

The Electric Power Industry and Climate Change: Issues and Research Possibilities

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Abstract— This paper summarizes issues and research opportunities related to global climate change for the electric power industry. The following issues are considered: (i) power infrastructure response to extreme weather events; (ii) impact on system operating strategies, configuration, and expansion plans; (iii) effects of an expanded use of renewable and alternative energy technologies; and (iv) impacts of market rules and policy mandates on power system operation.

Index Terms—global climate change, electric power research, extreme weather, alternative technologies, government policy

I. INTRODUCTION

THE interaction of the electric power industry with climate is manifested in both the effect that severe weather has on the power system and the contribution of electric power to the production of greenhouse gases (GHG) and other pollutants. It is estimated that the United States is the source of one-fourth of the world's GHG emissions and that the electric power industry accounts for one-third of these. Within the total GHG emissions, CO₂ emissions account for more than 80 percent of the overall U.S. contribution, and 38 percent of this amount is derived from the electric power sector [1].

A. Overview of the Problem

Analyses of climate change and society's response frequently refer to the need and ability for adaptation and mitigation. In terms of electric power systems and climate change, adaptation includes the hardening of power system equipment and developing new operating system strategies in response to system upgrades and changing weather patterns.

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The power system must also respond to new market rules, proposed laws and regulations, expanded energy conservation, energy efficiency, use of renewable energy sources, and demand-side participation programs. The power industry is confronted with the need to adapt to current and anticipated market structures and government mandates relating to climate change and sustainability.

Mitigation refers to the need to lessen the negative impacts of climate change on society and the economy, as well as mitigating the power industry's production of pollutant emissions. This area of power system-climate interaction focuses on reducing the production of GHGs from combustion and energy conversion processes.

The sources of greenhouse gas emissions are much broader than the electric power industry, being both natural (biogenic) and human (anthropogenic). A brief overview of emissions from land use, agriculture, transportation, and electric power is provided below in order to provide context for the role of electric power in climate change discussions.

Land Use Patterns and Agriculture: Land use plays an important role in GHG emissions and carbon sequestration in the United States. Land use types that affect GHG emissions and sequestration include forest land, grassland, pasture, rangeland, cropland, wetland, and urban land. The effects of land use on natural emissions estimates are complicated by distinguishing between anthropogenic and biogenic emissions [2]. In 2000, agriculture was responsible for 14 percent of the GHGs, divided among fertilizers, livestock, rice cultivation, manure management and waste burning.

Agricultural practices also produce CO₂ via soil and biomass management practices that disturb natural carbon sinks. In addition, agriculture is responsible for emissions in other sectors, including deforestation, production of fertilizers, use of equipment that requires fossil fuel, and transportation of agricultural inputs and outputs [3].

Transportation: The share of total emissions from transportation rose from 17 to 24 percent between 1990 and 2004, an increase of 41 percent, or 2.5 percent per year on average. Emissions from international aviation and shipping rose by 86 and 45 percent, respectively, and accounted for 22 percent of transportation emissions in 2004 [4].

Electric Power: The electric power industry in the United States accounts for one-third of the nation's GHG emissions,

and 38 percent of the nation's overall CO₂ emissions, equivalent to 2.2 billion metric tons [1].

B. Organization of the paper

This paper summarizes a report by the Power Systems Engineering Research Center (PSERC) [5]. Section 2 discusses the science and technology background of the interaction between the production of GHGs and the production, consumption, and delivery of electricity. Section 3 discusses extreme weather statistics and events, and the potential impact on power system blackouts and component failures. U.S. federal and state policies on climate change, to the extent that they affect the electric power industry, are discussed in section 4, and section 5 continues this discussion with electricity market issues that relate to climate change. Section 6 discusses long-range planning in electric power and other industries with respect to climate change. Section 7 concludes.

II. THE PRODUCTION OF GHGS AND ELECTRIC POWER: THE SCIENCE AND TECHNOLOGIES

The public and the electric utility industry are showing greater interest in environmental issues, including global climate change. This section discusses the interaction between the production of GHGs and the production of electricity, including discussions on emission-reducing technologies and likely impacts on the transmission grid.

A. The Greenhouse Effect and Greenhouse Gas Emissions

Key naturally occurring GHGs are CO₂, methane (CH₄), nitrous oxide (N₂O), and water vapor. Studies have shown that water vapor and CO₂ are responsible for most of the Earth's greenhouse effects. Through a process known as the carbon cycle, the concentration of CO₂ in the atmosphere is regulated. The carbon cycle involves the movement of CO₂ between the atmosphere, the land and the oceans, with natural processes such as photosynthesis playing a dominant role.

The past century or two has seen a marked increase in the concentration of GHGs in the atmosphere. This change has been attributed, in part, to the industrial revolution and the tremendous increase in fossil fuel consumption. This has perturbed the normal carbon cycle, resulting in a gradual increase in atmospheric CO₂ concentration from approximately 280 parts per million (ppm) prior to 1800 to about 379 ppm today [6]. As a result, increased CO₂ (along with other GHGs) in the atmosphere traps more radiation, resulting in a gradual increase in the Earth's average temperature.

B. United States' CO₂ Emissions

In 2005, CO₂ emissions in the U.S. and its territories were estimated at 6,008.6 millions of metric tons (MMT), an increase of 208.6 MMT from 2003 [7]. Of this number, the amount related directly to the production of electricity was 2,375.0 MMT.

Table 1 summarizes U.S. CO₂ emissions from the electric power sector in the year 2005, demonstrating that coal

generation provides approximately 50 percent of our electric energy and is responsible for approximately 82 percent of electricity-related CO₂ emissions. The production of one megawatt hour (MWh) of electric energy with coal results in the release of approximately 0.97 metric tons of CO₂ (almost a one MWh to one metric ton ratio).

TABLE 1
U.S. CO₂ EMISSIONS FROM THE ELECTRIC POWER SECTOR [7]

Fuel	MMT of CO ₂ in 2005
Petroleum	100.3
Coal	1,944.2
Natural Gas	318.9
Other	11.5
Total	2,375.0

Comparing these numbers to the carbon storage capability of a forest provides some perspective. A single acre of forest can sequester the CO₂ produced from generating 2.2 MWh. Hence, sequestering the CO₂ produced by a 500-megawatt coal-fired power plant with a 75 percent capacity factor would require 1.5 million acres of forest. Nationally, there are 193 million acres of national forest and grasslands [8].

The most important conclusion from this section is that coal is responsible for the majority of GHGs, most importantly CO₂, generated by the U.S. electric power sector. Either reduction in the use of coal to generate electricity or an increase in the sequestration of the resultant CO₂ will significantly reduce the amount of GHGs produced.

