel of experts in energy technologies (T) to review and improve knowledge of the technology landscape. Additional expert panels can include industry and government leaders (O), as well as consumer and social behavior experts (P), to review and refine the baseline process. Although it is possible to combine experts from all three perspectives into one panel, capturing the multiple perspectives separately at first is likely to be the best method for the development and calibration of the reusable forecasting models.

3.3 Model Building, Scenario Development, Validation

A variety of computer models can be used to integrate key concepts and data, to clarify inter-relationships, and to anticipate behavior over time. Although SD models are expected to be quite useful in accounting for the impacts of complex feedback loops, discrete system simulation models are needed to analyze uncertainties in these manifold impacts. To study the technology diffusion processes at the level of the individual, agent-oriented simulation may also be employed. Once promising models have been developed, they need to be thoroughly tested. Once the testing has been completed, then the models can be confidently relied upon to produce useful inferences. The models can be used to evaluate a variety of scenarios in order to identify strategies and policies for "optimizing" the diffusion of technologies for clean electricity generation, and for efficiently distributing that electricity to the point of use. It is possible to find robust solutions that provide the best possible outcomes over a reasonably broad and plausible search space. At the heart of these models will be several diffusion models that depict both the adoption of new technologies—for which these types of models have been classically used—as well as the spread of the social innovations and changes that will be needed to facilitate the rapid adoption of these new technologies. The necessary social innovations may include such things as the acceptance of: (1) smaller and perhaps very different-looking types of vehicles; (2) wind turbines located in heretofore pristine locations; (3) solar panels attached to the roofs of houses, and so on. The dynamic models will also reflect the status of fossil fuel reserves and discovery rates, as well as changes in efficiency over time. Demand for electricity should also be represented in the model, as driven by population growth and increases in the overall standard of living per capita. As the demand for power and mobility increases and outstrips supply, pressures will mount to accelerate the development and implementation of alternative means for generating electricity from both renewable and non-renewable sources, for both home use and transportation use. These models can be designed to explain recent trends, and to estimate the likely future trends under various assumptions regarding the cost sensitivity and public acceptance of different technologies. Contributions to knowledge will include the models, the explanations of past trends, and the estimates regarding likely future trends.

3.4 Policy Recommendations

The process of technology implementation is based on the development paths enabled by government policy at the federal and at the state level. Local government action can block development at key points of the implementation process. Split payments for technology changes have led to suboptimal solutions as the cost-benefit analysis is incomplete or biased. Side payments for technology development can lead to spiraling costs, as has happened in the nuclear industry, when future taxes were earmarked for unknown technology solutions.

Customers fail to implement energy efficiency projects when the cost savings are obscure, or too far into the future. As noted by Friedman, the problem is with the price signals. Government has to focus on changes in technology as a complete picture with clear economic comparisons. Government then has to clearly show citizens the cost of each path with incentives and with disincentives to bring the future impacts into the present. Insurance for nuclear waste transportation, processing, and long-term storage are one such cost. Carbon emissions are one such future impact which will have to be reduced through open and transparent market allocations established by governments. The intended and the unintended impacts have to be embedded into the previous models for a fully developed simulation to include price signals established at the federal, state, and local levels.

As outlined throughout the paper, by modeling all the adoption processes through multiple perspectives, this approach covers all governance elements and, therefore, the results would provide an appropriate set of actions for all elements of governance.

4 Discussion and Conclusions

By studying how to synchronize the spread and adoption of facilitative social changes to coincide with processes that are developing and deploying new technologies, the proposed process will reveal high leverage points for accelerating the overall acceptance rates for clean energy sources. Technical strengths of the proposed process include the synthesis of multiple methods and the creation of operational models of the processes that drive technological and social innovation. Although these methodologies, models, and validation approaches will represent an important scientific contribution in their own right, they will also, and perhaps more importantly, open up new lines of research and development, and enhance the scientific basis for further research in the long-term development and deployment of sustainable energy technologies. Follow-up studies by researchers and others are likely to include: (1) field research to better understand and validate assumptions and model attributes on the mechanisms which accelerate or impede the spread of social innovations and to identify the most effective types and magnitudes of incentives/interventions for stimulating these particular social changes; (2) quantitative studies to determine specific parameter values and sensitivities; (3) the development of monitoring processes and systems; and (4) the creation of educational and motivational materials that show how technological and social processes interact and complement each other.

The proposed process will also assist policy-makers at the DoE and other agencies focused on energy efficiency and conservation by providing them with configurable models and specific strategies and tactics for accelerating the transition to alternative energies, reducing fossil fuel consumption, and slowing the pace of adverse climate change. Specific interventions will be needed to provide high leverage means for accelerating the adoption of beneficial technologies, with particular emphasis on how to amplify complimentary social trends regarding the acceptance of smaller and possibly less convenient vehicles, increased tolerance for the visual impacts associated with wind and solar technology, and greater willingness to use virtual communication technologies in place of in-person communications.

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