Designing a Collaborative Visual Analytics Tool for Social and Technological Change Prediction

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An interdisciplinary team designed and developed GreenOracle, a collaborative visual analytics tool for predicting global climate change's impact on US power grids and its implications for society and national security. These future scenarios provide critical assessments and information to help policymakers and stakeholders formulate a coherent, unified strategy toward shaping a safe, secure society.

Climate change can involve an increase in atmospheric temperature, which increases electricity consumption when people turn to fans and air conditioning to find relief from the heat. Increased temperature also affects precipitation, which changes the natural hydrological process and thus hydroelectric generation. It also influences wind electricity generation. Together, these supply-and-demand changes could adversely affect power grids and cause a widespread outage. The problem doesn't stop there. Society depends on a networked infrastructure of natural, man-made, and human resources—food and water supplies, electric power and other fuel sources, communication, transportation, and medical and emergency services. Although these resources are seamlessly integrated into the fabric of society, electric power has the highest network reachability (that is, the notion of being able to move from one point in a network to some other points), and all the other network resources depend on it to operate. Losing electric power inevitably impairs other resources' ability to perform, which could bring a range of social and economic problems that could threaten society's stability.[1]

Our ongoing research on collaborative visual analytics (VA) extends the latest modeling theories derived from atmospheric physics, electrical engineering, building engineering, social sciences, economics, public policy, and national security to create viable scenarios of society in the foreseeable future. The far-reaching research goal is to model and predict global climate change's impact on US power grids and its wider implications for society and its critical infrastructures. These future scenarios provide critical information that policymakers and stakeholders can use to formulate a coherent, unified strategy for shaping a safe, secure society.

The underlying research is part of a larger *technosocial predictive analytics* (TPA; http://predictive-analytics.pnl.gov) R&D effort recently launched at the Pacific Northwest National Laboratory (PNNL).[2] TPA is a hybrid science that promotes knowledge discovery through the integration and synthesis of technological and social modeling (for more information, see the "Technosocial Predictive Analytics" sidebar). Here, we focus on the design and development of GreenOracle—a collaborative VA system that integrates modeling theories and interacts with users. Our modeling results are available elsewhere.[3]

GreenOracle's VA platform lets domain scientists collaboratively study the combined efforts of their modeling work toward a common scientific goal. Beneath GreenOracle's visual interface is a federation of models and simulations that share the resources and model results in a tightly coupled environment. Domain scientists are respon-

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Technosocial Predictive Analytics

The Technosocial Predictive Analytics (TPA) Initiative focuses on developing new methods for predictive analysis that support decision-making through the integration of human and physical models, leveraging insights from the social and natural sciences. TPA helps users provide better analysis and response by enabling naturalistic decision-making while countering adverse influences on human judgment through the integration of three main components:

- *Knowledge encapsulation* deals with the acquisition, vetting, and dissemination of expert knowledge and evidence to support the modeling task and provide knowledge feedback during analysis and decision-making.
- *Technosocial modeling* addresses the integration of physical and human models.
- *Analytic gaming* exploits visual interactivity and collaborative workflows to stimulate creative and competitive thinking for decision-making.

The TPA Initiative is integrating these three components into a simulation laboratory that provides a physical and virtual space, with associated processes, computing hardware, and capabilities (see Figure A). The modeling and knowledge encapsulation components inform human judgment during analysis, decision-making, and gaming to stimulate creativity and insight through collaborative and competitive role-playing interaction. Such real-time simulations let analysts and policymakers stress-test their analytical models, theories, and theses without waiting for history to prove them right or wrong.