C. Technologies to Reduce GHG Emissions in the United States

Carbon Capture and Sequestration: The Department of Energy (DOE), through its Carbon Sequestration Program, is pursuing the goal of producing new coal-fired power plants with almost 90 percent lower CO₂ emissions. Through a process called carbon capture and sequestration (CCS), carbon is captured from these plants and stored in permanent repositories.

There are three technological options to capture CO₂, referred to as post-combustion, pre-combustion, and oxygen combustion (oxy-combustion) [9]-[12]. After the CO₂ is captured, it must be transported from the source to the sequestration location. One approach is to build a direct pipeline. Alternately, new power plants could be constructed near the carbon sink site along with required investment in the transmission infrastructure to deliver the power to the grid.

A final issue is that the carbon must remain sequestered for many centuries. There are currently three leading alternatives to this sequestration: geological formations, terrestrial ecosystems, and the oceans. These options are discussed further in references [9] and [14].

In response to the widespread reliance upon coal, there is broad interest in CCS among policy makers and industry. Nationally, there are six CCS regional partnerships: West Coast Regional Carbon Sequestration Partnership

(WESTCARB), Southwest Regional Partnership on Carbon Sequestration (SRPCS), Big Sky Partnership on Carbon Sequestration, The Plains CO₂ Reduction (PCOR) Partnership, Midwest Geological Sequestration Partnership (MGSC), and Southeast Regional Carbon Sequestration Partnership (SRCSP). Overviews can be found at [15].

One area of concern is that CCS technology is quite expensive. For pulverized coal plants, the cost of retrofitting CO₂ capture to these facilities could add at least 70 to 100 percent to the cost of electricity [15].

Technologies for Reducing SO_x and NO_x: For the reduction of NO_x, one alternative is simply to reduce the number of high-emission plants. Alternatively, modifications could consist of installing low-NO_x burners or adding post-combustion technology, such as selective catalytic, or noncatalytic, reduction (SCR) equipment [16].

For sulfur dioxide (SO₂), there are also several alternatives. These range from simply varying the utilization of low-sulfur fuel to reducing the use of high-emitting plants. The most common alternative is adding flue gas desulphurization (FGD) to the plants. According to the Annual Energy Outlook 2006, most utilities have plans to install FGD by the year 2030 [17].

Dispatchable Generation: Hydropower & Nuclear Energy: GHG emissions can be reduced by supplementing or replacing fossil fuel energy sources with ones that produce no GHG emissions, such as hydropower. However, most hydro-resources that could be economically developed have already been developed, with little if any growth in net electric energy production from hydropower for decades.

Nuclear energy is the other major dispatchable energy source that is increasingly presented as climate friendly, although it has been recognized that the mining of uranium results in CO₂ emissions [18]. In 2005, nuclear energy provided slightly more than 20 percent of total U.S. electric energy. Reference [17] estimates a slight increase between now and 2030 in nuclear capacity from 100 to 109 GW. Currently, six major U.S. power providers are preparing requests for combined construction and operating licenses to the Nuclear Regulatory Commission (NRC) to allow construction to begin within the next five years. The extent to which our future electric energy needs could be supplied by nuclear power is both a political and a technical question, with key issues related to nuclear waste and public safety perceptions.

Abroad, some nations are considering building their first reactors, and other countries are considering building additional reactors. Two 1,600 MW pressurized water reactors being built in Europe are slated for completion in 2008 and 2012. Britain and Canada both have plans to build new reactors. China plans to construct 30 nuclear reactors by 2020. China also views nuclear power as a major export opportunity and is currently exporting nuclear-generated electricity to Pakistan. India has nine plants of its own under construction [19].

Wind Energy: While wind energy can be harvested using

small turbines, most wind energy in the United States is generated in large wind farms which site turbines together. Currently, wind-generation capacity in the United States is 9,500 MW, with plans for 7,000 MW of new capacity. In 2005, wind energy provided approximately 0.38 percent of our total electric energy, with this percentage expected to triple by 2010 [20].

While the potential for wind energy is promising, there are several significant issues that need to be considered. One issue is that wind is intermittent, resulting in the capacity credit for wind typically ranging between 25 to 40 percent. Improvements in wind-speed forecasts will provide better estimates of the hourly availability of wind power [20]-[23]. Energy storage, demand response and/or backup generation paired with wind are other options for mitigating wind intermittency [24], [25].

Another significant issue associated with wind is that locations with the strongest wind resources tend to be remote. The transmission grid in the U.S. was not designed to deliver energy over large distances without reactive power compensation, indicating the need for upgrading the transmission system if it is to support significant wind power.

Solar Energy: As with wind energy, solar radiation is an intermittent resource. One conversion technology is the photovoltaic cell (PV), which generates dc electricity that is converted to ac with the use of a dc-to-ac inverter. A second method for converting solar energy to electricity is the concentrating solar thermal (CST) power plant. CST produces electricity by converting the energy of the sun into heat using mirrors. This heat is then used to generate steam, which is later transferred to a turbine generator to produce electricity.

Geothermal and Ocean Energy: One other possible source of energy with low GHG emissions is geothermal energy. This technology uses geothermal hot water or steam reservoirs deep in the earth. The water or steam is used to drive a turbine using a binary plant or is taken from the steam source itself. The binary plant process does not produce any emissions, but the process of taking the steam directly from the source generates a small amount of GHG. In total, the geothermal production of electricity generates 2,200 MW, mostly in California. Currently, resources are estimated at over 20,000 MW, mostly in the western states [26].

Another source of renewable energy is the ocean. This technology uses the energy of waves to drive linear generators or pumps connected to a generator. Currently, research is being done to create a generator to be used in the sea. This technology does not generate GHG but has a direct ecological impact on sea life.

Plug-in Hybrid Vehicles: Plug-in hybrid vehicles are a technology targeted as a solution to the transportation sector's need to reduce GHG emissions. Widespread use of plug-in hybrids would serve to transfer the production of these emissions from the transportation sector to the electric power sector. Wide-ranging issues relating to which generating technologies would be used in charging these vehicles, the

likely need to reinforce the transmission system to meet increased demand, the need to understand the effect on the daily load profile of vehicle charging, and the possibility of using charged batteries as distributed storage to meet system needs, all raise interesting research questions.

Demand-Side Participation: The widespread inclusion of active and responsive load in system operations, along with active participation of the demand side in electricity markets is recognized as an important, and essentially absent, element in the electric power industry. Technologies that facilitate customer involvement in the power industry are increasingly available and are likely to improve system efficiency, reduce demand, and subsequently reduce the use of fossil fuel-based technologies. This topic is discussed further in section 5.

