Predicting the Impact of Climate Change on U.S. Power Grids and Its Wider Implications on National Security

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Abstract
We discuss our technosocial analytics research and development on predicting and assessing the impact of climate change on U.S. power grids and the wider implications for national security. The ongoing efforts extend cutting-edge modeling theories derived from climate, energy, social sciences, and national security domains to form a unified system coupled with an interactive visual interface for technosocial analysis. The goal of the system is to create viable future scenarios that address both technical and social factors involved in the model domains. These scenarios enable policymakers to formulate a coherent, unified strategy towards building a safe and secure society. The paper gives an executive summary of our preliminary efforts in the past year and provides a glimpse of our work planned for the second year of a multi-year project being conducted at the Pacific Northwest National Laboratory.

Introduction
The paper presents our ongoing technosocial analytics research and development (R&D) on predicting the impact of climate change on U.S. power grids and its wider implications on national security. The interdisciplinary R&D effort extends the latest modeling theories and practices derived from atmospheric physics, electrical engineering, building engineering, social sciences, economics, and public policy to form a tightly coupled technosocial predictive analytics system. A major challenge in our work is the granularity differences, in terms of both data and methodology, among the domain models. One solution is to provide a highly interactive visual analytics layer on top of the domain components to facilitate the integration of evidence and arguments required by and generated from the different models. The integrated system creates viable future scenarios that address both technical and social factors involved in all model domains. These scenarios enable policymakers and stakeholders to formulate a coherent, unified strategy towards building a safe and secure society.

The paper describes the background and motivation of our work and summarizes our R&D efforts carried out in the past year. Preliminary results on predicting the impact of climate change on both social and technical aspects of our society in the next 50 years are discussed. More advanced features and parameters are suggested at the end of the paper.

Background and Motivation
To communicate the significance of our work, we first describe the background of the problems and our motivation to pursuing them.

We live in a society that is vitally dependent on a network infrastructure of natural, man-made, and human resources to function—from food to water supplies, from electric power to other fuel sources, and from communication and transportation to medical and emergency services. While these resources are seamlessly integrated into the fabric of our society, electric power has the highest “network reachability”—and all the other network resources depend on it to operate. Losing electric power inevitably impairs the ability of the other resources to perform, which...
could cripple society if a widespread outage persisted for prolonged periods.

The August 2003 blackout in the Northeast and Great Lakes provides a glimpse of the struggle for survival brought by a widespread power loss. In a matter of hours, the lives of 50 million people in these areas were significantly affected by overwhelmed or disrupted infrastructure services.

Even though power to most of the affected areas was restored within a day, the official estimation of the outage-related financial losses was $6 billion USD. Similar blackouts happened in the western grid in July and August of 1996. The high summer temperature played a critical role in pushing the electric power systems to the point of failure when people turned to fans and air conditioning to beat the heat.

Soon after the 2003 blackout, the vulnerability of our nation’s electric power grids was the focus of attention of policy makers and their scientific advisors. A scientific panel (United States Congress, Office of Technology Assessment 1990) testified before the U.S. Congress and painted a grim scenario of the consequences of an organized terrorist attack on our electric power systems:

“…with the power out even a day or two, both food and water supplies would soon fail. Work, jobs, employment, business and production would be stopped. Our economy would take a major hit. All in all our cities would not be very nice places to be... Haves and have-nots would get involved. It would not be a very safe place to be either. Martial law would likely follow.…”

While the congressional panel focused mainly on the terrorist attack scenario, the climate change impact on the power grids would only act as a “threat multiplier” that would greatly increase the likelihood of a widespread extended blackout and further intensify the scope of damage to our society. In a highly influential and widely publicized 2004 article in the journal Science, Meehl and Tebaldi (Meehl, G.A. and Tebaldi C. 2004) predicted that “more intense, more frequent, and longer lasting heat waves” will arrive soon in the 21st century. To remind people about the threat of an extended heat wave, the article cited the 2003 Paris heat wave when the death toll reached nearly 15,000.

Meehl and Tebaldi’s prediction, if correct, would almost guarantee extended periods of blackouts in our future. Our underlying motivation is to attempt to take a view into the probable future of our society and predict likely scenarios that may very well come into being in our life time.

