

SANDIA REPORT

SAND2009-6521

Unlimited Release

Printed October 2009

Decision Support for Integrated Water-Energy Planning

Vincent C. Tidwell, Peter H. Kobos, Len Malczynski,
Geoff Klise, William E. Hart, and Cesar Castillo

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technisa Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



Decision Support for Integrated Water-Energy Planning

Vincent C. Tidwell, Peter H. Kobos, Len Malczynski, Geoff Klise, Cesar Castillo
Earth Systems Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1137

William E. Hart
Discrete Math and Complex Systems Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1318

Abstract

Currently, electrical power generation uses about 140 billion gallons of water per day accounting for over 39% of all freshwater withdrawals thus competing with irrigated agriculture as the leading user of water. Coupled to this water use is the required pumping, conveyance, treatment, storage and distribution of the water which requires on average 3% of all electric power generated. While water and energy use are tightly coupled, planning and management of these fundamental resources are rarely treated in an integrated fashion. Toward this need, a decision support framework has been developed that targets the shared needs of energy and water producers, resource managers, regulators, and decision makers at the federal, state and local levels. The framework integrates analysis and optimization capabilities to identify trade-offs, and “best” alternatives among a broad list of energy/water options and objectives. The decision support framework is formulated in a modular architecture, facilitating tailored analyses over different geographical regions and scales (e.g., national, state, county, watershed, NERC region). An interactive interface allows direct control of the model and access to real-time results displayed as charts, graphs and maps. Ultimately, this open and interactive modeling framework provides a tool for evaluating competing policy and technical options relevant to the energy-water nexus.

Acknowledgments

The authors wish to acknowledge the early contributions of Michael Baca, his guidance on electrical power systems was valuable to our efforts. We are also indebted to Chau Dam for her assistance in gathering, reducing and managing the large quantities of data utilized by this project. This work was supported through Sandia National Laboratories Laboratory Directed Research and Development Program.

Table of Contents

1. Introduction.....	7
2. Methods.....	10
2.1 System Dynamics.....	10
2.2 Reference Systems and Scaling	11
2.3 Database.....	12
2.4 Model Architecture	13
2.4.1 <i>Demographic Sector</i>	13
2.4.2 <i>Electric Power Sector</i>	15
2.4.3 <i>Water Sector</i>	17
2.4.4 <i>Interactive Interface</i>	21
3. Results.....	25
3.1 Baseline Case.....	25
3.2 Cooling Technology Mix.....	34
3.3 Fuel Type Mix.....	38
4. Summary	43
5. References.....	46
Appendix A: Analysis of Current Power Plant Water Use.....	49
2004 Power Plant Data.....	49
2000 Power Plant Data.....	53
References.....	55
Appendix B: Optimization.....	56
References.....	56
Appendix C: Model Interface Users Guide	57

Figures

Figure 1. Example of different boundaries in geospatial data.	12
Figure 2. Schematic of the general structure of the integrated energy-water planning model.....	14
Figure 3. Selected interface screenshots.	22
Figure 4. Change in water demand by sector from 2004-2030.	23
Figure 5. Change in water use in the thermoelectric sector from 2004-2030 by NERC region..	23
Figure 6. Water availability metric at the 4th level HUC..	24
Figure 7. Change in built electrical power capacity, 2004-2030, for the baseline case (e.g., current fuel mix).....	26
Figure 8. Change in thermoelectric water use and consumption in 2030 for the baseline case and below how new power plant withdrawals are distributed by fuel type.....	27
Figure 9. A comparison of water withdrawals (use) and consumption between the municipal, industrial and thermoelectric sectors. Show here is only the growth between 2004 and 2030.	27
Figure 10. Change in water use, 2004-2030, distributed by different water sources (i.e., surface water, groundwater, and non-potable).....	28
Figure 11. Electrical power demand for primary water supply and waste water treatment.	28
Figure 12. Green house gas emissions including CO ₂ , SO _x and NO _x	29
Figure 13. Built electrical power capacity in 2030 distributed by fuel type and by NERC region.....	29
Figure 14. Thermoelectric water use by NERC region as well as a comparison between thermoelectric use and all other uses.....	30
Figure 15. Distribution of total water use, thermoelectric water use, and electricity demand at the county level for the continental United States in 2004.	31
Figure 16. Maps showing the areas of potential water stress. Shown are the ratios of water supply to demand on a watershed basis (accounting unit level). Three different supply metrics are used, normal supply (top) mean gauged stream flow, drought supply as given by the 5 th percentile gauged flow (middle), and sustainable recharge given by the gauged base flow (bottom).	32
Figure 17. Counties suitable for siting future power plants. Criteria include a water supply to demand ratio greater than 5, and the presence of at least one power plant in the county prior to 2004.	33
Figure 18. Thermoelectric water use and consumption aggregated at the national level for three different cooling technology mix scenarios.....	35
Figure 19. Change in thermoelectric water consumption by county from 2004 to 2030.....	37
Figure 20. Change in the water supply to demand ratio in 2030 given two different mixes of cooling types employed for future electric power generation.	38
Figure 21. Comparison of built capacity out to the year 2030 for the four different fuel mix scenarios....	39
Figure 22. Comparison of CO ₂ emissions out to the year 2030 for the four different fuel mix scenarios. 40	
Figure 23. Comparison of thermoelectric water use and consumption out to the year 2030 for the four different fuel mix scenarios.	41
Figure 24. Counties that meet power plant siting requirements in 2030 for two different fuel mix scenarios, RPS and Pro Nuclear cases.	42

Tables

Table 1. Plant characteristics according to generation fuel type.....	16
Table 2. Water use and consumption according to the generation fuel type and cooling technology.....	17
Table 3. Green house gas production by generation fuel type.....	17
Table 4. Comparison of water use projections.....	26

1. Introduction

Water use has grown by 230% since 1950 while electric power production has increased 12 fold (EIA 2003), stimulating a 43 fold increase in the nation's economy as measured by gross domestic product (BEA 2007). The linkage between electricity, water and the economy are apparent when one considers that on average droughts costs the U.S. \$6-8B/yr, while the 1988 drought cost \$40B (NDMC 2008), and similarly the 2003 blackout in the Northeast U.S. incurred damages of \$6-10B (NextGen Energy Council, 2008). Although extreme cases, these examples point to our nation's need for a secure and reliable source of water and electricity. Unbridled demand for these resources represents a very real internal threat to our nation's security. Further intensifying this issue is the fact that electricity and water are inextricably linked; that is, considerable quantities of water are required in thermoelectric power production while a sizeable fraction of that power is required to lift, convey, treat, store and distribute water.

So, what is the extent of this linkage between energy and water? In 1995, the last year the U.S. Geological Survey conducted a comprehensive analysis of water use and consumption (USGS 1995), total freshwater use in the U.S. was 342 billion gallons a day (BGD), while consumption measured 100 BGD. Of this, thermoelectric freshwater use accounted for 132 BGD or 39%, while consumption (3.3 BGD) only accounted for 3.3% of the national total. Water use by thermoelectric power generation was second only to irrigated agriculture (134 BGD at 39%); however, when considering total water use (potable and non-potable sources) thermoelectric sector was the leading water user accounting for 48% of all water use. In terms of consumption, thermoelectric power production was roughly equivalent to all other industrial uses in the U.S. Conversely, significant energy is expended to extract, convey, treat and deliver water and waste water. While the total energy requirement by water utilities is highly location-specific, on average 3% of all electrical power generated is used in the energy sector (EIA 2003). According to the California Energy Commission (2005) this percent is much more significant if water heating is also considered, where it is estimated that almost 20 percent of California's electricity demand, and over 30 percent of California's natural gas demand, are associated with water use.

The lack of integrated energy and water planning and management has already impacted energy production in many basins and regions across the U.S. In three of the fastest growing regions, the Southeast, Southwest, and Northwest, new power plants have been opposed because of potential negative impacts on water supplies (Tucson Citizen 2002; Reno-Gazette Journal 2005; U.S. Water News Online 2002 and 2003; Curlee and Sale 2003). For similar reasons, Idaho recently placed a 2-year moratorium on construction of coal-fired power plants (Reuters 2006). Concerns over falling water levels in Lake Norman, Lake Mead, and reservoirs all along the Apalachicola River have water managers and utility operators perplexed over how to supply water to cool thermoelectric power plants and/or generating hydroelectric power while maintaining adequate flows for environmental and human needs (Webber 2008).

So what does the future hold? The Energy Information Administration projects the U.S. population will grow to 364 million people by the year 2030, increasing electric power demand by 22 percent between 2005 and 2030 (EIA 2003). Depending on the type and number of power plants built, cooling technologies used, and emission requirements water use in the thermoelectric industry is projected to decrease between 0.5 and 30% while consumption is projected to rise between 21 and 48% (Reeley et al. 2007). Increasing population will likewise

put pressure on the municipal, industrial and agricultural water sectors. This growth in water demand will occur at a time when the nation's fresh water supplies are seeing increasing stress from limitations of surface-water storage capacity, increasing depletion and degradation of ground water supplies, increasing demands for the use of surface water for in-stream ecological and environmental uses, and the uncertainty about the impact of climate variability on future surface and ground water resources. In fact, a recent report by the Congressional General Accounting Office (2003), based on a survey of water managers, documents that 36 states anticipate water shortages in the next 10 years, even under normal water conditions, and 46 expect water shortages under drought.

To address this emerging energy and water interdependency challenge, Congress directed the DOE in 2005 to "initiate planning and creation of a water-for-energy roadmap". This road mapping process relied heavily on stakeholder input gathered through three regional needs workshops and two technology identification workshops. Almost 500 stakeholders from over 40 states participated in the five Energy-Water workshops representing a broad range of energy and water agencies, developers, regulators, users, managers, utilities, industry, and academia. Participant input and suggestions were used to define the future research, development, demonstration, and commercialization efforts needed to adequately address emerging water-related challenges to future, cost-effective, reliable, and sustainable energy generation and production (<http://www.sandia.gov/energy-water/>).

While results from the road mapping exercise identified the need for technology innovation, such solutions alone were recognized as insufficient. Specifically voiced was the need for long-term and integrated resource planning supported with scientifically credible models. Similarly, the National Research Council (2004) recognized that although a number of resource planning tools and models exist, additional efforts are needed in the development, integration, and dissemination of decision support tools and system analysis approaches to help communities and regions better address emerging natural resource - energy, water, land, and environment - demand and availability challenges.

Toward these needs there have been at least two noteworthy efforts. Using county-level data on rates of population growth, utility estimates of future planned electricity capacity additions in the contiguous United States, and scientific estimates of anticipated water shortages, 22 counties were identified as the most likely locations of severe shortages brought about by thermoelectric capacity additions (Sovacool 2009; Sovacool and Sovacool 2009a:b). Efforts have also been made to develop a framework to evaluate water demands and availability for electrical power production on a watershed basis (EPRI 2005). This framework to date has been applied to a handful of basins across the U.S. While these studies raise important issues and potential solutions, the Sovacool studies are limited to a narrow set of assumptions while the ERPI model does not currently encompass the entire United States.

Building on the work of these previous studies, the objective of this work is to develop a decision support framework for integrated energy-water planning and management that spans the United States. This modeling framework is designed to be open and interactive, providing a real-time environment for evaluating competing policy and technical options relevant to the energy-water nexus. The decision support framework targets the needs of energy and water producers,

resource managers, regulators, and decision makers at the federal, state and local levels.