D. The impact of GHG reduction on the transmission grid

The technologies that help reduce GHGs often present additional challenges. One of the most noticeable is the direct impact on the transmission grid. Many of these technologies will be located in remote locations with the result that any expansion in the utilization of these technologies will require the construction of new transmission lines.

MicroGrids: One alternative to expanding the high voltage transmission grid is the implementation of microgrids. Microgrids are a cluster of power sources, storage systems, and loads that can be controlled independently of the independent system operator (ISO) or other grid operator. The most notable of these proposed approaches is the CERTS Microgrid Concept [27], based on the aggregation of cogeneration systems, other generators such as microturbines, fuel cells, and reciprocating engines, and controllable loads. The generators are of small capacity and many produce low GHG emissions. The microgrid would provide power and also heat, improving overall system efficiency inside the microgrid. The generators and loads could be programmed with control characteristics to provide energy to the microgrid under different operating conditions using an Energy Management System (EMS). Currently this microgrid concept is under research and is in the process of validation on a testbed [28].

Regional transmission grids: For most of the past decades, transmission planning in the U.S. has been done to satisfy the local requirements of an area and in accordance with the North American Electric Reliability Corp. (NERC) regulations. In recent years, with restructuring and deregulation efforts, the U.S. Federal Energy Regulatory Commission (FERC) through Orders 2000 and 890 has placed the responsibility for transmission planning on regional transmission organizations (RTOs) [29]. This regionalizes transmission planning, with the requirement that any new transmission expansion needs the approval of the RTO for that region.

E. Possible Research Areas

- Develop a model to simulate the future transmission grid and system operation scenarios.

- Develop and analyze methods to improve energy conservation and efficiency.
- Analyze the effects on system load shape, transmission system expansion, system dispatch, and new control needs in response to an increased use of plug-in hybrid vehicles.
- Analyze the impact of an expansion of nuclear energy, in terms of impacts on the transmission system and power system operation, and in GHG reductions.
- Analyze system impacts and control needs of a significant penetration of large, remote wind farms.
- Research the most cost-effective CCS technologies and develop policies and/or financial instruments to clarify who will bear the costs.
- Clarify and define the objective of transmission planning in the new regime.

III. EXTREME WEATHER, BLACKOUTS, AND COMPONENT FAILURES

Electric power systems have been designed during periods of relatively stable weather and loading patterns. These design assumptions may be strained by extreme weather due to climate change. The extreme weather of interest includes directly destructive events such as hurricanes and ice storms as well as extremes of heat and cold, which affect both individual equipment failure and system operations. The effects of climate change will combine with the effects of other changes such as population migration and changes in water availability. Since power systems need to be designed and operated with respect to extremes of weather and peak loading, it is necessary to quantify likely changes in the statistics of these extremes due to changes in climate. This section evaluates the prospects for estimating the frequency and impact of equipment and system failures. A readable account of the climate science supporting the extreme weather trends and predictions is in [30].

A. Extreme Weather

Over the next 20 years, the average global surface temperature is expected to rise about 0.2 degree Celsius per decade [6]. Over the next 100 years, the average global surface temperature is expected to rise between 0.2 to 0.4 degree Celsius per decade, depending on the human response to climate change [6]. This slow average temperature increase is likely to have a slight direct impact on power systems. The key issue is the increase in the variability of temperature, precipitation, and other weather extremes.

The IPCC 2007 report [6] identifies the following trends and expects them to continue for the next 100 years, with the likelihood of these future trends exceeding 90 percent: (i) warmer and more frequent hot days and nights, and more frequent heat waves, (ii) increased proportion or frequency of heavy precipitation, and (iii) fewer cold days and nights. Also predicted with likelihood greater than 66 percent are changes in hurricane intensity; that is, hurricanes are likely to have

stronger winds and more precipitation.

It is clear that these changes in weather extremes can impact the power system infrastructure, but assessing this impact requires quantifying the rate of change of the weather extremes and comparing this to the rate of change of the power system infrastructure. The power system infrastructure changes on a time scale of decades. If extreme weather changes occur on a timescale slower than decades, then the power system can adapt to the extreme weather changes by designing expansion and equipment according to the current weather extremes. On the other hand, if the extreme weather changes significantly on a timescale of decades, then either the power system will require updated designs and more upgrades and maintenance, or the power system reliability will decrease.

The warmer and more frequent hot days will increase the peak load in summer-peaking regions at the same time as stressing power system components. Thermal limits on components are more restrictive on hot days. If components are not derated to allow for this, they may fail more frequently, age faster, and require more maintenance and earlier replacement. Control equipment may require recalibrating to derate the equipment. Problems have occurred with transformers designed to cool off at night being unable to cool down sufficiently during warm nights.

If more extreme wind gusts occur, they would cause tower and conductor damage and more faults due to galloping and trees falling. If an increase in hurricane intensity occurs, it would be necessary to update designs and to consider shifting more resources to emergency planning and restoration. This is particularly true if population migration brings more citizens to vulnerable areas.

Changes in precipitation and water runoff would affect hydro energy resources and scheduling. River water runoff is very sensitive to changes in climate, and small changes in temperature and the amount of precipitation can have a significant influence on the volume of runoff [30].

Climate change is also thought to contribute to catastrophic wildfires in the western United States, Alaska, and Canada as a result of longer, warmer growing seasons. Once trees have died back, the landscape is prone to intense crown fires rather than surface fires that are more easily suppressed. Drought and subsequent wildfires directly dries other fuels, leaving forests of healthy, living trees that are more vulnerable to crown fires [31]. Increased fire activity could have significant repercussions for the transmission system infrastructure.

B. Extreme Loading of the Power System

Growth in the demand and change in load patterns may create major bottlenecks in the delivery of electric energy. This would cause power system stress as operational conditions approach thermal and mechanical ratings of power system elements. These conditions may contribute to deterioration of dielectric materials, operating mechanisms, supporting structures, and cooling/insulating liquids. As a result, overall wear and tear impacts may be greater, leading to increased vulnerability to faults and/or breakdowns.

The effects from climate change will be exacerbated by other unusual changes not caused by climate change but whose effects combine with the effects of climate change. For example, population migration in the U.S. will affect loading patterns significantly, particularly in the West and South. Two issues need to be considered: (i) population increases in the areas most affected by climate change puts additional stress on the system, and (ii) population increases in areas with high risk for weather-related disasters brings a new dimension to planning for emergencies electricity service restoration.