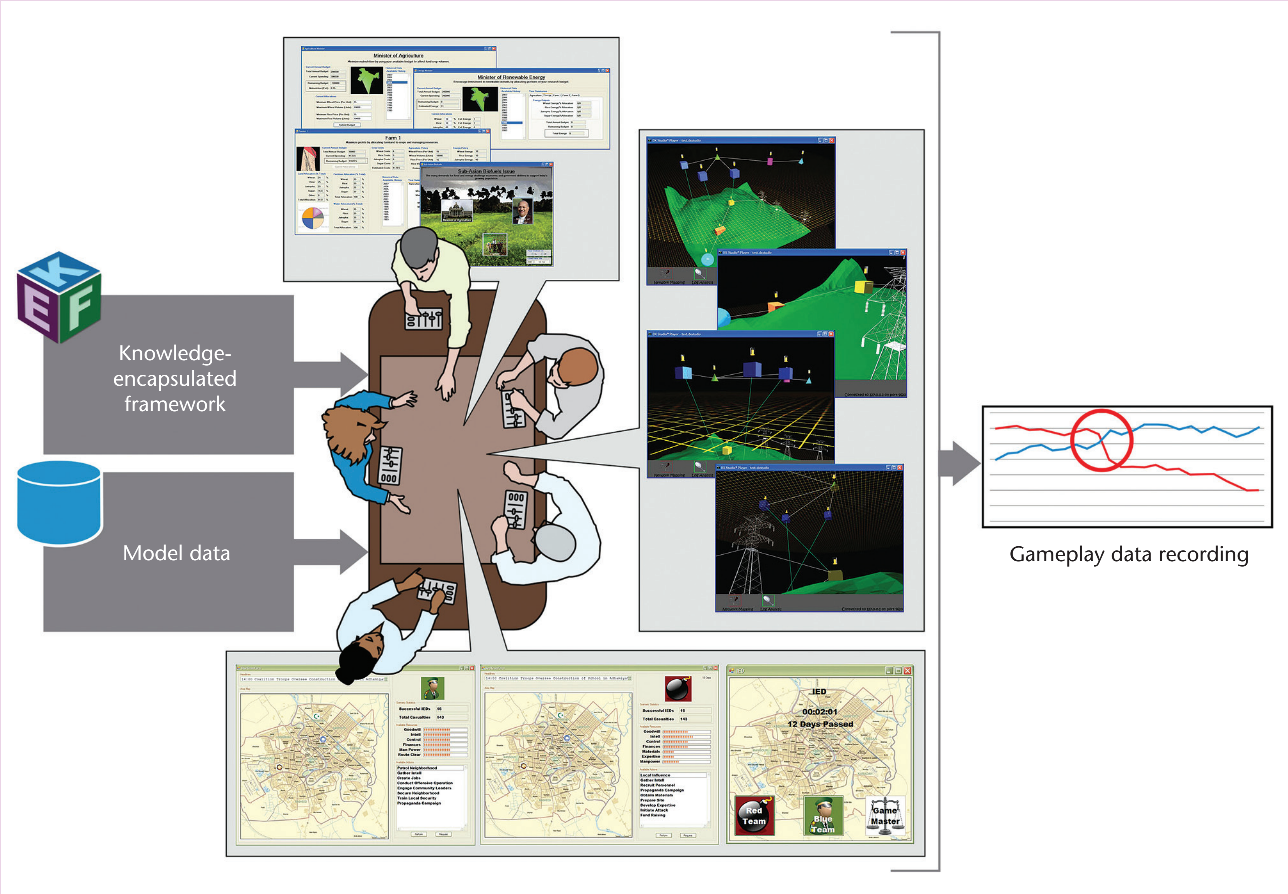

Figure A. A conceptual view of the technosocial simulation laboratory. The framework integrates modeling theories, data and databases, and serious gaming for predictive decision-making.

sible for initial development of the corresponding problem domain models. The entire research team then collaboratively and collectively exploits various domain models' strengths and fine-tunes the interactions among them using an interactive VA approach.

GreenOracle—a Collaborative VA Tool

GreenOracle's predictive model involves four independent but interrelated components covering the domains of climate simulation, power grid simulation, social science, and critical infrastructure (see Figure 1).