Specifically the model will help answer such questions as:

- What are possible energy and water shortfall scenarios for a particular region?
- What are tradeoffs between alternative energy futures to meet projected shortfalls?
- What are tradeoffs between alternative water allocation schemes?
- What technology options can be employed to mitigate water and energy demands?
- Where are coupled energy-water demands likely to be most acute?

The framework integrates analysis and optimization capabilities to identify trade-offs, and “best” alternatives among a broad list of energy/water options and objectives. The decision support framework is formulated in a modular architecture that facilitates tailored analyses over different geographical regions and scales (e.g., national, state, county, watershed, NERC region). An interactive interface allows direct control of the model and access to real-time results displayed as charts, graphs and maps.

This paper is organized by three major sections. The methods section describes in detail the general model architecture as well as the main model systems of demography, energy, and water. Details concerning the supporting optimization toolbox are contained in an appendix. Additionally, an appendix contains a PowerPoint presentation that navigates one through the user interface. Attention then turns to exercising the developed model and a discussion of the results for both a base case and two sets of competing scenarios. Finally, the paper is concluded with a summary of the model and results.

2. Methods

In this section both the overarching framework for the integrated energy-water model is given as well as the details on the model itself. This section begins with a description of system dynamics, the platform on which the model is formulated, and the reason for its selection. Attention then turns to the strategy employed to deal with the disparate reference systems characteristic of the energy-water nexus. A brief description of the database accompanying the model is then given. Finally, a detailed description of the model is provided organized according to key operational systems.

2.1 System Dynamics

The adopted architecture for our decision support tool is based on two criteria. First, a tool is needed that provides an “integrated” view of resource management—one that couples the complex physics governing resource supply with the diverse social and cultural values defining resource demand. Second, a tool is needed that can be taken directly to the public for involvement in the decision process and for educational outreach. For these reasons we adopt an approach based on the principles of system dynamics [e.g., Forrester 1990; Sterman 2000]. System dynamics provides a unique framework for integrating the disparate physical and social systems important to water resource management, while providing an interactive environment for engaging the public.

System dynamics is a systems-level modeling methodology developed at the Massachusetts Institute of Technology in the 1950s as a tool for business managers to analyze complex issues involving the stocks and flows of goods and services. System dynamics is formulated on the premise that the structure of a system – the network of cause and effect relations between system elements – governs system behavior [Sterman 2000]. “The systems approach is a discipline for seeing wholes, a discipline for seeing the structures that underlie complex domains. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots, and for seeing processes rather than objects” [Simonovic and Fahmy 1999].

In system dynamics a problem is often decomposed into a temporally dynamic, spatially aggregated system. The scale of the domain can range from the inner workings of a human cell to the size of global markets. Systems are modeled as a network of stocks and flows. For example, the change in volume of water stored in a reservoir is a function of the inflows less the outflows. Key to this framework is the feedback between the various stocks and flows comprising the system. Feedback is not always realized immediately but may be delayed in time, representing another critical feature of dynamic systems.

There are a number of commercially available, object-oriented simulation tools that provide a convenient environment for constructing system dynamics models. For purposes of this project Studio Expert 2007, produced by Powersim, Inc. is used (www.powersim.com). With this tool model construction proceeds in a graphical environment, using objects as building blocks. These objects are defined with specific attributes that represent individual physical or social processes. These objects are networked together so as to mimic the general structure of the system. In this way, these tools provide a structured and intuitive environment for model development.

2.2 Reference Systems and Scaling

One of the challenges to developing any integrated modeling system is the disparate reference systems that define the physical boundaries, institutional boundaries, and the scales over which data are measured. Relative to the energy-water nexus, several reference systems are at play. Specifically, water resources are traditionally measured and to some extent managed according to the natural watershed boundaries. Electrical power production is regulated and managed within the context of utilities and the North American Electric Reliability Corporation (NERC) regions. Political regions, county, state and federal, play an important role as well. Thus, modeling of this nexus will require a means of seamlessly working across these disparate reference systems.

The model is seeded with data representing the highest level of detail that is publically available. These data include such factors as electrical power capacity at the plant level, population at the county level, and stream gage data at the watershed level. From these disparate scales the data are translated to a compatible reference system for analysis and observation. For most cases this translation involves upscaling (i.e., aggregation of information); however, there are a few circumstances in which the translation involves downscaling (a disaggregation of information). Translation is accomplished according to a simple areal or population weighted aggregation (or disaggregation). Specifically, the data value x undergoes a translation from one reference system to another by

$$w_{i,j}x_j = x_i \quad 1$$

where w is the weight (population or area) and the subscripts i and j designate the different reference systems. Lookup tables of the weighting functions necessary to move from one reference system to another have been developed to streamline this process. For example, an array of weights has been developed to move from the county to the watershed reference system. Each element of the array is formed by taking the ratio of the area of the county in a given watershed to the total area of the county.

The tedious part of this translation process is in developing the various lookup tables of weighting factors. This effort has been accomplished through the pre-processing of geospatial data organized in a Graphical Information System (GIS) database. The common file format used in the GIS is the shapefile, which has a graphical representation of either a point, line or polygon and each attribute within the file resides in a table that describes useful information such as line length and polygon area, to name a few.

The data used in the analysis consists of polygons that show the boundaries of NERC regions, states, counties and watersheds, and points that represent stream gauging stations at the outlets of each watershed or locations of power plants. NERC region shapefile data originated from Platts (2006). The data utilized for analysis included the polygon area and NERC region acronym. State data was obtained from the E-Gov (2008) website that includes the state represented as a polygon, with information that includes the state area, state abbreviation and state FIPS code. County data was obtained from the E-Gov (2008) website that includes the county represented as a polygon, with information such as county area, county name, state FIPS code, county FIPS code and a joined 4-digit state/county FIPS code. Watershed data was obtained from the E-Gov

(2008) website that includes watersheds at many different levels. The level chosen for analysis consists of the accounting unit, which is identified by a 6-digit code. Data used within these polygons includes the accounting unit code, name and area. Long-term high, low and averages, as well as exceedance probabilities (chance of occurrence) for stream gauging data at watershed outlet locations were obtained from the USGS. Both the watershed and stream gauge data comes from research completed by the USGS through the National Hydrography Dataset (NHD) program (Stewart et al. 2006).

To get the appropriate area-weighted averages for both upscaling and downscaling of the relevant information, the following process was used.

1. The first step included merging the state, county and NERC region data. Since the NERC boundaries cut through the states and counties, the layers are merged together and a percentage of the county within a specific NERC region is calculated as well as the new areas associated with a county, in some cases, consisting of two polygons instead of one because a NERC region boundary cuts it into two pieces. The area of the county is the same, however it has two polygons due to the different NERC regions.
2. Next, the data from step one is merged with the accounting unit watersheds and areas are again re-calculated. By overlapping all of the shapefiles and breaking up each intersection into a unique polygon, the re-combination of unique IDs for each shape will allow the program to translate water supply information at a watershed level to an area-weighted average of water supply at a county level, whether the county is entirely within the watershed, or three different watersheds intersect within the county.

To gather water supply information, a method was used that pulled data from the closest stream gauge at the outlet of an accounting unit (excluding tidally influenced gauges). Relevant data including low, high and average flows was transferred from the shapefile to a spreadsheet for further processing to calculate an approximation of both surface and ground water supply for each watershed. As described above, once this data is available, water supply can then be calculated by state, county or NERC region instead of residing just within the watershed.

Figure 1 shows the intersection of the different political and natural boundaries used in this analysis. The dark gray line represents a state boundary; the light gray lines represent counties. The yellow line represents boundaries between NERC regions and the purple and green polygons represent two different watersheds at the accounting unit level. Figure 1 demonstrates that watershed boundaries are rarely coincident with political boundaries.

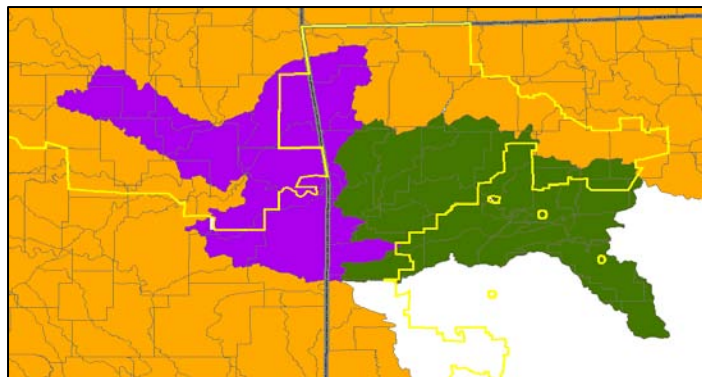


Figure 1. Example of different boundaries in geospatial data.

2.3 Database

Data supporting the Energy-Water model is organized and managed within an Excel Database that communicates directly with the

model software. The database stores initial conditions as well as key parameters and rates of change needed by the model. The database is organized according to a number of worksheets each of which contain data supporting a specific module of the model (see below). Specifically, there are worksheets that contain data concerning, population; gross state product; power plant locations, capacities, capacity factors (percent time plant operates in an average year), water use, and emissions; water use rates by sector and location; mean and exceedance gauge data by watershed; and, location and area of NERC Regions, states, counties and watersheds.

Beyond the baseline data used by the model, the database also includes various calculations needed to prepare these data for use in the model. Calls to the database from the model are fully automated within the simulation environment.

2.4 Model Architecture

The integrated energy-water planning model is formulated within a system dynamics architecture, designed to operate on an annual time step. The spatial extent of the model includes the continental United States, Alaska and Hawaii. At its highest level, the model is organized according to three primary sectors (Figure 2), demography, electric power, and water. The demographic sector model simulates changes in population and gross state product (GSP). The demographic sector in turn drives the demand for electric power and water. Within the electric power sector the demand for power is simulated along with the accompanying construction of new power plants to meet the growing need. The analyst has control of the type of plant (i.e., coal, oil, natural gas, nuclear, hydroelectric, geothermal, wind, and other) as well as the type of cooling system (i.e., once through, recirculating cooling tower, recirculating cooling pond, or air cooled) employed in the new construction. Water demand for the new power plants is calculated and included as a demand to the water sector. Within the water sector the demand for water (both use and consumption) is calculated according to the other primary uses, municipal, industrial, mining, livestock, and agriculture. Additionally, the demand for electricity by the growing water industry is computed and included as part of the growing demand for electricity.

The model includes an interactive user interface that allows construction of alternative future scenarios as well as viewing model results. In this way, results are displayed in real time in the form of graphs, charts, and spatially rendered maps (through a link to Google Earth™).

2.4.1 Demographic Sector

Population and gross state product are the primary factors influencing the demand for electricity and water within the model. Both are simulated on an annual basis, computed at the county level. Population and gross state product growth rates are treated as exogenous variables to the model and thus allow full control by the user. The manner in which population and gross state product influence the demand for electricity and water are individually defined within the sections on electrical power production and water use below.