C. Estimating the Effect on Blackouts

Estimating overall blackout risk is an emerging topic, and it may become feasible to estimate the effects of climate change on overall reliability [32]. The likelihood of blackouts of various sizes is thought to be mainly affected by the size of the initial disturbance to the power system (such as caused by extreme weather) and the extent to which the disturbance propagates via cascading failure. The size of the initial disturbance when the weather is more extreme is probabilistic, and it would be necessary to quantify the statistics of the extreme weather parameter, such as wind speed, and relate it to the initial damage to the power system. Some extreme weather events such as a heat wave would also tend to load the power system so as to increase the propagation of cascading failure.

D. Effect on Component Design and Maintenance

The existing power system infrastructure in the United States is valued at \$800 billion. Replacing such an infrastructure with new components having ratings required to sustain climate and load changes is unrealistic. Hence, incremental strategies for making improvements are more likely and may lead to new requirements for designing power system infrastructure as well as power apparatus. It may also lead to the development of new and more complex techniques for estimating the combined impacts of climate and load extremes.

E. Possible Research Areas

- Use predictions of regional climate change to estimate the rate of change of power system design parameters.
- Investigate robust monitoring and control techniques for harsh weather and increased load demand.
- Combine climate predictions of extreme weather with emerging blackout risk assessment.
- Develop methods for improving system restoration in case of natural disasters.

IV. U.S. FEDERAL AND STATE GOVERNMENT POLICIES

A. Federal Policies

The first federal action related to GHG emissions came in the 1990 Clean Air Act, which requires electric generating facilities subject to the acid rain provisions of the Act to also monitor CO₂ emissions [33]. In 1992, Title XVI, Global Climate Change, of the Energy Policy Act of 1992, directed

the Secretary of Energy to assess the global warming mitigation and adaptation recommendations in the 1991 National Academy of Sciences report, “Policy Implications of Greenhouse Warming” [34]. The 1992 act also established a voluntary system of reporting GHG emissions, DOE’s Voluntary Reporting of Greenhouse Gases Program, for those not covered by the 1990 rules. Both monitoring systems are still in place in 2007 [35].

Further 1992 action on climate change came with full ratification of the United Nations’ Framework Convention on Climate Change (UNFCCC), a nonbinding commitment to reduce atmospheric GHGs. The treaty itself did not set limits on GHGs but instead provided for later protocols that would set actual limits. This resulted in the December 1997 Kyoto Protocol to the UNFCCC, which committed signatories to legally binding reductions in emissions of six GHGs, including, most significantly for the electric power industry, CO₂. The U.S. goal would have been a 7 percent reduction below 1990 levels between 2008 and 2012. The Kyoto Protocol was signed by the Clinton Administration in November 1998 but was never submitted to the Senate for consent. In 2001, the Bush administration disengaged from the protocol [36].

Since 1992, all three presidential administrations have relied on voluntary limits to CO₂ emissions, and no direct federal limits have been established. Limits are in place for methane (CH₄) emissions from landfills, and U.S. Environmental Protection Agency (EPA) rules on ozone-depleting substances list global warming as one of the risk criteria for evaluating alternatives. Energy conservation initiatives indirectly reduce GHG emissions by reducing total energy use. These include appliance and commercial building efficiency standards, automotive fuel economy standards, and the conservation and renewable energy provisions of the 1978 Public Utilities Regulatory Policies Act (PURPA) [33].

Four bills that would impose mandatory limits on GHGs were introduced in the 110th Congress, which convened on January 4, 2007. All direct the EPA to impose absolute caps on emissions from electric power generation and decrease cap levels in subsequent years. Programs would begin as soon as 2010. All propose a tradable allowance system similar to that used now for acid rain reduction [37] (discussed further in section 5).

B. State Policies

In the absence of federal limits on GHGs, a number of states and even some municipal governments have implemented GHG limits. Electric generators in nine states will be subject to mandatory limits beginning in 2009 under the Regional Greenhouse Gas Initiative (RGGI). RGGI is a “cooperative effort by Northeastern and Mid-Atlantic states to reduce CO₂ emissions” [38]. RGGI is a mandatory cap-and-trade program with emissions trading.

A second regional initiative was announced by the governors of Arizona, California, New Mexico, Oregon, and Washington on February 26, 2007 [39]. This initiative will set

a regional goal for GHG emission reduction. It will be implemented with a regional emissions market and monitoring program that will cover multiple sectors and be designed by summer 2008. New bills are now being considered in various state legislatures in their 2007 sessions, and the list of states with mandatory GHG reduction programs is likely to continue growing.

California Assembly Bill 32 (AB32): The state of California is the largest contributor of GHGs in the nation, and the twelfth largest in the world, with annual emissions comparable to those of Australia [40]. While RGGI addresses only electric power generators, the California Global Warming Solutions Act of 2006 (AB 32) caps GHG emissions from all sources. AB32 was approved by the governor and filed with the Secretary of State on September 27, 2006 [41]. The key purpose of this bill is to mandate reduction in state emission levels to those of 1990 by 2020. By 2050, it will reduce emissions to 80 percent below 1990 levels. The regulation will require monitoring of all electricity consumed in the state, including transmission and distribution line losses from electricity generated within the state or imported from outside the state. This applies to all retail sellers of electricity.

C. Possible Research Areas

- Analyze the effect of system operations from changing dispatch patterns that result from production caps and changes in merit order as a result of emissions regulations.
- Analyze the impact on both existing generating plants and the power system from possible government regulations constraining the dispatch of specific types of generators.
- Analyze the effect of bills such as California’s AB32 on power system operations.
- Analyze the effect of inconsistent/conflicting regional emissions policies (in conjunction with an analysis of inconsistent/conflicting regional permit markets) in contrast to uniform, national policies.

V. MARKET MECHANISMS IN RESPONSE TO CLIMATE CHANGE

There is widespread consensus regarding the scientific understanding of climate change, with considerably less agreement concerning the appropriate responses. Market mechanisms such as a cap-and-trade policy, carbon taxation, renewables portfolio standards and price-responsive load are those that feature most prominently in the climate change literature. Although emissions trading has emerged as the frontrunner, methods to effectively combine multiple market mechanisms are also important to explore.

A. “Cap-and-Trade” Emissions Trading

Cap-and-trade emissions reduction programs have emerged as the leading market mechanism to address emissions reductions. First introduced to the electric power industry for controlling SO₂ emissions, cap-and-trade programs establish emissions limits, or caps, along with permits to produce

specified amounts of a pollutant that can be traded among producers. The market created for trading permits allows the specified emissions reduction to be achieved, while ensuring that the reductions are made by those producers who can do so at least cost [42], [44].