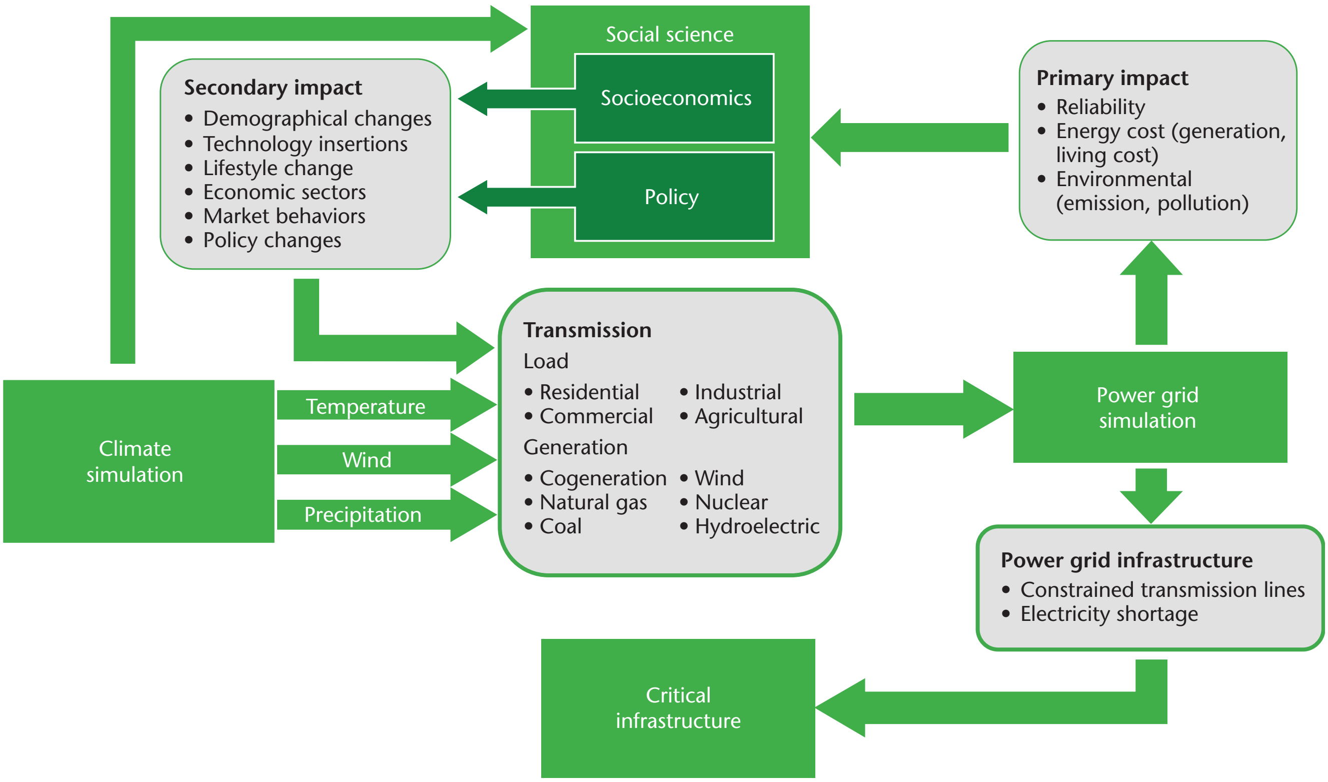

Figure 1. Design overview of GreenOracle. The tool's main components cover climate simulation, power grid simulation, social science, and critical infrastructure. The gray rectangles contain input and output information of the four components.

First, the climate simulation component models time-series temperature, wind, and precipitation data for a future time period (see the "Developing Climate Change Scenarios" sidebar). GreenOracle feeds these data to the power grid simulation component, which analyzes electric power transmission, load, and generation for selected regions (see the "Modeling Climate Change's Impact on Power System Load" sidebar). This simulation's output becomes the primary impact of global climate change on the corresponding regions' power grid, without considering any other factors. GreenOracle then feeds these primary-impact indicators into the social-science component, which also considers the climate model data as depicted to predict climate change's secondary impact on society. The simulation loop repeats until a specified termination condition occurs. The power grid component then identifies vulnerabilities in the power grid infrastructure, which the critical-infrastructure component uses to model the consequences on society's other critical infrastructures.

Because development team members don't generally have sufficient depth of knowledge outside their specialization areas, we rely on a VA interface to facilitate communication, exchange ideas, and engender awareness during GreenOracle's development. Although we could negotiate the coupling between two model components orally or in writing, finding concord among all four components using the same approach is particularly difficult. Visuals are the most effective means for conveying ideas and concepts, letting us actually see the input and how individual components run.

GreenOracle's four components have potentially hundreds of functions and parameters that users need to manage and explore. Even a limited modeling scope would involve a variety of combinations in various circumstances to compare and assess. To address this information overload problem, GreenOracle uses an interactive spreadsheet-oriented approach that traces the simulation from beginning to end. This allows scientists to, among other things,

- debug each other's model theories and algorithms,
- detect multivariate outliers both locally (in a component) and globally (over the whole model),
- evaluate risk and uncertainty and their overall implications, and
- most important, collaborate toward a common goal.

When using GreenOracle as a presentation tool for audiences with varying roles and responsibilities, we want to be able to customize the degree of detail and match the audience's backgrounds and interests. This might mean showing or hiding some technical details or protecting or masking sensitive results. This design approach also echoes the "walk-in usability" goal[4] of VA design—that is, customizing just the right number of features and amount of support for different tasks.

Developing Climate Change Scenarios

Since the preindustrial era, global mean temperature has increased by 0.75°C—a quarter of the difference between the ice age and the present. In 2007, the Intergovernmental Panel on Climate Change announced that global warming was "unequivocal" and the observed global temperature changes can't be explained without considering human impact on the concentration of greenhouse gases.[1] Much of what we can do about climate change depends on how climate will change in the future and how it will influence human lives and the environment. Adaptation and mitigation strategies must be informed by the projected climate change at both the global and regional levels.

Climate change scenarios are developed mainly using global climate models (GCMs).[2] First-generation GCMs weren't much different from numerical models used to forecast the weather. Over the past few decades, GCMs have evolved into more-sophisticated models of the atmosphere, ocean, land, and biogeochemical cycle as a coupled system. To project future climate, GCMs are run over long time periods (for example, decades to centuries) using prescribed scenarios of greenhouse gas concentrations or emissions. The four commonly used emission scenarios are distinguished by the assumptions used in projecting future economic and technological changes.[3] For each scenario, researchers provide annual greenhouse gas emissions and concentrations as inputs to GCMs to project future climate.

For the *Climate Change 2007* report, researchers used about two dozen GCMs developed by research and operational centers around the world to project future climate.[1] These simulations used the same emission scenarios to facilitate comparison and analysis of uncertainty. Different GCMs can display different climate sensitivities that are intricately related to how each model represents physical processes such as clouds and aerosols. Because GCMs typically only resolve processes that are several hundreds of kilometers in scale, scientists have developed techniques to downscale the scenarios to spatial resolutions that more appropriately represent regional climate. Downscaling has been particularly useful for regions with complex orography, where climate can vary significantly over relatively short distances.[3] Using the GCM future climate scenarios and the downscaled scenarios, researchers have assessed different regions' vulnerability to climate change and applied the knowledge to develop strategies to mitigate and adapt to climate change.