Population growth is assumed to follow an exponential trajectory according to the relation

$$P_c(t) = P_c(t-1) + \Delta P_c(t)$$

$$\Delta P_c(t) = P_c(t-1) * PGR_c * \Delta t$$

2

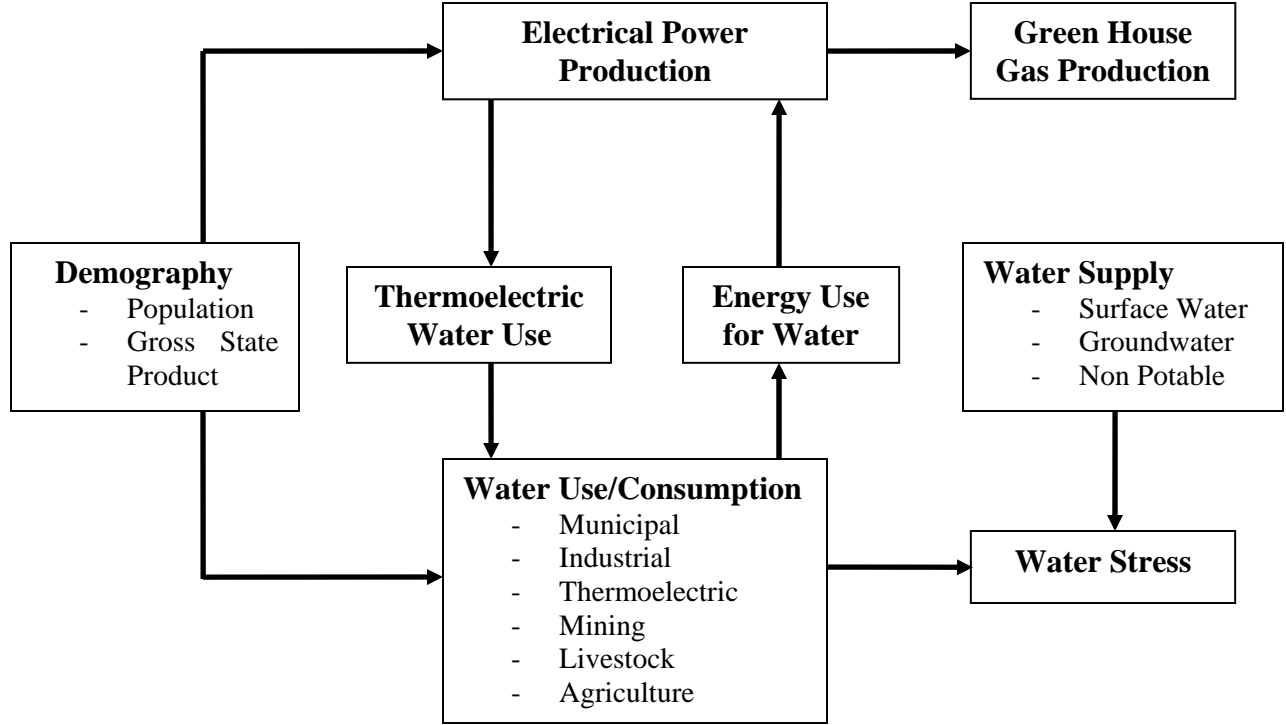


Figure 2. Schematic of the general structure of the integrated energy-water planning model.

where P [persons] is the population, ΔP [persons] is the change in population experienced in a year, PGR is the population growth rate [yr^{-1}], t is time, Δt is the time step (one year), and the subscript c designates the county level. The source of data for the model is the 2000 Census (U.S. Census Bureau 2004). Specifically, the measured population in 2000 is used as the model's initial condition, while PGR s are determined from the change in population over the period 1990-2000. The measured PGR values can be used or adjusted by the model user.

Gross state product is modeled in essentially the same fashion

$$GSP_s(t) = GSP_s(t-1) + \Delta GSP_s(t)$$

$$\Delta GSP_s(t) = GSP_s(t-1) * GSPGR_s * \Delta t$$

3

where GSP [\$] is the gross state product, ΔGSP [\$] is the change in gross state product experienced in a year, $GSPGR$ is the gross state product growth rate [yr^{-1}] and the subscript s designates a state level. The source of data for the model is the Bureau of Economic Analysis (BEA 2007). As the name implies, gross state product calculations are implemented at the state level. In this way, GSP values for 2000 form the initial conditions for the model, while $GSPGR$ s are determined from the change in gross state product over the period 1990-2000. GSP is then estimated at a county level by simply downscaling the state level value by the ratio of county population to state population (see Equation 1). In a fashion similar to population, the $GSPGR$ values based on historical trends can be used or adjusted by the model user.

2.4.2 Electric Power Sector

The electric power sector module simulates the increase in demand for electricity as well as the accompanying expansion of power plant capacity and production. The model affords control over the desired mix of fuel types (i.e., coal, oil, natural gas, nuclear, hydroelectric, geothermal, wind, and other) and boiler cooling technologies to be implemented in the new plants. The resulting impact on water use and consumption as well as green house gas production can subsequently be evaluated.

Electric power generation is modeled at the power plant scale with 4841 individual plants simulated. Plants are distinguished by fuel type; utility vs. non-utility designation; geographic location; installed capacity; annual power output; build date; cooling type; and boiler type. Supporting data were acquired from the 2007 eGRID database (EPA 2007). Initial estimates for green house gas production in terms of NO_x, SO_x and CO₂ were acquired from the EPA (2007). Power plant water use and consumption statistics were much more difficult to come by as data are available for only a fraction of the facilities. For this reason, initial power plant water use estimates were developed by combining information available in the eGRID database with county level information provided through the U.S. Geological Survey (USGS 1995). Details of this analysis are given in Appendix A.

The electric power sector module is driven by changes in electrical power demand. For purposes of this model, changes in electrical demand are assumed to be related to behavior of the Gross State Product (as discussed above). Changes in long run electrical demand are related to GSP through the initial result reported by Silk and Joutz (1997). The model assumes the long-run price elasticity of 0.5, whereby the model user may adjust this parameter when new information is available. Electricity demand, E_d [MWh], is assumed to follow a relationship based on the quantity demanded, Q_d [MWh], relative to the price at a given demand level, P_d [\$], similar to the following equation:

$$E_d = \frac{\Delta Q_d / Q_d}{\Delta P_d / P_d} \quad 4$$

In this way the annual growth in electrical power demand is calculated on a county-level basis.

Construction of new power plants is driven by increased demand for electricity. Specifically, new power plants are ordered anytime the demand exceeds the existing electrical power production. Production is used rather than capacity in order to maintain base to peaking load allocation practices as are used currently. Existing power plants are assumed to maintain similar power production to capacity ratios (i.e., capacity factors) as were measured and recorded in the eGRID database for 2007. Capacity factors for future plant construction are based on average values calculated by fuel type and NERC region from the 2007 eGRID data.

As power can easily be transmitted within a given NERC region the demand to production gap is calculated at the NERC level. That is, demand and production are aggregated from the county and plant level, respectively to the NERC region level and compared. NERC level production values are further adjusted by long term average power transfers between regions.

The model accounts for the time delay between when a power plant is ordered and when it comes on line. This time delay, which varies by fuel type, accounts for siting, permitting, and construction of the new plant (Table 1). New plants are assigned a fixed capacity based on the fuel type (Table 1). As noted earlier, the user can change the mix of power plant fuel types constructed in the future. The default is taken as the same as the fuel type mix for existing plants as of 2004. In each year, the number of plants of a given type is proportional to the desired mix ratio. However, construction is deferred if the unmet demand is not sufficiently large to justify the construction of a particular plant type (weighted by the fuel mix fraction).

Table 1. Plant characteristics according to generation fuel type.

Fuel Type	Capacity (MW)	Plant Life (yr)	Build Time (yr)
Coal	300	100	5
Natural Gas	250	100	2
Nuclear	1000	70	10
Oil	100	40	2
Geothermal	100	50	2
Hydroelectric	1000	150	5
Wind	100	25	2
Other	50	20	0

Once a plant completes construction, siting of the plant within the NERC region must be accomplished. An external optimization model assists with this siting process (see Appendix B). Currently, siting of the power plant is constrained to counties that have existing power plants, suggesting the presence of available transmission capacity. The optimization model then selects the county with the minimum population density subject to the constraint that the power plant's water requirements will not create water demands that exceed the available water supply.

The model also handles the retrofitting of aging power plants. A power plant replacement module tracks the aging of plants and replaces them once they exceed their life expectancy (varies by fuel type, see Table 1). When a power plant is scheduled to retire, the model updates the plant with a more efficient power plant; that is, the capacity factor, water demand and green house gas production values are set to the current average rates. The retrofitting process is subject to a time delay between decommissioning and recommissioning (half the time for full construction given in Table 1), while the location of the plant is assumed to remain unchanged.

Once the new and recommissioned plants come on line, both the water use and consumption are calculated. Existing power plant water use is based on 2007 eGRID data and county level water use statistics gathered by the USGS (1995). Water demand is assumed to remain unchanged for existing plants throughout the duration of the simulation. When a plant is decommissioned its water use is suspended and then reinstated once it is recommissioned. The recommissioned plants water use is assigned according to the plants prior fuel type, cooling type (once through, recirculating cooling tower, recirculating cooling pond, or air cooled), and production characteristics. The assigned water use/consumption (Table 2) are based on industry averages as given in (Reeley et al. 2007). There is also the option to replace the recommissioned plant's cooling system with something more efficient, like replacing a once through system with a

recirculating cooling tower. In like manner new power plants are assigned water use/consumption characteristics according to the fuel type, production characteristics, and the specified mix of cooling technologies to be implemented by new power plants.

Finally, green house gas production is calculated according to the existing, recommissioned and newly constructed power plant characteristics. The model tracks NO_x, SO_x and CO₂ individually. Production by existing plants is assumed to remain at levels consistent with those reported by EPA (2007) in the eGRID database. Production by decommissioned plants is suspended. Green house gas production by new and recommissioned plants (Table 3) is assigned according to average production rates for existing plants in 2007 (eGRID 2007).

Table 2. Water use and consumption according to the generation fuel type and cooling technology. All values are in gallons/kWh.

Fuel Type	Once Through		Recirculating Tower		Recirculating Pond		Air Cooled	
	Use	Consumption	Use	Consumption	Use	Consumption	Use	Consumption
Coal	27.088	0.113	0.506	0.437	17.902	0.779	0.01	0.0
Natural Gas	22.74	0.09	0.25	0.16	7.89	0.11	0.01	0.0
Nuclear	31.497	0.137	1.101	0.624	-	-	-	-
Oil	22.74	0.09	0.25	0.16	7.89	0.11	0.01	0.0
Geothermal	-	-	2.0	1.35	-	-	-	-
Hydroelectric	-	-	-	-	-	-	-	-
Wind	-	-	-	-	-	-	-	-
Other	UD	UD	UD	UD	UD	UD	UD	UD

- Not a common fuel type/cooling type pair
UD User Defined

Table 3. Green house gas production by generation fuel type. Data are based on average production rates for plants in current operation. All values are in lbs/MWh.

Fuel Type	SO _x	NO _x	CO ₂
Coal	2194.7	4.0	11.3
Natural Gas	1231.2	1.5	0.04
Nuclear	0	0	0
Oil	1823.2	15.9	2.8
Geothermal	42.9	0	0.2
Hydroelectric	0	0	0
Wind	0	0	0
Other	0	0	0

2.4.3 Water Sector

The purpose of the water sector model is to project future water demand across key water use sectors within the United States and to provide a framework for comparing these demands to a variety of water supply metrics. Such comparisons are possible at each of the five reference scales noted above (e.g., national, watershed, NERC). Demand is individually calculated according to six different use sectors: municipal (including domestic, public supply, and commercial), industrial, electrical power production, agriculture, mining and livestock. Water

use and consumption are tracked separately as are the resulting return flows. Each demand is related to its point of diversion, whether that be surface water, groundwater or a non-potable source (e.g., saline, treated waste water). Electrical power production trends described above inform water demand, while growing use and treatment of water impact electrical power demand. These water use trends are subsequently compared to a variety of water supply metrics including mean streamflow, streamflows associated with drought, and sustainable groundwater recharge.