Some areas of the United States already have experience with trading mechanisms in the form of regional efforts, such as the Regional Greenhouse Gas Initiative [36] and the Chicago Climate Exchange [44], as well as national experience with SO₂ trading programs and the NO_x emissions trading program administered by the EPA in the eastern United States. Lessons can also be learned from international trading schemes, such as the European Union Emissions Trading Scheme [45]. The Congressional Budget Office analyzed distributional effects of carbon allowance trading in 2000 [46], and released a report in April 2007 on the current debate in Congress for a national CO₂ cap-and-trade program [47].

A GHG emissions trading market design will be a complex endeavor balancing design elements affecting distribution, efficiency, and overall efficacy of the program. The growing number of GHG markets for auctioning and trading permits, each with significant variations, results in GHG markets having an increasingly fragmented nature. This fragmentation and potential incompatibility of markets is a concern because it hinders trading between and/or the expansion of these markets. The distribution of allowances and permits also has important implications for the acceptance and ultimate success of the programs [48].

B. Carbon Tax

A carbon tax is a tax on sources that emit CO₂ into the atmosphere. In the Wall Street Journal Monthly Economic Forecasting Survey, February 2007, 85 percent of economists were found to believe that the government should encourage the development of alternatives to fossil fuels, and 54 percent believe a carbon tax raising the price of purchasing fossil fuels would be the most economical method [49]. In late January 2007, the CEOs of ten major American corporations met and called on President Bush to create mandatory ceilings on U.S. GHG emissions, demonstrating corporate support for action in limiting pollutant emissions [50].

Economist support for a carbon tax stems from the fact that these taxes could yield a double dividend by reducing carbon emissions and simultaneously reducing costs of preexisting tax distortions through revenue recycling (*i.e.*, the revenue from a carbon tax could be used to reduce other taxes, which, in turn, could increase employment and investment). Caution is necessary when implementing such a tax, since countermeasures such as granting tax breaks to industries most affected or reducing fuel taxes could undermine its effects.

An advantage cited is the transparency of the carbon tax compared with the complex permit allocation process [51]. In January 2007, a Carbon Tax Center was launched to educate and inform policy makers about the benefits of an equitable, rising, carbon tax [52]. Lessons can also be learned from studying carbon taxes implemented in Sweden, Finland, the

Netherlands, and Norway, all of which were introduced in the 1990s.

C. Demand-Side Response

One way to reduce GHG emissions is to reduce consumption, which could be achieved via conservation and demand response. Demand-response programs can be either price-based or incentive-based. Price-based programs include real-time pricing, critical-peak pricing, and time-of-use tariffs, all of which vary electricity prices to reflect the changing value and cost of electricity during different time periods. For incentive-based demand response programs, customers are paid to reduce their loads at times requested by the program sponsor, triggered either by a threat to grid reliability or high electricity prices. Examples can be found at: the New York Energy Smart Program [53]; several ERCOT programs [54]; the California Demand Response Business Network [55]; the Community Energy Cooperative [56]; Toronto Hydro's Peaksaver AC program [57]; and critical peak pricing programs in California [58].

D. Renewables Portfolio Standards

Renewables portfolio standards (RPS), policies that mandate a specified megawatt amount or percentage of electricity to originate from a renewable resource, are increasingly being adopted by state governments. In many states the motivation for mandating RPS stems from economic interests such as promoting local industry and avoiding importing fuel. Decreasing greenhouse gas emissions is also part of the motivation behind mandating RPS.

Many RPS include market mechanisms to allow trading of both renewable energy generation, quantified in renewable energy certificates (RECs), and emissions permits, quantified through cap-and-trade mechanisms. The individual REC and cap-and-trade markets are neither well-coordinated between the states nor coordinated across these similar but distinct mechanisms. Both the Northeast and Southwest are developing de facto regional markets for both mechanisms, yet without specific coordination, there is the risk of double-counting the benefits of various measures and general chaos in attempts to design well-functioning markets.

As success with state-level RPS continues, interest in national renewable portfolio standards for electricity production is increasing. Research groups such as Resources for the Future (RFF) and the Pew Center on Global Climate Change advocate the implementation of a national RPS program. Their analyses have found that RPS, when compared to other policies, are likely to be the most effective at lowering greenhouse gas emissions [59].

E. Possible Research Areas

- Research the effect of conflicts and/or inconsistencies between regional cap-and-trade markets, and conflicts with renewable portfolio standards (RECs).
- Develop new planning and risk management tools, focusing on the risk introduced by uncertainty in climate

change and government policies designed to address climate change issues.

- Analyze the effect on system and market operations if automated control systems are installed at customer locations.
- Develop optimal bidding strategies for multi-period electricity markets with uncertainty in GHG policies and mandates.

VI. LONG RANGE INDUSTRY PLANNING

A. *Electric Power Industry's Long-Range Plans for Adapting to Global Climate Change*

The electric power industry is making long-range plans along several fronts to adapt to global climate change. As introduced previously in this paper, these measures include (i) demand reduction and conservation, (ii) electricity infrastructure efficiency improvements, (iii) increased used of renewables (wind, solar, biomass, bio-fuel) and distributed generation, (iv) renewed interest in nuclear generation, and (v) CO₂ reduction, capture, and sequestration.

As with the electric power industry, most industries are planning for changes in their operating environment due to global climate change. The financial incentives motivating industry to make plans come from four main pressure points: (i) anticipated environmental regulations, (ii) opportunity to increase market share or offer a new product, (iii) prevention of financial losses, and (iv) avoidance of litigation. Monitoring activities in other industries could lead to opportunities for the electric power industry to work with these industries, and also could suggest new actions to be undertaken by the electric power industry.

B. *Other Industries' Long-Range Plans for Adapting to Global Climate Change*

Anticipating Environmental Regulations: In addition to the electric power industry, the industries furthest along in adapting to global climate change are the ones anticipating emissions regulations and adapting to keep their market share. All of the players in the automotive industry are aggressively pursuing plug-in hybrid vehicles. This technology presents opportunities and challenges for the electric power industry as discussed in section 2.

A group of corporations has partnered with environmental organizations to form the United States Climate Action Partnership (USCAP) in an effort to create a carbon-emissions cap and/or trading program in the United States [60]. USCAP members include BP, General Electric, and DuPont. The USCAP states in its first report that "Each year we delay action to control emissions increases the risk of unavoidable consequences that could necessitate even steeper reductions in the future, at potentially greater economic cost and social disruption" [61].

Opportunities to Increase Market Share: For some industries, global climate change produces new opportunities. The financial industry is developing carbon-reduction

portfolios for investors. The European Bank for Reconstruction and Development and the Dexia Group announced an equity fund that will invest in energy-efficiency projects including heating and energy [62]. In addition to regular returns, the fund also offers investors carbon-emission credits that could be traded in European markets [62]. Carbon credits have not passed the notice of larger firms. In 2006, Morgan Stanley announced a five-year program of investments in carbon credits and emissions reduction totaling approximately \$3 billion [63]. Morgan Stanley will sell the credits through its Commodities Trading Department to companies that must reduce their carbon emissions to comply with the Kyoto Protocol [63].