References

1. S. Solomon, D. Qin, and M. Manning, eds., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, 2007; http://ipcc-wg1.ucar.edu/wg1/docs/WG1AR4_SPM_PlenaryApproved.pdf.
2. W.M. Washington and C.L. Parkinson, *Introduction to Three-Dimensional Climate Modeling*, Univ. Science Books, 1986.
3. N. Nakicenovic et al., eds., *Special Report on Emissions Scenarios*, Cambridge Univ. Press, 2001.

Visualization and Collaboration Examples

Before we can work on a system-wide collaborative simulation, individual scientists work on their domain models using a combination of established theories and newly customized model programs. The output of these models has few interactions with the other model components until we integrate them under one roof. VA researchers work in parallel with individual domain scientists to develop the GreenOracle tool so that it satisfies the requirements of all the underlying models.

GreenOracle's visualization layout has four basic widgets:

- geospatial displays,
- charts and line graphs for technological and social analysis,
- temporal displays, and
- cause-and-effect graphs for describing model inputs and outputs.

Figure 2 shows a simple example of GreenOracle in action, with each of the four model components occupying a single window. The centerpiece is a US map (Figure 2a), which geographically ties together all four components and their results (Figures 2b to 2e). Users can interactively customize the window layout for different modeling tasks and requirements.

One of our initial simulations deals with a *typical meteorological year* scenario. During the collaboration sessions, climate model scientists present time-series data generated from approximately 30 models in 10 representative cities in the investigation area (see Figure 2b). Further background information on these time-series data sets is available elsewhere.[3] The team collaboratively decides which models to use and under what conditions during the simulation session. These time-series data trigger the execution of both the power grid (see Figure 2c) and social-science (see Figure 2d) models. Both use the selected time-series data as input to run the corresponding models on the fly.

Modeling Climate Change's Impact on Power System Load

The residential and commercial sectors are responsible for more than 70 percent of US electricity consumption, according to an Energy Information Administration Survey (www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html). Temperature variations are the most influential climate factor driving building energy consumption.[1] Although population and economic growth are the two major factors driving overall electricity consumption, temperature changes impact electricity demand in terms of load shapes, load composition, and peak load consumption. This is especially true for residential and commercial loads, much of which are temperature sensitive.

Researchers have used several methodologies to estimate climate change's impact on building energy use.[2] One methodology involved first creating hourly meteorological data based on global climate simulations, such as those archived for the Intergovernmental Panel on Climate Change (www.ipcc.ch). The researchers then used this data to drive an hourly building energy simulation program that let them quantify climate change impacts on different prototyped buildings. A disadvantage is that they had to use climate model simulated temperature in place of typical meteorological year (TMY) weather data used in building energy simulation programs. Furthermore, this approach required daily or hourly wind, humidity, and cloud cover data, which are rarely available from climate model outputs. Although the TMY-driven approach might better capture the effects of current storm episodes and heat waves on building energy consumption, it was too complex for our initial goal of studying the future wide-area impacts of climate change on the power grid. So, we chose a simplified approach based on sensitivity analysis, focusing on temperature and leaving a provision in the model for future improved climate change forecasts of increased granularity.

References

1. Y.J. Huang, "The Impact of Climate Change on the Energy Use of the US Residential and Commercial Building Sectors," Lawrence Berkeley Nat'l Laboratory, 2006.
2. M.J. Scott and Y.J. Huang, "Effects of Climate Change on Energy Use in the United States," *Effects of Climate Change on Energy Production and Use in the United States*, US Climate Change Science Program and Subcommittee on Global Change Research, 2007.

Our underlying modeling problem is rather complicated because it involves both human and technology factors. So, we must narrow our scope to study a single change factor or a small set of change factors at a time, as we describe later. On the basis of the visualization of the climate change prediction information, scientists collaboratively decide the study targets' priority and the model parameters' thresholds. They also make several other temporal and spatial decisions for each simulation run. By using GreenOracle, scientists can see their decisions' consequences along the simulation pipeline. They either discard intermediate results or store them in the GreenOracle databases for future reference. The models' outcomes suggest potential vulnerabilities of the critical infrastructure in the investigation area (see Figure 2e). The map in Figure 2a shows these areas' geographic locations.

What we have just described is a direct model process (see the "Direct and Reverse Modeling" section) that studies the consequences of independent parameters decided collaboratively by the scientists. A complementary approach to address the problem is to conduct reverse modeling, where the scientists decide on the desirable (or undesirable) outcomes and then work backward to identify the potential factors for the identified outcomes. For example, the warm, dry American southwest is identified as an area potentially vulnerable to global warming. What can we do socially and technologically now to alleviate climate change's impact on this area in the future? To answer this question, domain scientists collaboratively study and determine a series of simulation factors, such as demographics movement, policy changes, and technology improvement. GreenOracle provides a platform for them to argue their theories and then pursue the (simulated) truth on the basis of their computation models.