Water use statistics published by the U.S. Geological Survey (USGS) serve as the primary data source for the analysis. Every five years since 1950 the nation's water-use data have been compiled and published by the USGS for the purpose of providing a consistent and current water use picture for the U.S. Collection of this data is a collaborative effort between the USGS, state and local water agencies, and utilities. However, the level of detail at which these data are reported varies from year to year. Data from the 1985, 1990, and 1995 campaigns provide the most comprehensive picture of water use in the U.S., and hence form the basis of this analysis (USGS 1985, 1990, 1995).

Municipal water use, Q_M , is modeled at the county level according to the relation

$$\begin{aligned} Q_{M,c}(t) &= P_c(t) * PCU_c(t) \\ PCU_c(t) &= PCU_c(t_{1995}) + (\Delta PCU_s * t_e) \end{aligned} \tag{5}$$

where P [person] is the population, PCU [$L^3/\text{person} * t$] is the per capita water use, ΔPCU is the rate of change in per capita water use [$L^3/\text{Person} * t^2$], t is time, t_e is the elapsed time since 1995, and the subscripts c and s denote county and state levels of aggregation, respectively. In this way, municipal water use is a function of both changing population and per capita water use. Changes in population are calculated according to the county level population growth rates reported by the Census Bureau (2000), as described above, while ΔPCU is based on historical trends. Recognizing that care must be exercised when extending historical trends into the future, limits are placed on the total allowable change. Specifically, ΔPCU is not allowed to increase or decrease by more than 20% over the duration of the simulation. This limit is set based on the assumption that changes beyond $\pm 20\%$ would likely require major structural changes to the system, for example the extent to which an individual home owner might implement conservation measures. Once this maximum change is achieved ΔPCU is held constant throughout the rest of the simulation. Per capita water use rates published for 1995, $PCU(t_{1995})$, serve as the initial condition for the model.

Rates of change in per capita water use, ΔPCU , were calculated by simple linear regression using data from the USGS (1985; 1990; 1995). Recognizing that meaningful trends in PCU could not be extracted at the county/watershed level (data was erratic, displaying little correlation across the three data sets), ΔPCU values were calculated from data aggregated at the state level. Each regression was inspected according to "goodness of fit". In cases where the regression did not accurately represent the perceived trends (i.e., $R^2 < 0.6$) data were fitted by hand.

Industrial water use is relatively insensitive to changes in local population; rather, economic conditions, as represented by gross state product, act as a better indicator. As such, industrial water use, Q_I , is modeled as

$$\begin{aligned} Q_{I,c}(t) &= GSP_c(t) * WUI_c(t) \\ WUI_c(t) &= WUI_c(t_{1995}) + (\Delta WUI_s * t_e) \end{aligned} \quad 6$$

where GSP is gross state product [\$], WUI is the water use intensity [$L^3/ \$ * t$] and ΔWUI is the rate of change in WUI [$L^3/ \$ * t^2$]. In this case, industrial water use is a function of both changing gross state product and water use intensity (the amount of water required to produce a dollar of gross state product). Modeling of gross state product is described above, while modeling of WUI and ΔWUI are handled in a completely analogous manner to that described for PCU and ΔPCU above.

Irrigated agriculture, Q_A , is a function of the area irrigated, climate conditions and conservation practices

$$\begin{aligned} Q_{A,c}(t) &= A_c(t) * IR_c(t) \\ A_c(t) &= A_c(t_{1995}) + (\Delta A_s * t_e) \\ IR_c(t) &= IR_c(t_{1995}) + (\Delta IR_s * t_e) \end{aligned} \quad 7$$

where A is the area irrigated [L^2], IR is the irrigation requirement [L^3/t], ΔA the rate of change in the irrigated area [L^2/t] and ΔIR is the rate of change in the irrigation requirement [L^3/t^2] (irrigation requirement responds both to climate and conservation drivers). Over the last 35 years, water use in the agricultural sector has remained relatively constant largely due to limited increases in the area irrigated and offsetting improvements in irrigation efficiencies (USGS 1995). For this reason, irrigation water use is assumed to remain constant over the duration of the simulation. Nevertheless, the model is designed to easily permit future changes to irrigated agriculture.

Other water use sectors such as mining and livestock fail to show a strong trend with population, gross state product, or any other simple metric. Thus, water use in the livestock sector, Q_L , is simply modeled by extending its historical water use trend into the future

$$Q_{L,c}(t) = Q_{L,c}(t_{1995}) + (\Delta Q_{L,s} * t_e) \quad 8$$

where ΔQ_L is the rate of change in water use by the livestock sector [L^3/t^2]. It is calculated and implemented in a fashion similar to ΔPCU and ΔWUI above. Likewise, future water use by the mining sector is modeled according to Equation 8, with an appropriate change in parameters.

The sixth major water use sector is associated with electrical power production, Q_E . Here we do not rely on historical water use trends; rather, changes in water use are calculated based on growth in electric power demand and choices in plant design (e.g., fuel type and cooling technology). A full description of how Q_E is calculated is given above.

Once water use is calculated the fraction consumed and discharged to the waste water treatment plant is determined. Consumptive use is calculated in an identical fashion to that in equations 5-8 above. Waste water discharges are calculated as the difference between use and consumption.

As the demand for water in a particular sector changes over time, so to will the mix of withdrawals from groundwater, surface water and non-potable sources. Historical trends relative to changes in groundwater abstraction are used to project future supply choices

$$GWf_{n,c}(t) = GWf_{n,c}(t_{1995}) + (\Delta GWf_{n,s} * t_e) \quad 9$$

where $GWf_{n,c}(t_{1995})$ is the fraction of supply taken from groundwater in 1995 [%], $\Delta GWf_{n,s}$ is rate of change in the fraction taken from groundwater [%/t] and the subscript n designates the water use sector. $\Delta GWf_{n,s}$ is calculated and applied similarly to that of ΔPCU and ΔWUI .

Likewise the percent water coming from non-potable sources is allowed to change, in this case according to a user defined rate of change (set by a slider bar). The resulting supply taken from surface water is simply determined as that not taken from groundwater or non-potable sources.

As water use expands, so to does the demand for electricity to pump, convey, treat (both primary and waste water), and distribute the water. Electricity demand, E_{pw} , by primary water supply is modeled at the county level according to the relation (AWWArf 2007)

$$E_{pw} = 15.4917 + 0.988 * \ln(Q_m) \quad 10$$

where Q_m is the municipal water use as calculated above while the intercept and slope parameters are based on statistical regression of energy use with water use that explains 76% of the measured correlation. E_{pw} for that fraction which is pumped from groundwater is increased by an additional 30% for the additional energy demands required to lift groundwater (EPRI 2003). In the case of the waste water system, electrical demand, E_{ww} was modeled as

$$E_{ww} = Q_{ww} * PT * PS \quad 11$$

where Q_{ww} is the water discharged to the waste treatment system, PT is a factor that accounts for the type of treatment (trickling filter, activated sludge, advanced, advanced with nitrification), and PS is a factor for the design capacity of the plant (EPRI 2003). In this way, power demand is a function of the throughput of the system, and the type of waste water treatment (more advance techniques require more power). Data were again available at the plant level from EPA's Clean Watersheds Need Survey database (2004). These power demand versus water use relations developed at the plant level were subsequently aggregated to the county level weighting the influence of each plant by its through put relative to that of the other plants in that county. Ultimately through these two relations changes in water demand (as calculated above) are used to estimate the corresponding increase in electricity demand.

In contrast to water use data, information on water supply has not been so conveniently compiled. To comprehensively compile such information is well beyond the scope of the current

study. Rather, we have identified basic stream flow and aquifer data that provide a rough indication of water supply. Specifically, the USGS has stream flow data from 23,000 gages in which the available sampling record has been statistically analyzed to give the minimum and maximum flows, long term average, key percentiles, and the base flow index (Stewart et al. 2006). While these statistics provide some insight into how much water is normally available in any given basin, they fail to consider how much water is stored in reservoirs, interbasin transfers, local water rights, as well as compacts, treaties, and ecological flow requirements.

Three of these statistics are used in the model as measures of water supply. Specifically, average streamflow is used as an indicator of the surface water supply, the 5th percentile flow as an indicator of drought flows, and the base flow index as an indicator of sustainable groundwater recharge. As these indicators are estimated from long-term gauging records, their values are treated as constants. However, available supply is expected to be impacted by upstream development. As such, changes in consumptive water use (post 2004) are sequentially aggregated from headwater to the terminus point of the watercourse. These aggregated uses are then subtracted from the long term supply value to yield an adjusted water supply metric.

To identify regions most likely to experience water shortages, a ratio of water supply to water demand was formed. In this case the “adjusted water supply metric” was used, which considers the impact of upstream aggregated changes in water consumption on water supply. Forming this ratio requires the transformation of either the supply or demand term to a consistent reference system. That is, the supply metric is defined on a watershed basis according to the accounting unit level, while water demand is defined at a county level. The transformation is implemented in both directions, to county and watershed, according to the procedures described above.

2.4.4 Interactive Interface

The decision support tool is designed to be accessible to the professional and lay public alike, requiring no specialized software (Excel is the only requirement). The model operates on a laptop computer and can be used to demonstrate key variables and processes associated with the energy/water nexus. Specifically, the model will help understand how decisions made today, e.g., key policies, electrical power distribution, and water allocation, will affect supplies and the environment in the future. The model operates in real-time with a user-friendly interface that includes slider bars, buttons and switches for changing key input variables, and real-time output graphs, tables, and geospatial maps showing results. These features allow a wide range of users to experiment with alternative water/energy use strategies and learn from the results. Ultimately, the model can be distributed to users on CD or via the internet.

Model output is ultimately preserved at its lowest level of analysis that is by sector, source, and disposition. However, data have been aggregated at a variety of levels to aid in analysis. For example, data have been aggregated by total water use by sector, total water use by source, and water use aggregated at the national level. Data is presented both as total use, change in use and percent change in use (relative to 2004).

