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[1] 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. An example of climate change is an increased atmospheric temperature, which in turn increases electricity consumption. The increased temperature also affects precipitation, which changes the natural hydrological process and thus hydroelectric generation; it also influences wind electricity generation. Together, these demands could adversely affect the U.S. power grids and cause a widespread outage. If such an outage persisted, it would impair the ability of our entire critical infrastructure to perform and could potentially cripple our society. Our work is to investigate the potential impact and implications of these changes to the society in the next 50 years from both a technical and social perspective.

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

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[1] Technosocial Predictive Analytics Initiative is a Laboratory-Directed Research and Development project at the Pacific Northwest National Laboratory.

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.

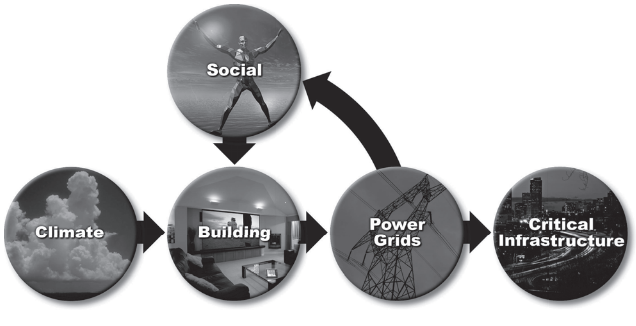

Figure 1: An overview of the model system.

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^{o}C, but larger increase in extreme daily maximum temperature by 4-6^{o}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_{daily}) as well as the peak hourly load (P_{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_{daily} and T-P_{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].

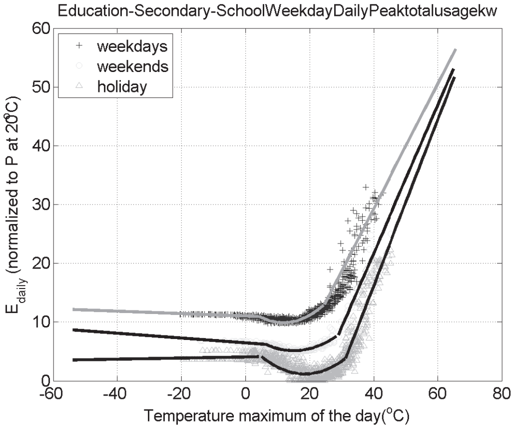

Figure 2: The temperature sensitivity of the total energy consumption of a typical secondary school building.

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_{max} and T_{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_{max} and T_{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.

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[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:

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

where E^{n}_{ave} is the monthly average consumption of the Year 1991 – 2000 and E^{f}_{ave} 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 increase by making appliances or electrical equipment more efficient or manage the load to shift the peak load to off-peak periods. Three technologies are studied: increase the a/c system efficiency, increase the lighting efficiency, and change the thermostat setpoints to manage peak loads. The results are shown in Figures 4 and 5.

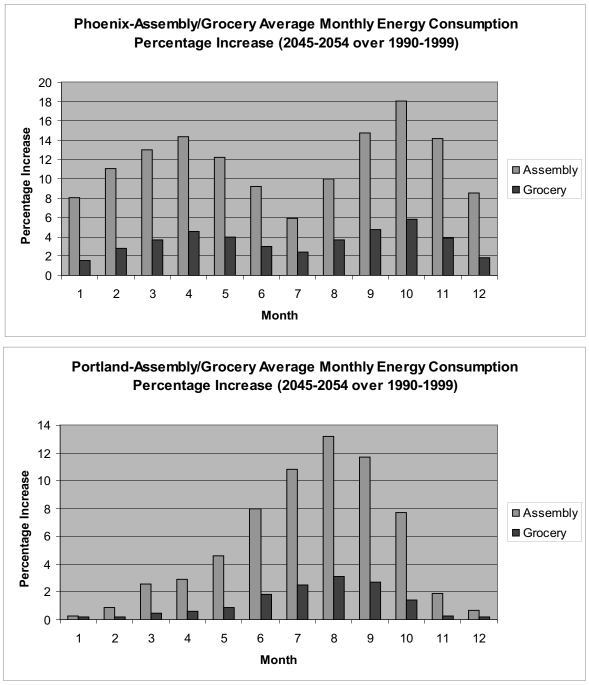

Figure 3: The trend of energy consumption increase in Portland and Phoenix area.