A collaborative session stops when we find that either the underlying models need improvement or the visualization front end needs additional features to continue the investigation. A new collaborative session occurs after we've addressed the identified problems. Achieving agreeable results requires not just one simulation run but a series of attempts. Developing a complete simulation takes from several months to a year.

Predictive-Modeling Strategy

Our problem's scope is so large and complicated that we probably won't be able to fully address the problem. However, we don't need a complete solution to fulfill our mission of predicting climate change's impact on society. Our goal isn't to predict what really would happen to our entire society in the future but to indicate what could be done to avoid undesirable future outcomes with respect to selected model variables.

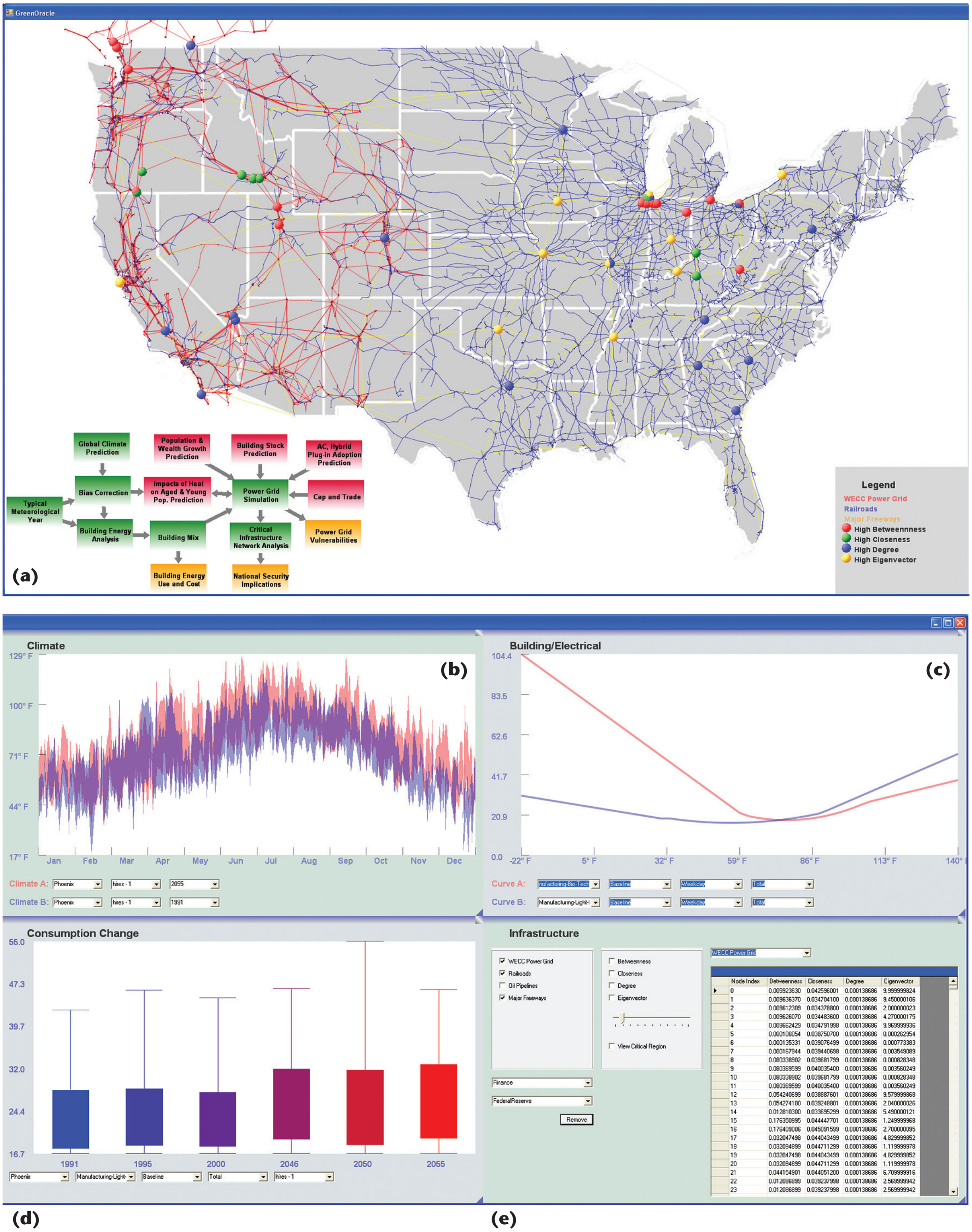

Figure 2. GreenOracle in action. (a) A map plots the outcomes of scientists' collaborative decisions. The graph in the lower left corner shows the flow of the model. Different windows show simulation results for the tool's four components: (b) time-series data from cities considered in the simulation, (c) power-grid and (d) social-science models triggered by the time-series data, and (e) the identified potential vulnerabilities.