To give a sense of the “look and feel” for the model interface a few selected screenshots are provided and discussed. Figure 3 shows some basic simulation controls; specifically, shown are controls for selecting the mix of power plant fuel types for replaced and new plant construction,

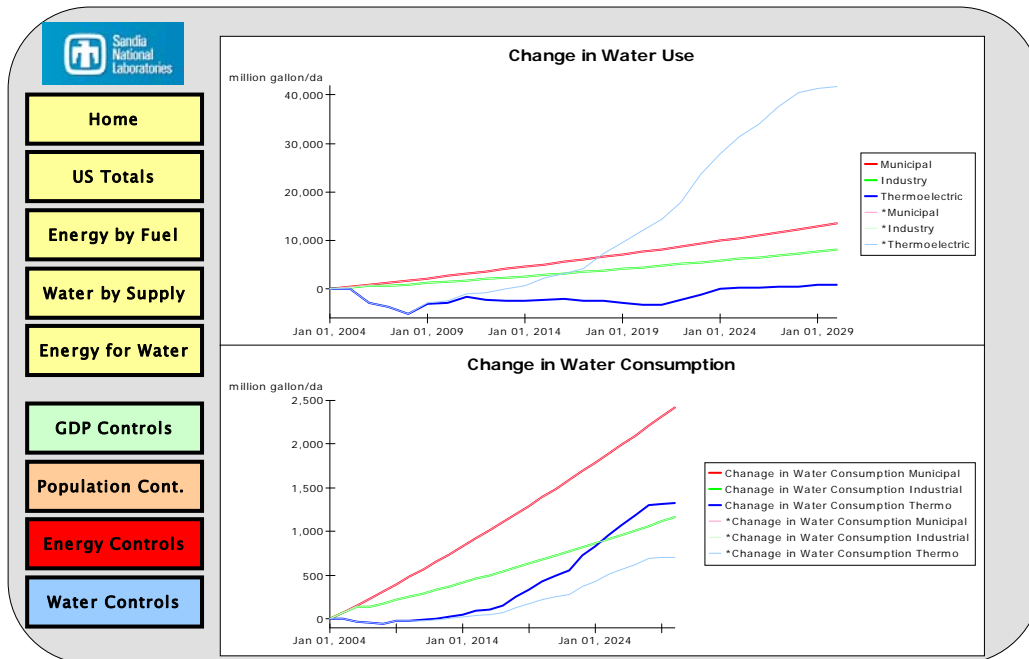


Figure 5. Change in water use in the thermoelectric sector from 2004-2030 by NERC region. Top graph shows change in thermoelectric water use, bottom graph thermoelectric water use vs. all other uses. In each graph the left-hand bar refers to the base case the right-hand bar to the test scenario. Base and scenario runs are same as described in Figure 4.

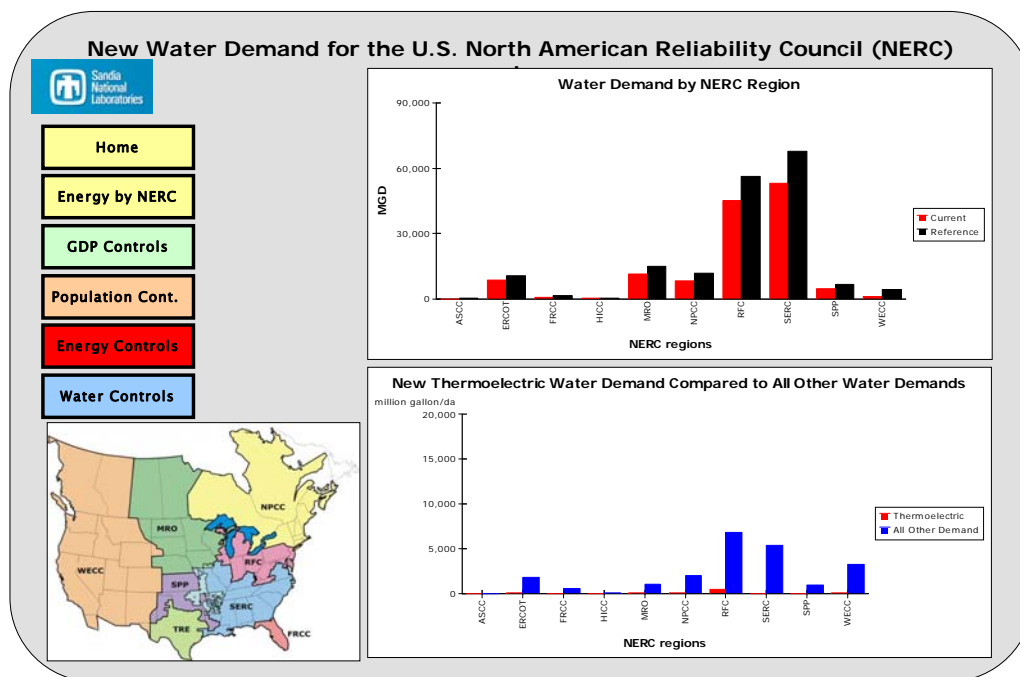


Figure 4. Change in water demand by sector from 2004-2030. Shown are results for the case assuming the current mix of cooling type is maintained into the future, relative to a scenario involving exclusive use of recirculating cooling in all new/retrofitted plants.

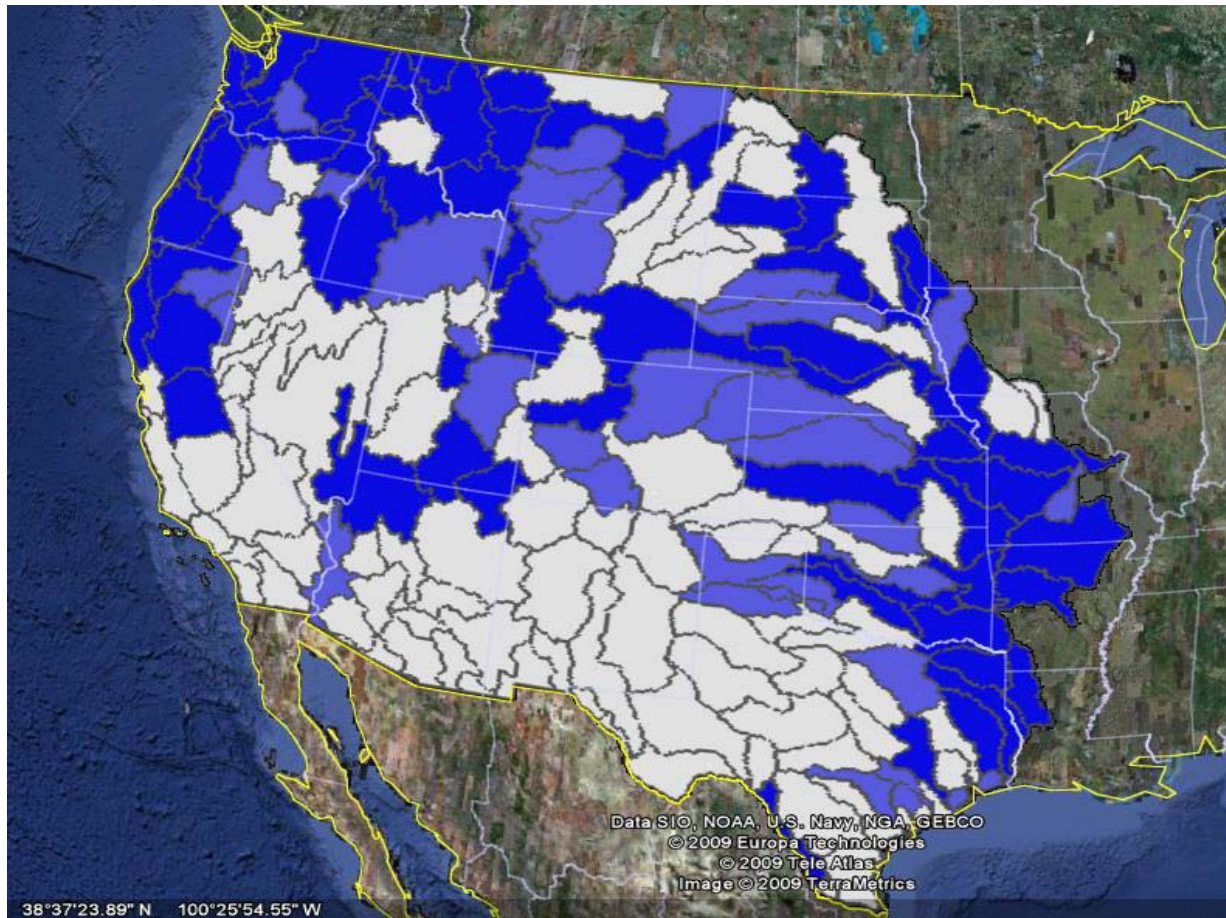


Figure 6. Water availability metric at the watershed level. Shown is the ratio between water supply (mean surface water flow) and water demand. White corresponds to areas with a ratio of 3 or less, light blue 10 to 3, while dark blue is for areas with a ratio above 10. The ratio is calculated within the Powersim model and interactively exported to Google Earth™.

3. Results

Here we exercise the model described in the previous section. As analyses are referenced to a baseline case, this subject is addressed first; that is, the baseline case is described, compared to other compatible analyses, and some general issues raised. Attention then turns to two overarching scenario analyses involving: 1) different mixes of cooling technologies applied to new and retrofitted power plants; and, 2) varying the mix of fuel types used to meet future electricity demands. In each case the consequences for water use, power capacity, and emissions are considered as well as how such change influences the nexus between water and energy (e.g., where water might limit the production of electricity). It should be noted that the scenarios considered here are but a small subset of scenarios, policies, and action metric that could be investigated with this tool.

3.1 Baseline Case

The baseline condition against which subsequent analyses are referenced is formulated as a “business as usual” case. Specifically, the baseline assumes that population and GDP progress at rates comparable to that of the 1990s and the mix of fuel types employed in newly constructed power plants matches the mix as of 2004. For this case we make the assumption that no new power plants will employ once through cooling, rather will adopt a recirculating technology (towers or ponds) or air cooled system consistent with the mix as of 2004.

To the extent possible, the dynamics of key variables have been calibrated to match published projections. Specifically, gross state product (GSP) and similarly GDP have been calibrated to follow the projected trends for U.S. Bureau of Economic Analysis’s high, reference, and low cases (BEA 2007), the reference case is used in our baseline analysis. Population growth at the county level aggregated to the national level is calibrated to the Census Bureau’s reference projections (U.S. Census Bureau 2004). Elasticities between electricity demand and GSP were calibrated to EIA’s energy projections out to 2030 (EIA 2003), disparities between EIA and modeled energy demands are less than 1% for the baseline case. Green house gas emissions were checked against EIA’s baseline projections (EIA 2003) and found to be within 10% for the base case.

Efforts have also been made to verify the water use projections produced by the model through comparisons drawn with other water use studies published in the open literature. Comparisons are drawn with three different studies each exploring the sustainability of our nation’s water supply (Guldin 1989, Brown 1999, Roy et al., 2005). Each study utilized the USGS water use database to establish initial water use figures. The Guldin and Brown studies then projected future use at the national level, while the Roy et al. studied approached future water use projections from a more regionalized view. Results from the three studies are provided in Table 4. Model results are also given in terms of total freshwater withdrawals. Most notable in this data is the relatively large spread in results. As such, this highlights the difficulty in exactly forecasting future water use. Nevertheless, the modeled results are seen to fall nicely in between the various other projections.

Table 4. Comparison of water use projections with those documented in other studies (BGD).