Many industries are offering carbon-neutral goods or services to consumers. In January of 2007, DHL announced "GoGreen," a carbon-neutral delivery service. DHL shipping pledged to use alternative and renewable technologies, including biodiesel delivery trucks, and claimed that its service would offset the CO₂ emissions involved in transportation and delivery [64]. This is by no means the first such announcement; in 2004, HSBC Holdings plc announced a program of energy use reduction, increased purchases of green power, and offsets through carbon credits in the European markets, in an effort to become carbon-neutral within three years [65].

In January of 2007, GE and AES Corporation announced a partnership meant to reduce greenhouse gas emissions [66]. The companies intend jointly to pursue reductions in methane and carbon emissions and renewable power generation, in order to cater to corporations interested in reducing their environmental impacts [67].

Some companies stand to gain from an increased focus on energy efficiency. DuPont is marketing thermal mass building materials designed to stabilize a room's temperature and reduce the need for air conditioning and heating. It is promoting these materials as a technology that will enable the construction of more sustainable and energy-efficient buildings [68]. An increased focus on alternative fuels has spurred the planning and construction of hundreds of biofuel production plants such as one in Mississippi, which is able to produce 6,000 gallons per day [69].

Preventing Financial Losses: Some industries are adapting their business to minimize or reverse anticipated losses due to global climate change. The insurance industry, which has traditionally set rates based on historical data, is now in the business of forecasting how global climate change is likely to change their risk. Actuaries, using new methods, will be proposing higher rates to accommodate higher risk. In a report released by a national coalition of investors, Ceres, it was found that "losses from weather-related insurance claims are rising faster than premiums, the population, and economic growth." The report concludes that governmental agencies, along with financial and insurance industries, have "failed to adequately study the problem and evaluate potential impacts" [70]. In an attempt to curb the losses stemming from increased

claims due to environmental conditions, the state insurance plan of Massachusetts has substantially raised rates in order to cover future natural disaster losses [70].

Avoiding Litigation: The desire to reverse/minimize losses, maintain/increase market share, or meet anticipated government regulations is the motivation for most companies to adapt to global climate change. The other adaptive pressure comes from lawsuits. Although unlikely, some industries may be found liable for their contribution to global climate change. General Motors, Ford, Toyota Motors North America, Honda North America, DaimlerChrysler, and Nissan North America are being sued by the Attorney General of California based upon a complaint that the companies are producing a product that causes economic and environmental harm to California. The companies are responding that the suit is “without merit” and planning on responding by filing for “dismissal as soon as practicable” [71].

C. Possible Research Areas

- Analyze the efficiencies of market structures where carbon trading is allowed within the electric power industry and between the electric power industry and other GHG producing industries.
- Evaluate the consequences on system stability and loss of responsiveness caused by the reduction in hydro-generation resulting from less rainfall
- Develop technology, system control methods, and market designs to improve power-system efficiency and demand-side management.

VII. CONCLUSION

Concern over global climate change and its effects on human society, sustainability and national economies is increasing. There are multiple sources of GHGs, both biogenic and anthropogenic. The electric power industry, though not the cause of the majority of these emissions, is the source of a considerable fraction which could increase if technologies such as plug-in hybrid vehicles are successful in transferring emissions currently attributed to the transportation sector over to the electric power sector. This paper has identified topics for potential research that address the interactions between the electric power industry and global climate change debate.

International attention is focused on developing mechanisms to reduce GHG emissions from electric power generation. Parallel efforts must be pursued to ensure that the power system is modernized as necessary in order to ensure that system reliability is not compromised either by changes in weather or by the efforts to reduce emissions through introducing new technologies. The objective of this paper is to facilitate continued discussion of power system—climate change interactions and to encourage integration of these issues into research projects.

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REFERENCES

- [1] Morgan, G., L. Lave, and J. Apt. (2005, Jun.). The US Electric Power Sector and Climate Change Mitigation. Pew Center on Global Climate Change. Available [Online]: http://www.pewclimate.org/docUploads/Electricity_Final.pdf
- [2] Energy Information Administration (2007, Aug.). Land Use Issues Overview. website: <http://www.eia.doe.gov/oiaf/1605/gg98rpt/land.html>
- [3] HM Treasury. (2006). Annex 7.g Emissions from the Agriculture Sector. Available [Online]: http://www.hm-treasury.gov.uk/media/2/7/annex7g_agriculture.pdf
- [4] European Federation for Transport and Environment. (2006). Greenhouse gas emissions from transport in the EU25; An analysis of 2004 data submitted to the UNFCCC. Available [Online]: http://www.transportenvironment.org/docs/Publications/2006/2006-07_ghg_emissions_transport_eea_analysis_2004.pdf
- [5] Overbye, T., J. Cardell, I. Dobson, W. Jewell, M. Kezunov, P. Sen, D. Tylavsky, “The Electric Power Industry and Climate Change: Power Systems Research Possibilities,” Final Project White Paper, PSERC Publication 07-16, Jun. 2007, Available [Online]: www.pserc.org.
- [6] Intergovernmental Panel on Climate Change, Working Group I, Climate Change 2007: The Physical Basis of Climate Change, Summary for Policymakers, (2007 Feb.). Available [Online]: <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>
- [7] Energy Information Administration, (2006, Nov.). Emissions of Greenhouse Gases in the United States. DOE/EIA-0573(2005). Available [Online]: <http://www.eia.doe.gov/oiaf/1605/ggrpt/pdf/057305.pdf>
- [8] Institute for Lifecycle Environmental Assessment. (2007). Carbon Storage and Accumulation in U.S. Forests. Available [Online]: <http://www.ilea.org/birdsey/carbon.html>
- [9] National Electric Technology Laboratory. (2006, Jun.). Carbon Sequestration Technology Roadmap and Program Plan 2006. US Department of Energy Office of Fossil Energy. Available [Online]: http://www.netl.doe.gov/publications/carbon_seq/project%20portfolio/project_portfolio2/2006%20Roadmap.pdf
- [10] D. W. Bailey and P. H. M. Feron, “Post-combustion decarbonisation process,” *Oil & Gas Science and Technology*, Rev. IFP, Vol. 60 (2005), No. 3, pp. 461-474.
- [11] International Energy Agency. (2003). CO₂ Capture and Storage in Geological Formations. Paris, France. Available [Online]: http://www.iea.org/textbase/papers/2003/CO2_Storage_Fossil_Fuels.pdf
- [12] L. I. Eide and D. W. Bailey, “Precombustion decarbonisation processes,” *Oil & Gas Science and Technology*, Rev. IFP, Vol. 60 (2005), No. 3, pp. 475-484.
- [13] National Electric Technology Laboratory and Kansas Geological Survey, National Carbon Explorer Atlas (NATCARB). website: <http://www.natcarb.org/>
- [14] United Nations Foundation. (2007, Feb.). Confronting Climate Change. Available [Online]: <http://www.unfoundation.org/SEG/>
- [15] National Energy Technology Laboratory. (2007). Technologies: Carbon Sequestration. website: http://www.netl.doe.gov/technologies/carbon_seq/index.html
- [16] T. Valdés-Solis, G. Marbán, and A. B. Fuertes, “Low-temperature SCR of NO_x with NH₃ over carbon-ceramic supported catalyst,” *Elsevier Applied Catalysis B: Environmental*, pp. 261-271, Nov. 2003.
- [17] Energy Information Administration. (2006, Feb.). Annual Energy Outlook 2006 With Projections to 2030. DOE/EIA-0383(2006). Available [Online]: [http://tonto.eia.doe.gov/FTP/ROOT/forecasting/0383\(2006\).pdf](http://tonto.eia.doe.gov/FTP/ROOT/forecasting/0383(2006).pdf)