To address this challenge, we first generate a base case (do nothing/business as usual) that lets nature take its course. We then change one independent variable at a time to see the dependent variables' cause-and-effect relationships. Our investigation considers climate change's direct and indirect impacts on energy use by looking at changes in consumer behavior, energy price responsiveness, policy, and demographics. Qualitatively, we can consider socioeconomic factors—for example, with and without climate change, with and without energy cost changes, and with both climate change and energy cost changes. We then compare the outcomes of individual simulations with the base case and identify the net impact. Figure 3 depicts this modeling task's four options.

GreenOracle's four components make many independent variables available. The number of independent variables grows every day as scientists around the world gain better understanding of the underlying social and technological modeling problems.

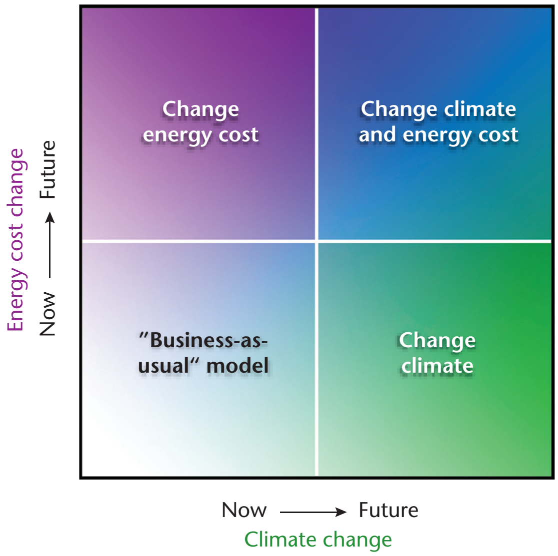

Figure 3. Four options to explore climate change and energy cost change factors. The *x*-axis shows the climate change between now and the future. The *y*-axis shows the energy cost change between now and the future.

Direct and Reverse Modeling

GreenOracle provides both direct- and reverse-modeling capabilities to answer questions posed by our multidisciplinary scientists.

In the more traditional direct modeling, causes serve as independent variables and effects serve as dependent variables.

In reverse modeling, we search for the values of independent variables (causes) that result in the observed values of dependent variables (effects). Reverse modeling lets scientists anticipate plausible future trends while providing viable solutions or alternatives for today's society. For example, to reduce greenhouse gas emissions by 25 percent in 2050, society can follow several technological and social options. We can reduce energy consumption by lowering the room temperature in winter (or raising it in summer). We can also improve the energy efficiency of home appliances and motor vehicles.

Asynchronous and Synchronous Analytics

Individual scientists use GreenOracle asynchronously to design and modify their own model components by varying the immediate inputs and outputs and studying the corresponding impact. Parameters of the other model components are unlikely to change dynamically during the simulation. This use is mainly an investigation of an individual model's localized impact on its immediate components. After scientists document the results of individual components, they pass both the model parameters and results on to the other scientists for system-wide simulations.

In synchronous analytics, scientists representing all four model domains study their components' direct and indirect impacts on the rest of the system. Given the domain scientists' lack of familiarity with visualization and in-depth domain knowledge of the other fields associated with different models, the most effective way to collaborate with them is through a visualization designer. This designer is familiar with the system's complexity and can effectively communicate with the domain experts. This collaborative approach to system design distinguishes GreenOracle from less sophisticated systems requiring narrower domain expertise.

Usage Examples

GreenOracle is useful for a variety of applications involving consequences of long-term demographic trends and consumer technology and lifestyle choices. Current investigations include planning of power systems to address a combination of demographic and climate change and planning for interventions to reduce climate change's adverse consequences. These are longer-term (from months to a year) investigations requiring extensive collaborative simulations among the domain scientists to fully understand the models' behavior and sensitivity.

Utility Planning

Individual utility customers typically don't consider electric power system viability when choosing where they'll live or how they'll equip their households, leaving power system planners to discover and account for consequences of these decisions. Yet, climate change itself will likely increase the planning challenges on a time scale (10 to 50 years) comparable to the electric-utility long-term planning horizons. On such a time scale, climate change compounds the usual planning uncertainties caused by economic and demographic change.

Using GreenOracle, we project that climate change will increase demand for electricity for space cooling in households and businesses with air conditioning while increasing demand for air conditioning in mild-climate locations that previously had low market penetration. Utility planners can blend what they know about future population growth and change, trends in technology adoption that are known to be economically and socially motivated, and climate change scenarios to understand and plan for long-term contingencies.

We're constructing GreenOracle to project long-term demographic, market behavior, and technological change, which will help utility planners investigate four problems. The first involves projecting electricity consumption in major load centers in the Western US grid in 2020 and 2050, accounting for population growth, further market penetration of key energy technologies such as air conditioning and plug-in electric vehicles, the effects of demographic change on housing type, and the impact of temperature change due to climate change on space-conditioning demand. The second involves evaluating the probability of grid failure, which has both technical components (temperature changes, building energy efficiencies and consumption, and the location and capacity of power grid and generation elements) and social components (the size and distribution of population and the adoption rates of efficient technologies, particularly of air conditioning and plug-in hybrid vehicles). The third involves projecting the likelihood and potential locations of grid failure (brownouts, blackouts, and islanding) under changes in these circumstances. The final problem involves determining which critical infrastructure (such as hospitals, military bases, and traffic-control systems) would be affected.