Related Work

From a literature review standpoint, our work represents a unique opportunity to “connect the dots” of several domain-specific modeling efforts that constitute our underlying predictive analytics problem. We have yet to find similar work that shares a comparable degree of ambition and complexity as our problem. On the other hand, a number of recent investigations have examined problems similar to portions of our work, but with different approaches and emphases.

The State of California has recently sponsored an investigation on the impact of global climate change on building energy usage (Xu, P. et al. 2007). The study, which focuses geographically on the state of California, pays great attention to the building energy usage and does not consider the impact of electric power stability and social dynamics.

The National Infrastructure Simulation and Analysis Center (NISAC) (National Infrastructure Simulation and Analysis Center 2008) at Sandia National Laboratory has a suite of modeling tools to simulate different national security problems from bioterrorism to natural disasters. Multi-agent technology for adaptation in dynamic environments is applied extensively to play out possible scenarios, which is very different from our approach that relies heavily on scientific evidence and consensus.

Finally, researchers at the Pacific Northwest National Laboratory are investigating the vulnerability of food security and energy infrastructures to climate change and terrorism (Vulnerability of Food Security and Energy Infrastructures to Climate Change and Terrorism 2008). The study, which focuses on the areas of India, Pakistan, and Bangladesh, models the “broad domains that are crucial to the understanding of global issues involved in climate change and human security.” This project shares a common theme with our research that demonstrates the link between climate change, security, and social development.

Technosocial Predictive Analytics

This section presents an overview of our multidisciplinary technosocial predictive and analytics project, highlights research and development results to date, and discusses new tasks planned for the next phase of this research.

Overview

Our interdisciplinary project involves four major components that address problems arise in the 1) climate, 2) social, 3) building and power grids, and 4) security and infrastructure analytics domains. Figure 1 shows an overview of the system with various modeling features highlighted in individual model components. While the climate component accepts input mainly from external sources, the other three accept input from each other as well as from external sources. On top of these components is a thin visual analytics layer that facilitates the integration of evidence and arguments required by and generated from the model components.

Preliminary Results

The R&D activities of this project are ordered and coordinated gradually and sequentially. The lead components will provide just enough groundwork for the next component to take off before returning to the refinement stage to enrich the component models.
We have completed the climate analytics work on temperature modeling and finished most of the building energy simulations, which are required for the power grid simulation. On the social study front, we have focused our investigation on the impacts of demographic and technological changes to our study. A preliminary visual analytics system prototype has been developed to guide analysis among the domain components and present results.

We have so far made progress on all four domain components. While the linkages among the components have not been fully established after the first year of the work, individual results have already shed some light on possible issues in the future.

Climate Analytics

In the past year, we downloaded climate model outputs archived at the Program for Climate Model Diagnostics and Intercomparison (PCMDI) (Program for Climate Model Diagnosis and Intercomparison 2008) for the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change 2008). We obtained hourly simulation outputs from 23 global climate models that used the IPCC Special Report on Emission Scenarios (SRES) A1B emission scenario. We focused on two 10-year periods around 2000 and 2050 for comparison of future and current climate. The simulated surface temperatures were bias corrected based on the observed climatology for Calgary (AB, Canada), Vancouver (BC, Canada), Portland (OR), Billings, Salt Lake City, Sacramento, Los Angeles, San Francisco, Boulder, and Phoenix in the United States and Canada.

The bias-corrected hourly temperature data (a total of 260 time series) for the above ten cities have been used in developing the building, energy, and power grid analytics described below. The global climate simulations show an increase in the mean daily maximum temperature of 2-3°C, but larger increase in extreme daily maximum temperature by 4-6°C, especially during late summer and fall. Analysis is being performed on potential changes in extreme temperatures and heat waves. The bias corrected surface temperatures for the ten cities are stored in a relational database system, which can be interactively queried using our visual analytics tool when it is ready for deployment.