Year	Guldin, 1989	Brown, 1999	Roy et al., 2005	Model
2020	461	349	-	347
2025	-	-	451	361
2030	495	356	-	366

Results for the baseline analysis are given in Figures 7-17. These figures are copied directly from the model interface to provide a sense of the look-and-feel of the output display. Results are first explored at the national level. Figure 7 shows the change in built electrical power capacity. Capacity increases in a largely linear manner except during the early years. This early delay in construction is a function of an unusually large number of power plants that have reached their service limit and are thus taken offline, which basically balances new production coming on line. Capacity grows from 1.05 MMW in 2004 to 1.31 MMW in 2030 a 25% increase. Figure 8 shows the associated thermoelectric water withdrawals in 2030 of 204.0 BGD (up from 194.5 in 2004, a 5% increase) and water consumption of 4.7 BGD (up from 3.7 BGD, a 27% increase). The trend in growth strongly mimics that of the growth in electrical capacity. Figure 9 shows how thermoelectric withdrawals and consumption stack up against the municipal and industrial sectors. For both use and consumption, growth in the thermoelectric sector outpaces industrial but is less than municipal. Industrial use grows from 17.7 to 22.5 BGD (27% increase) and consumption 2.1 to 2.9 BGD (38% increase), while municipal use grows from 49.8 to 63.4 BGD (27% increase) and consumption 8.6 to 11.0 BGD (28% increase). Figure 10 indicates that most of this new water use will come from surface water supplies. Finally, Figure 11 shows the effect of the water industry on electrical power demand (remains approximately 1% of total electricity demand), while Figure 12 reports growth in green house gas emissions for the baseline case.

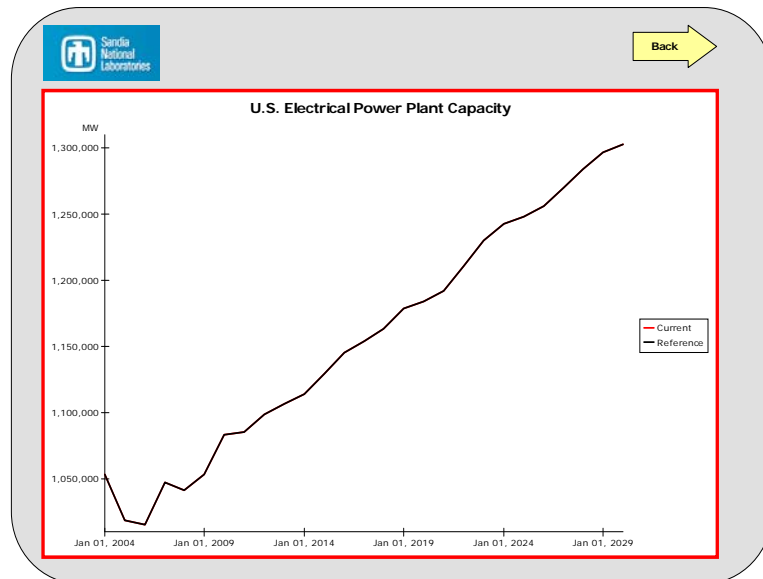


Figure 7. Change in built electrical power capacity, 2004-2030, for the baseline case (e.g., current fuel mix).

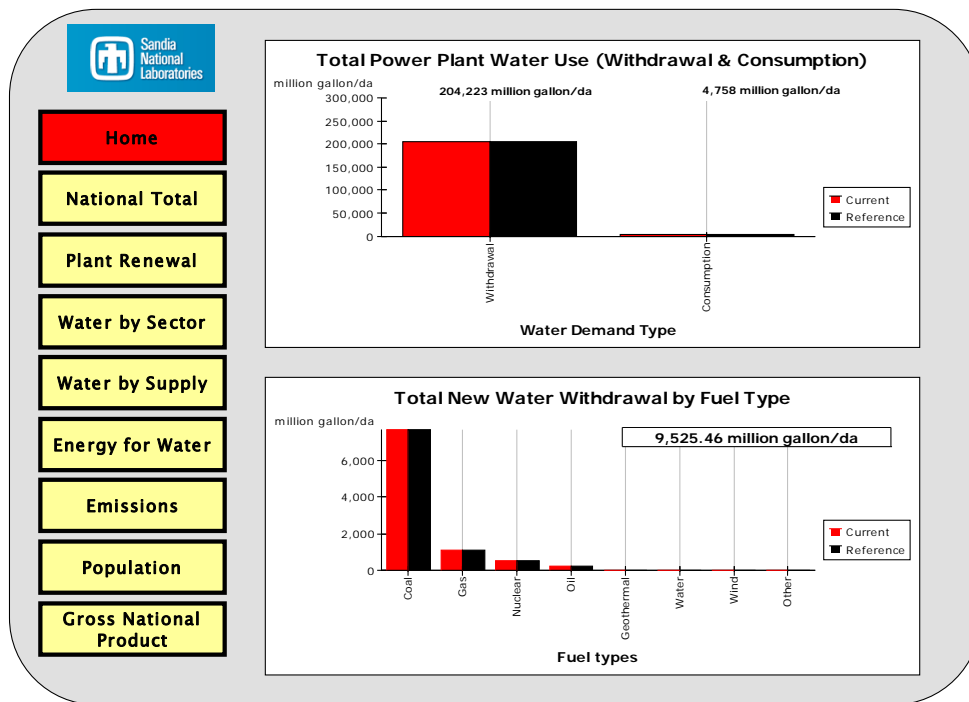


Figure 8. Change in thermoelectric water use and consumption in 2030 for the baseline case and below how new power plant withdrawals are distributed by fuel type.

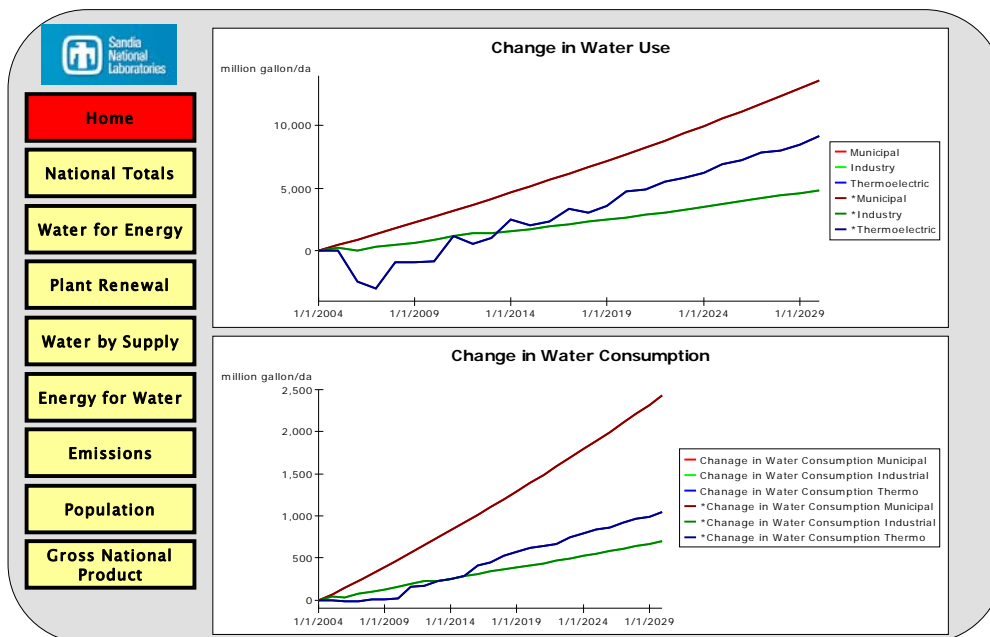


Figure 9. A comparison of water withdrawals (use) and consumption between the municipal, industrial and thermoelectric sectors. Show here is only the growth between 2004 and 2030.

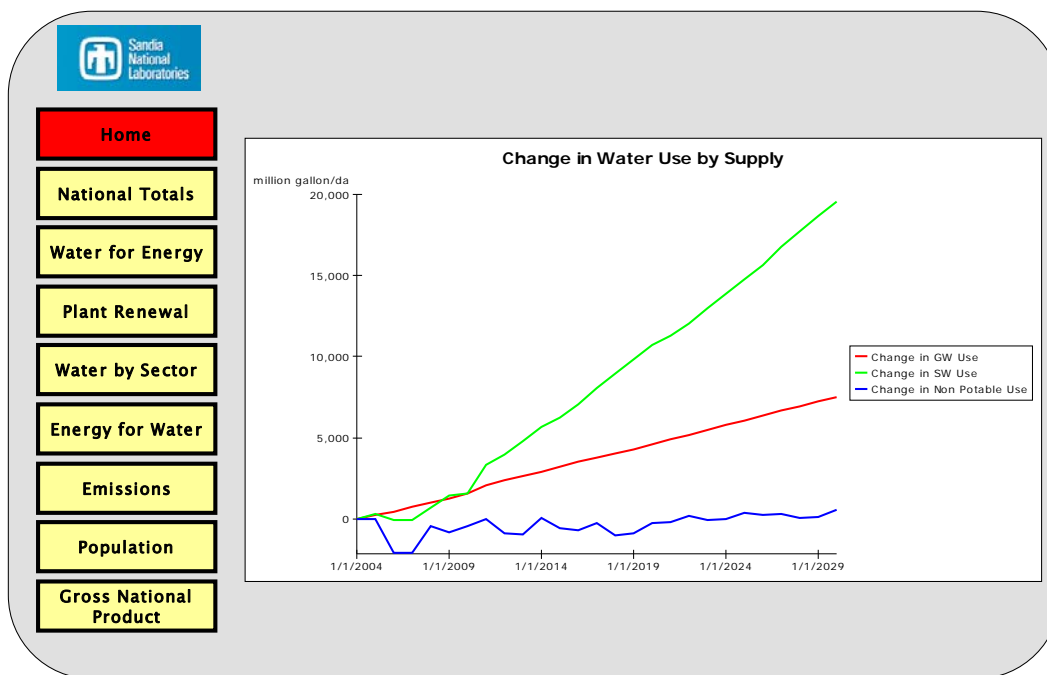


Figure 10. Change in water use, 2004-2030, distributed by different water sources (i.e., surface water, groundwater, and non-potable).

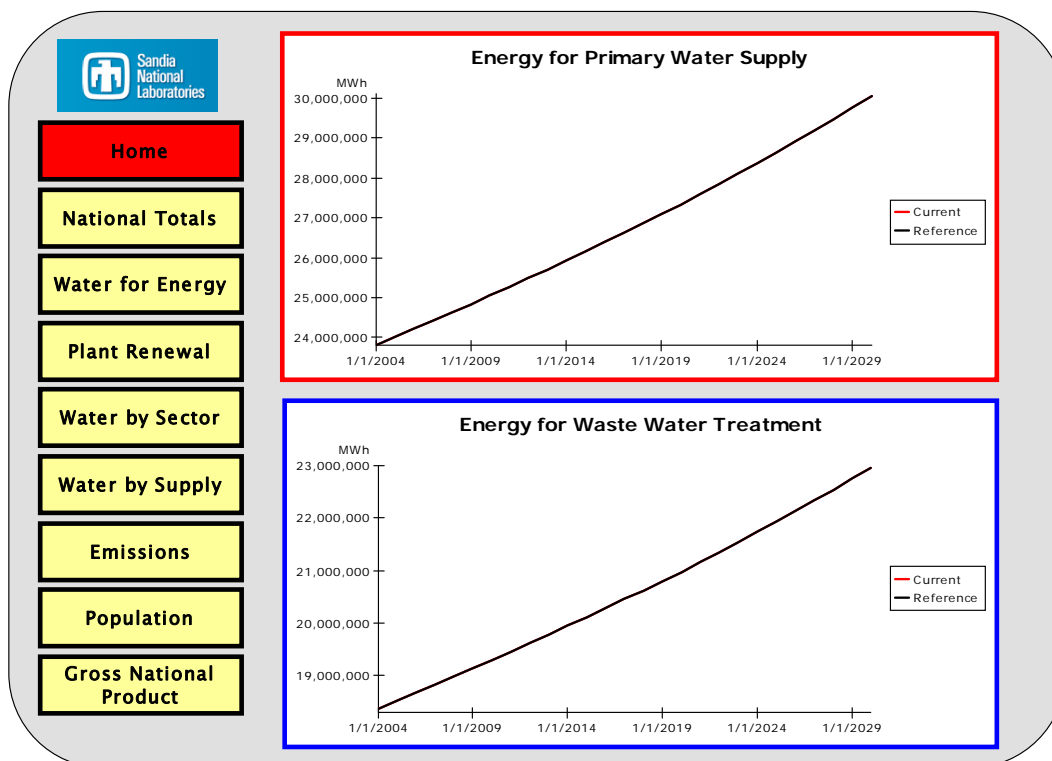


Figure 11. Electrical power demand for primary water supply and waste water treatment.