- [18] Energy Central. (2007). Rogers: Global warming reversible: Duke CEO says keys are an emissions cap, carbon dioxide program. Available [Online]: http://www.energycentral.com/centers/news/daily/article_share.cfm?aid=5284577
- [19] Guinnessy, P. (2006, Feb.). Stronger Future for Nuclear Power. PhysicsToday.org. Available [Online]. <http://www.physicstoday.org/vol-59/iss-2/p19.html>
- [20] National Grid. (2006, Sep.). Transmission and Wind Energy: Capturing the Prevailing Winds for the Benefit of Customers. National Grid. Available [Online]: http://www.nationalgridus.com/non_html/c3-3_NG_wind_policy.pdf
- [21] EnerNex Corporation, "Final Report – 2006 Minnesota Wind Integration Study Volume 1," Nov. 30, 2006, [Online] Available: http://www.puc.state.mn.us/docs/windrpt_vol%201.pdf
- [22] R. Piwko, G. Boukarikm, K. Clark, G. Haringa, G. Jordan, N. Miller, Y. Zhou, J. Zimmerlin, (2004, Feb.). The Effects of Integrating Wind Power on Transmission System Planning, Reliability, and Operations. GE Power Systems Consulting. Schenectady, NY. Available [Online]: http://www.nyserda.org/publications/wind_integration_report.pdf
- [23] J. Blatchford, D. Hawkins, J. Lynn. (2007, Apr.). Analysis of CAISO Participating Intermittent Resource Program (PIRP) Forecasting Methodology. California Independent System Operator. Folsom, CA. Available [Online]: <http://www.caiso.com/1bbe/1bbe9f1750420.pdf>
- [24] R. Takahashi, L. Wu, T. Murata, and J. Tamura, "An application of flywheel energy storage system for wind energy conversion," 2005 *IEEE International Conference on Power Electronics and Drives Systems*, Vol. 2, pp. 932-937, Nov. 2005.
- [25] J. McDowall, "Integrating energy storage with wind power in weak electricity grids," *Elsevier Journal of Power Sources*, pp. 959-964, Nov. 2006.
- [26] C. F. Kutscher, "The Status and Future of Geothermal Electric Power," National Renewable Energy Laboratory, DE-AC36-99-GO10337, 2000.
- [27] R. H. Lasseter, "MicroGrids," *IEEE Power Engineering Society Winter Meeting*, Vol. 1, pp. 27-31, Jan. 2002.
- [28] D. K. Nichols, J. Stevens and R. H. Lasseter, "Validation of the CERTS Microgrid Concept the CEC/CERTS Microgrid Testbed," *IEEE Power Engineering Society Meeting*, Montreal, Canada, June 2006.
- [29] U.S. Department of Energy. (2002, May). National Transmission Grid Study. Available [Online]: <http://www.oe.energy.gov/DocumentsandMedia/TransmissionGrid.pdf>
- [30] J.T. Houghton, *Global Warming: The Complete Briefing*, Third Edition, Cambridge University Press, Cambridge UK 2004.
- [31] US Department of Agriculture Forest Service. (2007, May). Research and Development – Climate Change. Available [Online]: <http://www.fs.fed.us/research/fsgc/climate-change.shtml>
- [32] I. Dobson, Where is the edge for cascading failure?: challenges and opportunities for quantifying blackout risk, IEEE Power Engineering Society General Meeting, Tampa FL USA, June 2007.
- [33] B. D. Yacobucci and L. Parker. (2006, Feb.). Climate Change: Federal Laws and Policies Related to Greenhouse Gas Reductions. Congressional Research Service, Washington, DC. Available [Online]: <http://www.ncseonline.org/NLE/CRSreports/06Mar/RL31931.pdf>
- [34] National Academy of Sciences, Committee on Science. (1991). Engineering, and Public Policy, Policy Implications of Greenhouse Warming. National Academies Press. Available [online]: <http://books.nap.edu/openbook.php?isbn=0309044405>
- [35] US Department of Energy, Energy Information Administration. (2005). Voluntary Reporting of Greenhouse Gases Program. US Department of Energy, Washington, DC. Available [Online]: <http://www.eia.doe.gov/oiaf/1605/frntvrgg.html>
- [36] S. R. Fletcher. (2005, Jul.). Global Climate Change: The Kyoto Protocol. Congressional Research Service. RL30692. Available [online]: <http://fpc.state.gov/documents/organization/50815.pdf>
- [37] L. Parker (2007, Jan.). Climate Change: Greenhouse Gas Reduction Bills in the 110th Congress. Congressional Research Service. Washington, DC. Available [online]: <http://fpc.state.gov/documents/organization/80247.pdf>
- [38] Regional Greenhouse Gas Initiative, website: <http://www.rggi.org>
- [39] Western Regional Climate Action Initiative. (2007, Feb.). Available [Online]: http://www.governor.wa.gov/news/2007-02-26_WesternClimateAgreementFinal.pdf
- [40] J. Eilperin. (2006, Sep.). California Tightens Rules on Emissions. The Washington Post Page A01. Available [Online]: <http://www.washingtonpost.com/wp-dyn/content/article/2006/08/31/AR2006083100146.html>
- [41] California Secretary of State. (2006, Sep.). California Global Warming Solutions Act of 2006. Available [Online]: http://www.law.stanford.edu/program/centers/enrlp/pdf/ab_32_bill_20060927_chaptered.pdf
- [42] Union of Concerned Scientists. (2005, Spring). Cap and Trade Systems. Catalyst Vol. 4, No. 1. Available [Online]: <http://www.ucsusa.org/publications/catalyst/page.jsp?itemID=27226959>
- [43] Union of Concerned Scientists. (2006, Jul.). Cap-and-Trade: Policy Framework for Reducing Global Warming Emissions. Available [Online]: http://www.ucsusa.org/global_warming/solutions/climate-stewardship-act.html
- [44] Chicago Climate Exchange, website: <http://www.chicagoclimatex.com/>
- [45] Pew Center on Global Climate Change. (2006, Feb.). Agenda for Climate Action. Available [Online]: http://www.pewclimate.org/docUploads/PCC_Agenda_2.08.pdf
- [46] Dinan, T. and D. L. Rogers. (2000, Jun.). Who Gains and Who Pays Under Carbon Allowance Trading?: The Distributional Effects of Alternative Policy Designs. Congressional Budget Office, Washington, DC. Available [online]: <http://www.cbo.gov/ftpdocs/21xx/doc2104/carbon.pdf>
- [47] Congressional Budget Office. (2007, Apr.). Trade-Offs in Allocating Allowances for CO₂ Emissions. Available [Online]: http://www.cbo.gov/ftpdocs/80xx/doc8027/04-25-Cap_Trade.pdf
- [48] Palmer, K., D. Burtraw, and D. Kahn. (2006, Jun.). Simple Rules for Targeting CO₂ Allowance Allocations to Compensate Firms. Resources for the Future Discussion Paper 06-28. Washington, DC. Available [Online]: <http://www.rff.org/Documents/RFF-DP-06-28.pdf>
- [49] Wall Street Journal. (2007, Feb.). Monthly Economic Forecasting Survey: February 2007. Available [Online]: http://online.wsj.com/public/page/2_0891.html
- [50] Mufson, S., "CEOs Urge Bush To Limit Greenhouse Gas Emissions," *Washington Post*, January 23, 2007, Page A06.
- [51] Parry, I. (2003, Dec.). Fiscal Interactions and the Case for Carbon Taxes over Grandfathered Carbon Permits. Discussion paper 03-46 Resources for the Future. Washington, DC. Available [Online]: <http://www.rff.org/Documents/RFF-DP-03-46.pdf>
- [52] Carbon Tax Center, www.carbontax.org
- [53] New York State Energy Research and Development Authority (NYSERDA). (2007). Energy Smart Program, Available [Online]: <http://www.GetEnergySmart.org>
- [54] U.S. Department of Energy, Energy Efficiency and Renewable Energy. (2007, Jun.). Energy-Efficiency Funds and Demand Response Programs, Texas. Available [Online]: http://www1.eere.energy.gov/femp/program/utility/utilityman_em_tx.html
- [55] Vojdani, A., S. Neumann, and M. Cain. (2005, Mar.). California Demand Response Business Network, Executive Summary. No. 500-01-043, DR04-01, Utility Integration Solutions, Inc. Lafayette, CA. Available [Online]: http://www.ucop.edu/ciee/dret/d/wrkshps/documents/ws0405_exec_sum.pdf
- [56] Energy Smart Pricing Plan. Chicago, IL. website: <http://www.energycooperative.org/energy-smart-pricing-plan.php>
- [57] Toronto Hydro Peak Saver Program, PowerWISE. website: <http://www.torontohydro.com/electricsystem/powerwise/peaksaver/index.cfm>
- [58] Critical Peak Pricing Programs in California. PG&E website: http://www.pge.com/biz/demand_response/critical_peak_pricing/index.html
- [59] Palmer, K. and D. Burtraw. (2004, May). Electricity, Renewables and Climate Change. Resources For the Future, Washington, DC. Available [Online]: <http://www.rff.org/rff/Documents/RFF-RPT-Renewables.pdf>
- [60] Sissel, K., "Major Corporations Form Advocacy Group to Curb Climate Change" *Chemical Week*. Jan. 31, 2007. Pg 12.
- [61] United States Climate Action Partnership. (2007, Jan.). A Call for Change. Available [Online]: <http://www.us-cap.org/ClimateReport.pdf>
- [62] European Bank for Reconstruction and Development. (2000, Feb.). EBRD and Dexia sponsor an innovative equity fund for energy efficiency and emissions reductions investments. Press Release.