Building, Energy, and Power Grid Analytics

We use the DOE-2 (DOE-2 2008) program to simulate building electric energy end-use. DOE-2 uses a description of the building layout, construction, usage, conditioning systems (lighting, HVAC, etc.) and utility rates provided by the user, along with weather data, to perform an hourly simulation of the building and to estimate utility bills. The commercial building prototypes are from the Database for Energy Efficient Resources (DEER) (DOE-2 Weather Processor). The DOE-2 model uses building prototype and measure characterization information by building type, vintage, and climate zone in its estimation of measure savings.

The temperature (T) sensitivities of the building total energy consumption (E\text{daily}) as well as the peak hourly load (P\text{peak}) are derived from the DOE-2 simulation results using the temperature profile for a typical meteorology year (TMY). Then piece-wise curve fitting technique is used to derive the T-E\text{daily} and T-P\text{peak} curves for each building type based on day types. There are three day types: Weekday, Weekends, and Holiday. Note that all the Sundays and public holidays are included in the Holiday category. An example is shown in Figure 2.2

The bias-corrected IPCC modeling results of years 1991-2000 represent the temperature profile for period Now. For each day in a year within this period, there are 260 T\text{max} and T\text{min}. The 260 data points are bias corrected using TMY data. The bias-corrected IPCC modeling results of year 2045-2054 represent the temperature profiles for the period Future. Building level energy consumptions are then calculated using these temperature profiles as inputs.

The following assumptions are made to produce the baseline result for future building energy consumption: Assume that the 260 T\text{max} and T\text{min} predicted for a specific day in a year by the 26 IPCC climate models for a ten-year span are treated equally, i.e., they have equally likely chance of occurrence. For the base Future case, no new technology and no new policy are implemented. Everything stays the same for the building simulated over the next 50-year period.

2 Contact authors for color version of the graphics.
Heating loads are supplied by natural gas in the DOE-2 model and in the unit of btu. At this stage, we only study the influence of the cooling loads because it is the cooling load that puts stress on the power system when average temperatures in each region increase.

The percentage changes are calculated by:

$$L_{ave}^{E} = \frac{E_{ave}^{f} - E_{ave}^{n}}{E_{ave}^{n}}$$

where $E_{ave}^{n}$ is the monthly average consumption of the Year 1991 – 2000 and $E_{ave}^{f}$ is the monthly average consumption of the Year 2045 – 2054 for all the 260 model produced monthly energy consumptions.

So far we have made the following observations using the results from the Portland and Phoenix areas:

- The total building energy consumption for Portland shows a very small increase because of the decrease of the winter load and the mild increase of the summer load for an average year. For example, for each building type, under a baseline $T_{max}$ and $T_{min}$, which are 40ºF and 30ºF for January in Portland, the monthly consumption may decrease by 5% in 2045-2055, for which year, the $T_{max}$ and $T_{min}$ are 45ºF and 35ºF.
- For extreme cases, however, we will see a huge increase in the building load consumption. This suggests that for a typical hot year, the energy consumption can skyrocket, causing a power shortage in a wider area than now.
- The residential buildings see more increases because a/c load consists of a large percent of total building loads.
- Phoenix sees more cooling load increase than Portland in general, but the trends are different for the two areas as shown in Figure 3. Portland mainly sees load increase in summer months, while Phoenix sees an energy increase in winter, spring and autumn months, which suggests the hot days are spreading out to these “cooler” seasons.
- During winter, energy consumption may drop due to the drop of heating load. Note that the major heating load is not included in the total loads because in many areas, the major heating load is supplied by gas. In the future, we will present the climate impacts on the heating load.

Social Analytics The above study shows that the direct social impact is the penetration of a/c load. In residential buildings, to maintain a comfortable living environment, people who can afford to will install a/c in their households, and those who cannot afford will either move to areas with mild temperature changes, such as the Northern coastal cities, or seek help from government. This will result in a demographical change in population and create a social crisis from low-income homes.

For commercial building owners, a significant increase in load may saturate the a/c system and overload the electrical circuits. Much higher energy bills may incur if real time pricing is to be implemented in the future.