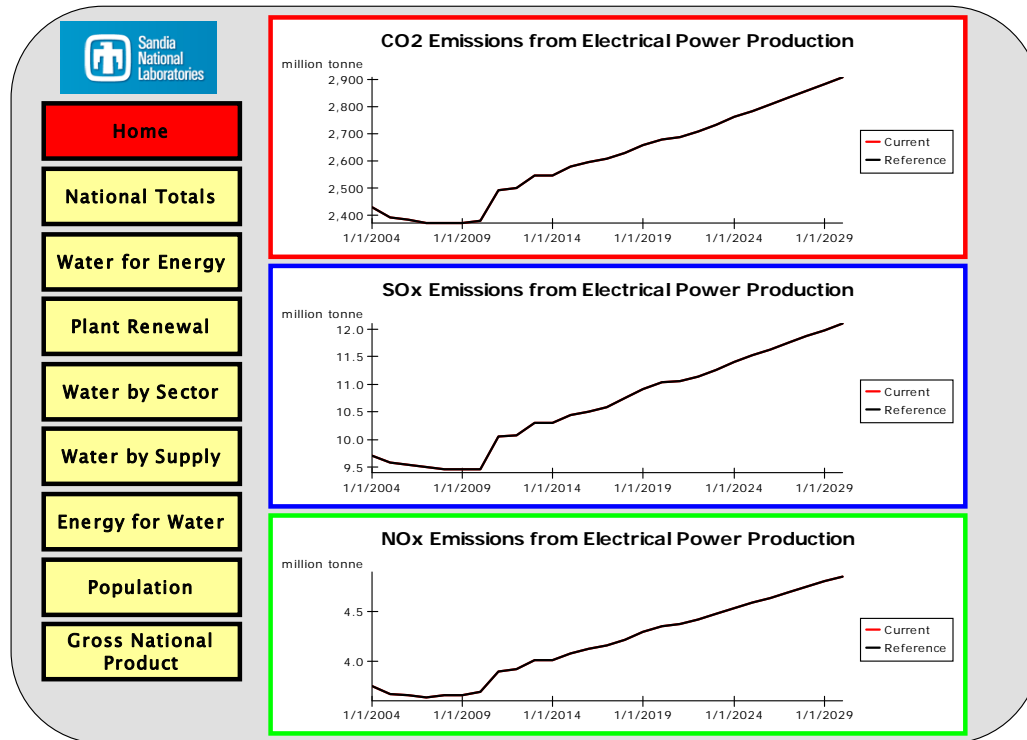


Figure 12. Green house gas emissions including CO2, SOx and NOx.

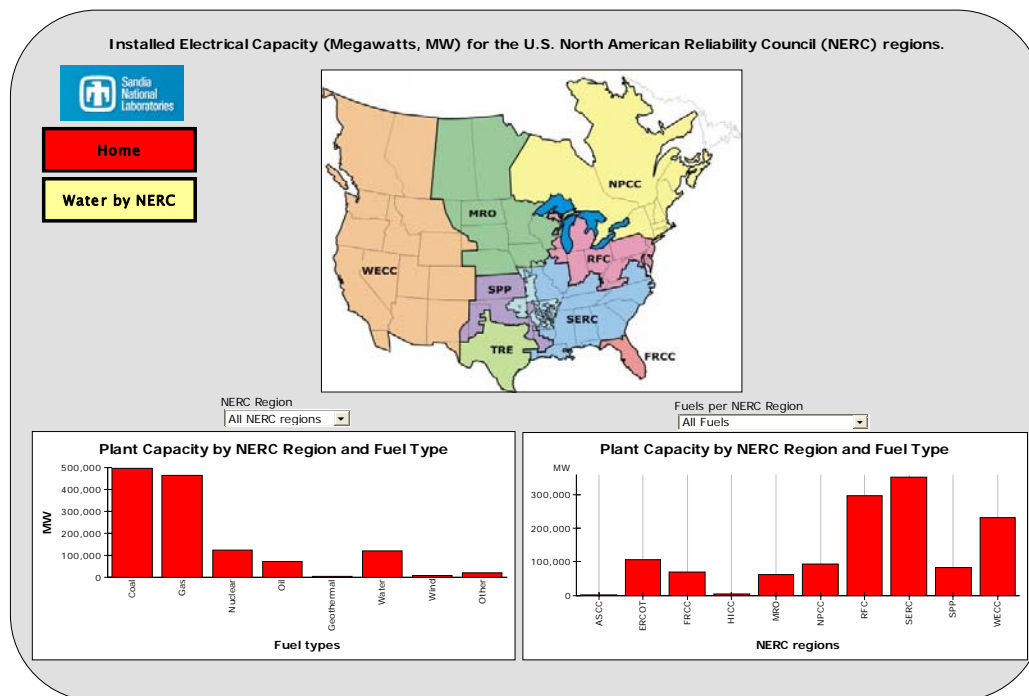


Figure 13. Built electrical power capacity in 2030 distributed by fuel type and by NERC region.

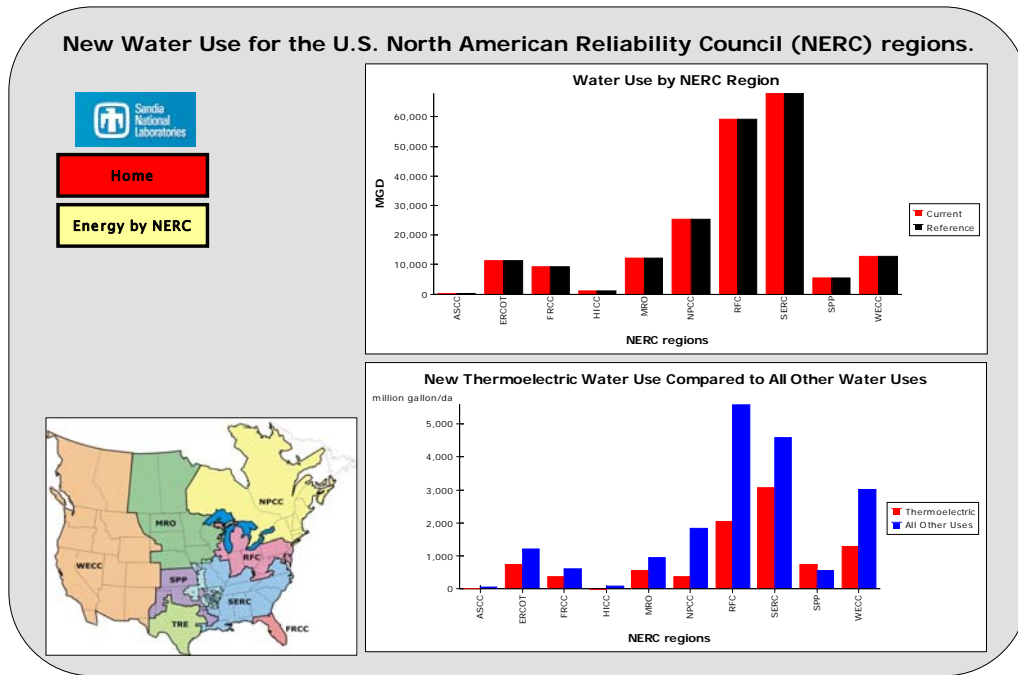


Figure 14. Thermoelectric water use by NERC region as well as a comparison between thermoelectric use and all other uses.

Figures 13 and 14 show how the new electrical power capacity and accompanying water use is distributed across the different NERC regions, respectively. Here we see that the capacity differs strongly by region and that most of this capacity is generated by coal and gas fired plants. Thermoelectric water use likewise varies across the NERC regions, in relatively similar proportions to capacity.

Results at the finest granularity, that is county or watershed level, are displayed using Google Earth™. Figure 15 presents three different maps, total water use, thermoelectric water use, and electricity demand for the continental U.S. The most striking feature of these three maps is the very different spatial arrangement of the demands. For total water use high values are clustered around densely populated cities, and broadly distributed in the West and Mississippi Valley reflecting the influence of irrigated agriculture. In contrast, thermoelectric water use has more of a shotgun pattern with little rhyme or reason to the distribution. Electricity demand on the other hand displays a much more uniform distribution across the U.S. than either of the other two metrics. While many other metrics could be displayed here, these three are sufficient to make the important point that place matters.

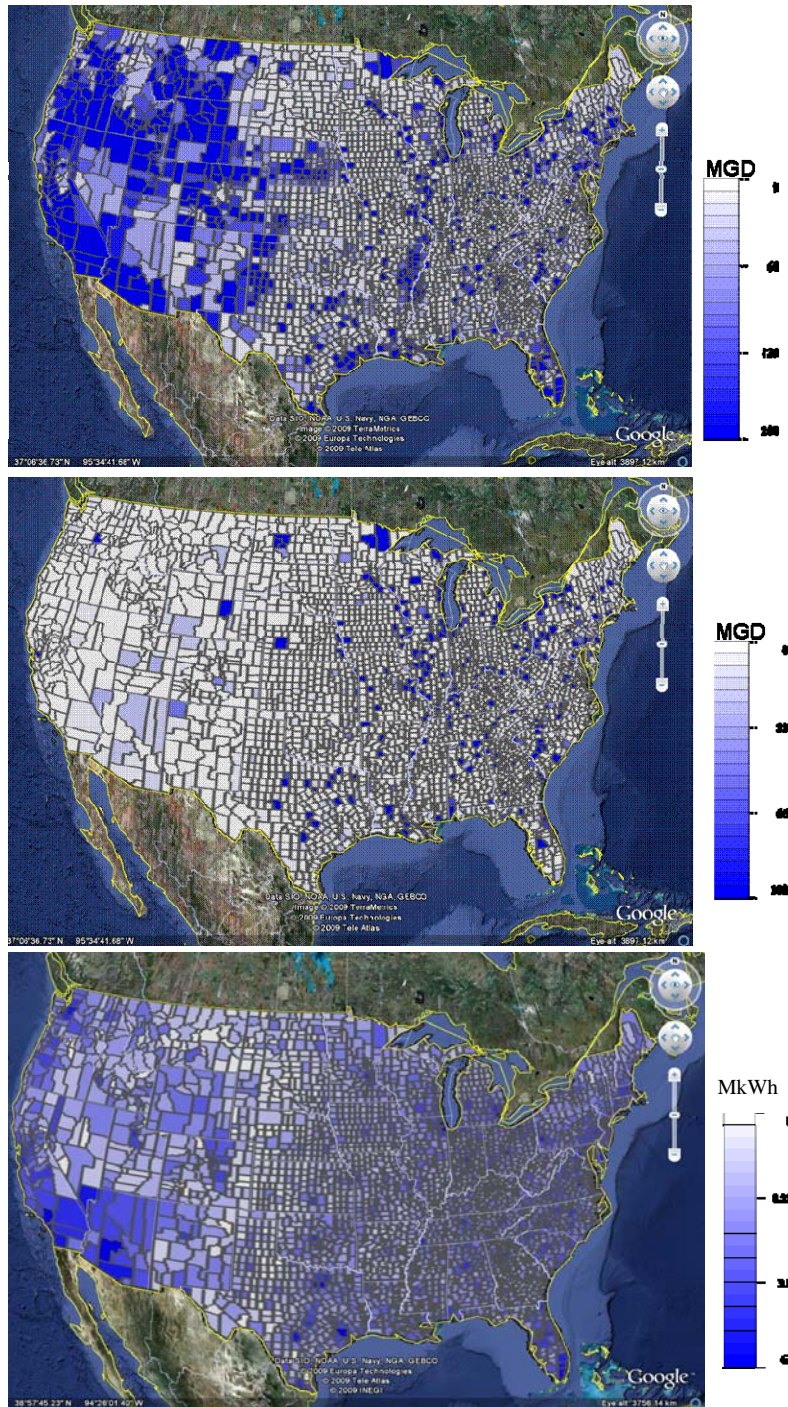


Figure 15. Distribution of total water use, thermoelectric water use, and electricity demand at the county level for the continental United States in 2004.