Social-Service Intervention

Because GreenOracle contains detailed databases of the projected population by age, we use it to map potentially vulnerable populations against predictions of extreme climate events. For example, the elderly (age 75+, and especially 85+) are exceptionally vulnerable to heat waves, particularly if air conditioning systems fail owing to brownouts or blackouts in high-demand conditions. GreenOracle's detailed regional climate forecasts let us map elderly populations against projected temperature events, both to project the such conditions' likelihood and to guide the planning of social-service interventions for these populations in the event of blackouts.

Development Issues and Challenges

Many complications related to multidisciplinary collaboration and model integration have arisen during GreenOracle's development. They remain open-ended problems with only partial solutions as we continue to investigate the tool more deeply.

In theory, collaborative investigation of all four model components can occur concurrently. In reality, model components accept input from each other (as well as external sources), which is inherently a sequential process. To address this chicken-and-egg engineering problem, our workflow is gradual and sequential. GreenOracle's lead components provide just enough groundwork for the next component to take off before returning to the refinement stage to enrich their model. Almost concurrently, supporting components prepare model templates to anticipate and later incorporate results from lead components. For example, we developed GreenOracle's central grid model initially with the current distribution of building stock and equipment to determine grid forecasts' temperature sensitivity. At the same time, ongoing socioeconomic and demographic research was developing estimates of the future distribution of building stock and equipment by load center.

Alignment among the four model components, which are linked to the four independent and disparate disciplines in Figure 1, remains a major research hurdle. Although we've conducted cross-disciplinary research, these efforts target the practical requirements for moving work forward in the individual domains rather than the benefits to the larger goals. For example, the science community has attempted to adapt power grid industry tools to predict future energy consumption's sensitivity to global climate change, but usually with little connection to the underlying demographic and technological changes that will likely occur over the same time periods. Many critical infrastructure protection studies have close ties to the social and behavioral research that affects the dynamics and evolution of the model components. However, these cross-disciplinary efforts often require additional focus realignment before we can integrate them into our model.

Many complications related to multidisciplinary collaboration and model integration have arisen during GreenOracle's development.

Take one classic example. The power grid industry focuses mostly on short-term prediction (ranging from 10 to 20 years of global climate changes). However, many of its challenges, such as grid placement and generation mix, extend to at least 25 years and, arguably, because of the extremely long lifetimes of utility equipment and site-selection decisions, to 50 to 100 years. GreenOracle goes beyond the limited 10-year period, extending at least to the mid-21st century.

Another major concern involves the granularity of the spatial and temporal data generated from or used by the four collaborative model components. For example, much global climate prediction focuses on yearly or seasonal modeling, partly because the model results rarely explain daily or even weekly differences. On the other hand, electric power modeling is mainly hourly based because the consumption pattern varies greatly during the day. The same data granularity issue appears in the components' geographical information. The global climate component generates area-based (such as the entire US Pacific Northwest) results, the power grid component deals with region-based information (such as a metropolitan area), and the social model studies census data as fine as a city block with an optimum population of 1,500 people. The incomplete or indeterminate information brought by various data granularity issues requires extensive interpolation, extrapolation, and data-regression work to fill in the model data's gaps.

GreenOracle is mainly designed and customized by scientists, for scientists. Scientists, in this case, aren't necessarily mainstream information analysts.

Lessons Learned

GreenOracle is mainly designed and customized by scientists, for scientists. And scientists, in this case, aren't necessarily mainstream information analysts and certainly aren't the general public. So, some of the lessons learned might seem to contradict conventional wisdom about a well-designed collaborative-visualization or VA tool for general-purpose applications.

A clear cultural divide exists between the disciplines, both technical versus social and theoretical versus experimental. One of the biggest controversies is the design of the visualization that presents the modeling results and interacts with the other model components. Our domain scientists generally appreciate the cutting-edge information visualization technology. However, they've expressed reservation about using less-familiar visualization techniques on a multidisciplinary collaborative research project that frequently requires compromise. In the end, they opted for more traditional visualization techniques such as charts, tables, and maps over modern visualization tools. This lowest-common-denominator approach lets scientists focus on the science using familiar terms.

One strong exception to using modern visualization techniques is the application of data brushing and linking among GreenOracle visualizations. The use of physical links, such as a taper-end arrow, to interactively correlate multiple entries in different visualizations is perhaps the best-received visualization technique implemented in GreenOracle. This visualization has gradually become a mini-graph layout problem as we attempt to organize both data and the links together properly.

Although the domain scientists contribute valuable domain expertise to the collaborative project, they also bring their own research tools, which are heavily customized for their prior research work. To maintain GreenOracle's architectural integrity, we reimplemented much of the third-party code. This complex collaboration challenge requires the scientists and software developers to put additional effort into maximizing the use of available resources.