Available [Online]:

<http://www.ebrd.com/new/pressrel/2000/17feb15x.htm>

- [63] Morgan Stanley. (2006, Oct.). Morgan Stanley to Invest in \$3bn of Emissions Reduction Credits and Other Related Initiatives. Morgan Stanley Press Release. Available [Online]:
<http://www.morganstanley.com/about/press/articles/3818.html>
- [64] DHL. (2007, Jan.). DHL's GoGreen service helps World Economic Forum meet its carbon neutral promise for Davos. DHL Press Release. Jan 18, 2007. Available [Online]:
http://www.dhl.com/publish/g0/en/press/release/2007/180107_high.html
- [65] HSBC. (2004, Dec.). HSBC world's first major bank to go carbon neutral. HSBC Press Release Dec. 6, 2004, Available [Online]:
http://www.hsbc.com/hsbc/news_room/news/news-archive-2004?cp=/public/groupsite/news_room/2004_archive/hsbc_will_be_the_worlds_first_major_bank_to_go_carbon_neutral.jhtml&isPc=true
- [66] A. Selko. (2007, Jan.). GE & AES Corp. Partner To Reduce Emissions. Industry Week. January 19, 2007. Available [Online]:
<http://www.industryweek.com/ReadArticle.aspx?ArticleID=13429>
- [67] General Electric. (2007, Jan.). GE, AES Plan Partnership To Lead US Market In Offsetting Greenhouse Gas Emissions. Joint Press Release, GE Energy Financial Services & AES Corporation. January 16, 2007. Available [Online]:
http://www.geenergyfinancialservices.com/press_room/press_releases/AES-GE%20PressRelease11507_FINAL_ForDistribution.pdf
- [68] DuPont (2007). DuPont™ Energain™ DuPont Corporate Website. Available [Online]:
http://www2.dupont.com/Energain/en_GB/index.html
- [69] A. Selko. (2007, Jan.). Green Fuel Production. Industry Week. January 22, 2007. Available [Online]:
<http://www.industryweek.com/ReadArticle.aspx?ArticleID=13445>
- [70] American Chemical Society, "Environmental Science & Technology," February 1, 2006.
- [71] Ford Motor Co., Quarterly Report, November 14, 1006.

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