To mitigate the adverse impact of the load increases resulting from climate change, technology should advance in a direction that helps to either directly reduce the load in-
al. 2000), to social networks (Wasserman and Faust 1994),
to identify structurally important nodes in an electricity
network. This information may be useful in determining
where the limited resource is allocated and thus prevent
undesired events (like blackouts).

Anticipating the results of the power grid simulation re-
sults using the Positive Sequence Load Flow Software
(PSLF) (Positive Sequence Load Flow Software 2008) si-
mulation from the power grid analytical component, we
use four network measures, which are betweenness centra-
lity, closeness, degree centrality and eigenvector, to identify
potential vulnerabilities of the Western Electricity Coordi-
nating Council (WECC) (Western Electricity Coordinating
Council 2008) infrastructure. These vulnerabilities are
ranked and the results will be correlated to the outcomes of
the PSLF simulation to better understand and predict the
future evolution of the North American power grid. Figure
6 shows the top-ranked locations that are ranked highly in
different centrality measures. For examples, from a net-
work security standpoint, breaking up of buses (network
nodes) that carry high betweenness ratings (red in Figure
6) can lead to serious islanding problems, which, if not
handled properly, may quickly result in a power blackout.)

**Visual Analytics** To address the problem of the “black
box” effect in many modeling processes, we include a thin
visual analytics layer to encapsulate the major domain
processes into one predictive system. The customized visu-
al analytics layer, which provides a high degree of anima-
tion and interactive modeling scenarios, allows the mod-
elers to analytically explore inputs, assumptions, and algo-
rithms of individual domain theories and their cascading
impacts contributing to the scenarios. The system, which is
currently under development, will support visualization of
climate scenario, energy consumption and generation, crit-
cial infrastructure implications, and environmental changes
alongside the corresponding geographic information.

**Figure 5.** Predicted changes of building energy consumption
for grocery store between 1991-2000 and 2045-2054: 1) No
technology improvement, 2) set point change, 3) more efficient
lighting, 4) and more efficient AC system.

**Figure 6.** Buses (network nodes) that are ranked highly in
different centrality measures are shown in red (betweenness),
green (closeness), blue (degree), and orange (eigenvector).

**Ongoing and Future Work**

The climate analytics study will continue to investigate the
potential impact of different temperature scenarios on the
WECC grid. We will study the influence of solar activities
and humidity on California building energy consumption.
The correlation of temperature in some coastal areas is not
as strong as the correlation in inland areas. Factors other
than temperature will also be included.

The building, energy, and power analytics study will
finish up the building energy model work for all ten se-
lected cities, run the PSLF regional level simulation to
study the system level impact, work with the social analyt-
cics colleagues to investigate and integrate the results of the
social analytics studies, and identify the potential impact to
the power grid infrastructure. We will also investigate ad-
verse impact of the extreme events on power system secu-

The social analytics study will continue to insert new
social factors into our predictive model. Major topics to
consider include lifestyle changes, economic sectors, mar-
ket behaviors, and policy changes. The results will be re-
dispached by the model to study their impacts on the pow-
er grids.

The infrastructure analytics study will investigate mul-
tiple critical infrastructures related to the power grid infra-
structure. Network graph theories will be applied exten-
sively to investigate the dependencies among the affected
infrastructures. The outcomes will be correlated with the
PSLF simulation results to discover hidden security vulne-
rabilities and identify necessary security safeguards and/or corrective actions.

The visual analytics study will continue to work on a prototype system that links all four models together into a working analytical tool. Much of the information underneath the system front-end will be made available for the users through interactive data visualization and navigation means.

Additionally, we will verify the accuracy of our work and results using our models to predict both the past and future. The past model results will be compared with historical archives from sources such as U.S. Climate Change Science Program (CCSP) (Climate Change Science Program 2008) and Western Electricity Coordinating Council (WECC) model validation working group.

**Conclusion**

The paper discusses our ongoing technosocial analytics research and development on predicting the impact of climate change on U.S. power grids and its wider implications on national security. Preliminary results from the past year provide significant evidence to support our hypotheses for individual components; however we will learn more when we have established all the linking among the components. We plan to report more in-depth results and discussion in the future when all the required linkages among the domain models, as depicted in Figure 1, are fully established.

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**References**