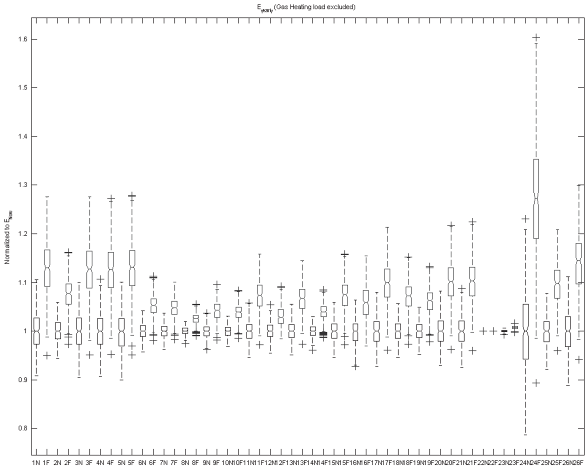

Figure 4: Predicted changes of energy consumption by buildings in Phoenix between 1991-2000 (black) and 2045-2054(pink).

Security Analytics The electricity infrastructure is a physical network where nodes represent transmission substations, power substations, and distribution buses, and edges represent transmission lines. We use network analysis (Newman, M.E.J. 2008), which has shed light on the properties of a variety of networks from the internet backbone (Faloutsos et al. 1999), transportation networks (Banavar et

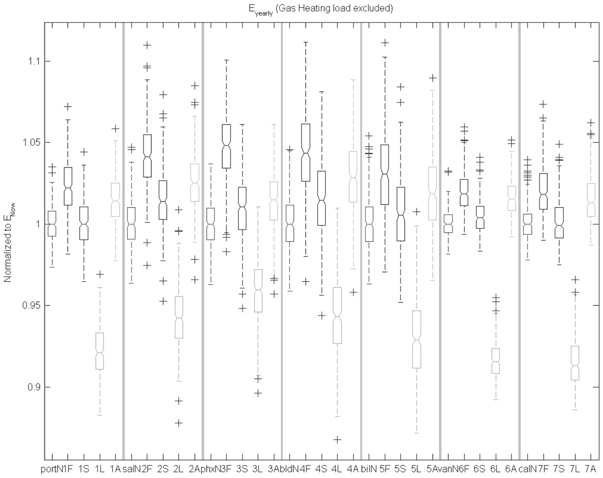

Figure 5. Predicted changes of building energy consumption for grocery store between 1991-2000 and 2045-2054: 1) No technology improvement, 2) set point change, 3) more efficient lighting, 4) and more efficient AC system.

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 results using the Positive Sequence Load Flow Software (PSLF) (Positive Sequence Load Flow Software 2008) simulation from the power grid analytical component, we use four network measures, which are betweenness centrality, closeness, degree centrality and eigenvector, to identify potential vulnerabilities of the Western Electricity Coordinating 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 network 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 visual analytics layer, which provides a high degree of animation and interactive modeling scenarios, allows the modelers to analytically explore inputs, assumptions, and algorithms 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, critical infrastructure implications, and environmental changes alongside the corresponding geographic information.

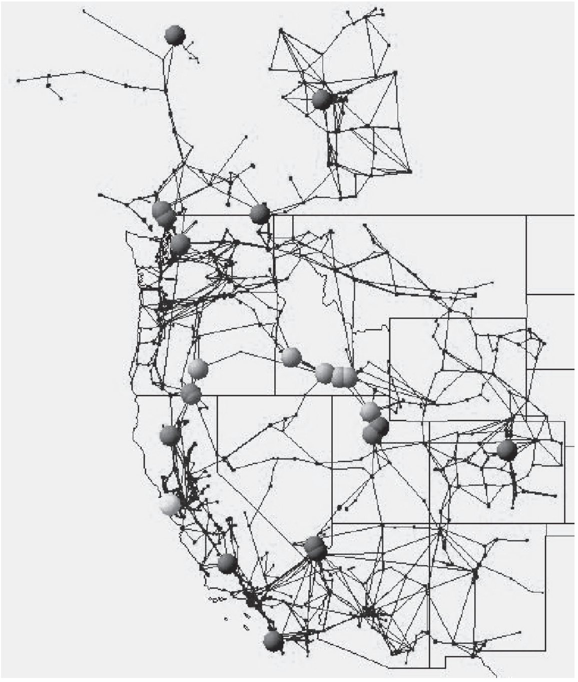

Figure 6. Buses (network nodes) that are ranked highly in different centrality measures are shown in red (betweenness), green (closeness), blue (degree), and orange (eigenvector).

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 selected cities, run the PSLF regional level simulation to study the system level impact, work with the social analytics 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 adverse impact of the extreme events on power system security and reliability.

The social analytics study will continue to insert new social factors into our predictive model. Major topics to consider include lifestyle changes, economic sectors, market behaviors, and policy changes. The results will be redispatched by the model to study their impacts on the power grids.

The infrastructure analytics study will investigate multiple critical infrastructures related to the power grid infrastructure. Network graph theories will be applied extensively to investigate the dependencies among the affected infrastructures. The outcomes will be correlated with the PSLF simulation results to discover hidden security vulnerabilities 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.

Acknowledgments

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