Through the development of GreenOracle, we observed that our scientists are intrinsically motivated to design visualization not just for their own domains but also for others. We can trace this enthusiasm back to the fact that some of them have prior R&D exposure to multiple domains. The unanticipated overlapping of expertise can work against the basic rule of thumb of a successful scientific collaboration, as Quentin Vicens and Philip Bourne describe.[5]

Unlike some collaborative tools that require voting to reach consensus solutions (see the "Related Work" sidebar), GreenOracle's analytics outcomes are based mainly on past history, proven theories, and established statistics. Our scientists tended to put more weight on scientific evidence and less on the cognitive or foraging aspect of sensemaking. This observation echoes our earlier discussion that cutting-edge visualization isn't necessarily the most logical choice for this collaborative VA research.

The development of GreenOracle is an ongoing R&D effort, and we intend to share the tool and modeling results with the general public in the future. The presented work is one of the four major models of the TPA initiative at PNNL, which will be integrated to become the technosocial simulation laboratory as we suggested in the "Technosocial Predictive Analytics" sidebar.

Acknowledgments

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Related Work in Collaborative VA and Predictive Modeling

The study of collaborative visual analytics (VA) was among the grand R&D challenges posed by an international advisory panel on VA in 2005.[1] Previously, the literature often referred to collaborative VA as collaborative visualization, which also facilitates data analysis. Among the most noteworthy collaborative-visualization tools and component libraries developed during this pre-VA era was VisAD (Visualization for Algorithm Development; www.ssec.wisc.edu/~billh/visad.html), which "allow[s] groups of scientists to collaboratively develop data analysis algorithms." VisAD has also contributed to the development of several popular collaborative visualization tools, including the GeoVista geographic information system (www.geovista.psu.edu/index.jsp).

The 2007 beta launch of Many Eyes expanded and redefined the scope of traditional collaborative-visualization R&D by promoting community initiatives rather than individual or institutional efforts.[2] Many Eyes encourages open source R&D collaboration and knowledge sharing within the visualization community and gives the general public access to cutting-edge visualization technology and analytical results. Its real challenge is to exploit the ever-evolving Internet space and the potential of global collaborative visualization and analytics.

More recently, Jeffrey Heer and Maneesh Agrawala listed design considerations for collaborative VA.[3] They provide a roadmap brimming with practical ideas and examples for collaborative VA research and development. They also give a comprehensive list of references for future research on the topic. The main article exemplifies and contrasts some of the design issues they suggest.

As for the predictive modeling work underlying GreenOracle, we've yet to find similar work (in terms of modeling scope) with a comparable degree of ambition and complexity. On the other hand, several recent investigations have examined problems similar to portions of our work but with different approaches and emphases. For example, the State of California has recently sponsored an investigation on global climate change's impact on building energy use.[4] Although the study pays great attention to building energy use in California, it doesn't consider the impact of electric power stability and social dynamics. Perhaps the most notable difference between this work and GreenOracle is the absence of an interactive VA interface that supports a team of multidisciplinary scientists in collaboratively planning, executing, and assessing the modeling work.

References

1. J. Thomas and K. Cook, eds., *Illuminating the Path—the Research and Development Agenda for Visual Analytics*, IEEE CS Press, 2005.
2. F.B. Viegas et al., "Many Eyes: A Site for Visualization at Internet Scale," *IEEE Trans. Visualization and Computer Graphics*, vol. 13, no. 5, 2007, pp. 1121–1128.
3. J. Heer and M. Agrawala, "Design Considerations for Collaborative Visual Analytics," *Proc. IEEE Visual Analytics Science and Technology* (VAST 07), IEEE CS Press, 2007, pp. 171–178.
4. P. Xu et al., *Effects of Global Climate Change on Building Energy Consumption and Its Implications on Building Energy Codes and Policy in California*, Calif. Energy Commission, 2007.

References

1. *Physical Vulnerability of Electric Systems to Natural Disasters and Sabotage*, OTA-E-453, US Government Printing Office, June 1990.
2. A. Sanfilippo et al., "Technosocial Predictive Analytics in Support of Naturalistic Decision-Making," *Proc. 9th Int'l Conf. Naturalistic Decision-Making* (NDM 9), British Computer Soc., 2009, pp. 144–151.
3. P.C. Wong et al., "Predicting the Impact of Climate Change on U.S. Power Grids and Its Wider Implications on National Security," *Proc. AAAI Spring Symp. Technosocial Predictive Analytics*, AAAI Press, 2009; http://predictiveanalytics.pnl.gov/aaai_symposium/abstract/presentation/02_Wong.pdf.
4. J. Thomas and K. Cook, *Illuminating the Path: The Research and Development Agenda for Visual Analytics*, IEEE CS Press, 2005.
5. Q. Vicens and P.E. Bourne, "Ten Simple Rules for a Successful Collaboration," *PLoS Computational Biology*, vol. 3, no. 3, 2007, p. e44.

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