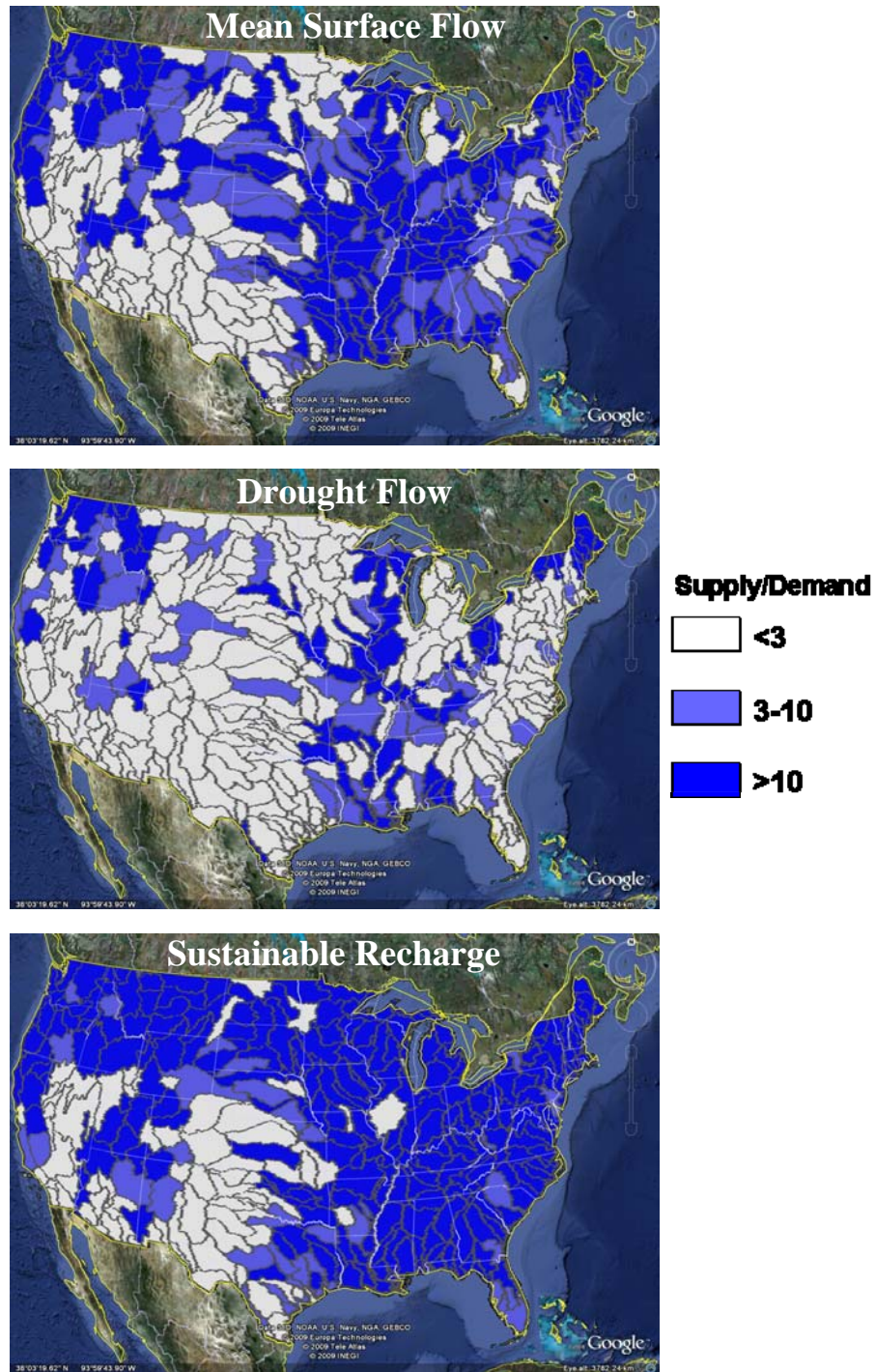


Figure 16. Maps showing the areas of potential water stress. Shown are the ratios of water supply to demand on a watershed basis (accounting unit level). Three different supply metrics are used, normal supply (top) mean gauged stream flow, drought supply as given by the 5th percentile gauged flow (middle), and sustainable recharge given by the gauged base flow (bottom).

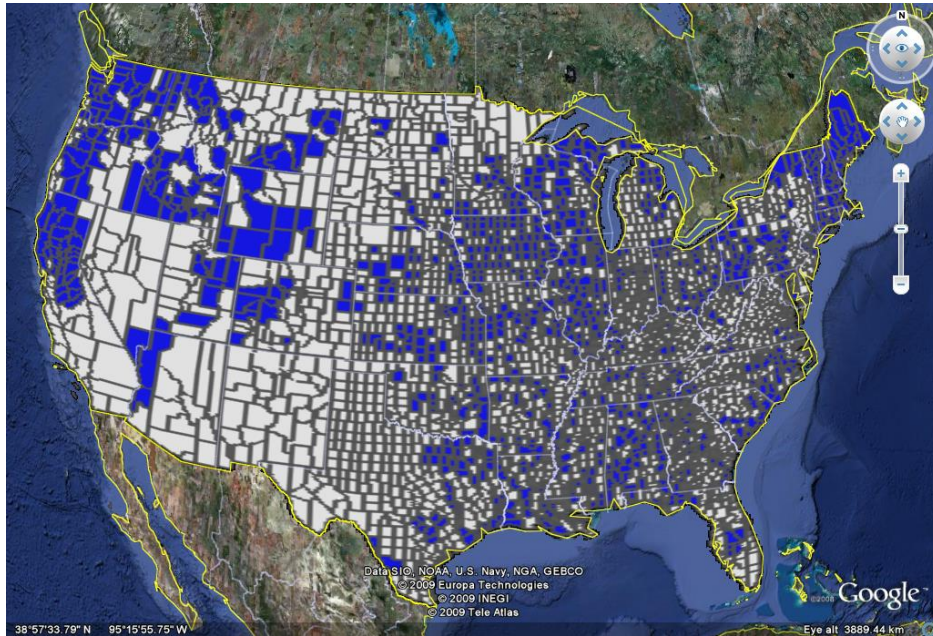


Figure 17. Counties suitable for siting future power plants. Criteria include a water supply to demand ratio greater than 5, and the presence of at least one power plant in the county prior to 2004.

According to Figure 15, it is the nexus of the demands and their spatial arrangement that are particularly important to this problem. Several general displays have been developed to identify locations where electrical power production is likely to compete with other water use sector demands for limited resources. As a first step toward visualizing this nexus we construct maps showing the ratio of water supply to water demand. Where this ratio is large, shortages of water are unlikely, where the ratio is small supply is on the order of demand thus there is little room for new growth. As noted above, three different ratios have been formulated one for surface water supply, another for drought supply and a third for groundwater. These are shown in Figure 16.

A quick review of the mean surface water supply and sustainable groundwater recharge ratios clearly reveals that ratios tend to be higher in the East and far Northwest, while the greatest opportunity for water stress is in the Southwest. This expected behavior is a result of both the aridity of the West and the higher water use due to irrigated agriculture. The drought ratio indicates that most all of the continental United States is susceptible to the effects of short term drought. It must also be recognized that these three metrics are not perfect indicators of useable water supply. In each case the metric only provides a measure of the amount of water present in the basin, but this says nothing as to whether that basin can use the water. That is, these metrics do not account for interstate compacts, treaties, or interbasin transfers. This fact is evident in Northern California and in the Colorado River basin where considerable water is generally present (high ratios), but is transferred outside the basin for use by others. Although these metrics are not perfect, they still provide a general sense of the water stress within a given region.

This view can be further refined by considering the availability of sites for new power plant construction. Hundreds of new power plants will be required to meet the growing demand for electricity through 2030. Where will we put all the new plants? Various siting criteria can be implemented and tested within the model to see the availability under different scenarios. Figure 17 shows those counties suitable for siting new power plants in 2004 given specific criteria, including a water supply/demand ratio greater than 5 (that is water is likely available for new uses), and there are other existing power plants in the county (a simple measure of whether there is likely transmission capacity and other necessary infrastructure for siting a new plant). Although these simple criteria limit many counties, there are still many suitable counties for siting. This is just one of many possible siting criteria that could be explored.

3.2 Cooling Technology Mix

Beyond the base case described above, many other scenarios can be explored with the Energy-Water Model. Here we explore one set of scenarios grouped around alternative mixes of cooling technologies utilized in the construction and recommissioning of power plants. In this set of scenarios all else is kept constant, identical to the base case, except assumptions concerning the future mix of applied cooling technologies. Three different scenarios are compared:

1. Future construction maintains similar cooling mix as of 2004 (current mix); specifically 43% once through cooling, 47% recirculating cooling towers, 9% recirculating cooling ponds and 1% air cooled. Recommissioned plants are assumed to retain prior cooling technology.
2. Future construction utilizes only recirculating cooling towers, while recommissioned plants retain prior cooling technology.
3. Future construction utilizes only recirculating cooling towers, while all recommissioned plants are likewise converted to recirculating cooling towers.

For purposes of the Energy-Water Model, changes in cooling technology only impact thermoelectric water use/consumption and overall competition among the different water use sectors. Figure 18 displays water use and consumption by the thermoelectric sector aggregated at the national level for the three scenarios. The “current mix” scenario is seen to have the highest water use (236,079 MGD in 2030) and lowest water consumption (4300 MGD in 2030), while the scenario utilizing recirculating cooling towers in all new construction and recommissioned plants has the lowest water use (184,860 MGD in 2030) but highest consumption (5015 MGD in 2030). The scenario involving exclusive use of cooling tower technology only in newly constructed plants falls in between with a use of 196,667 MGD and consumption of 4788 MGD. This behavior reflects the high water use intensity but low consumption of once through cooling, which is in direct contrast to recirculating cooling towers.

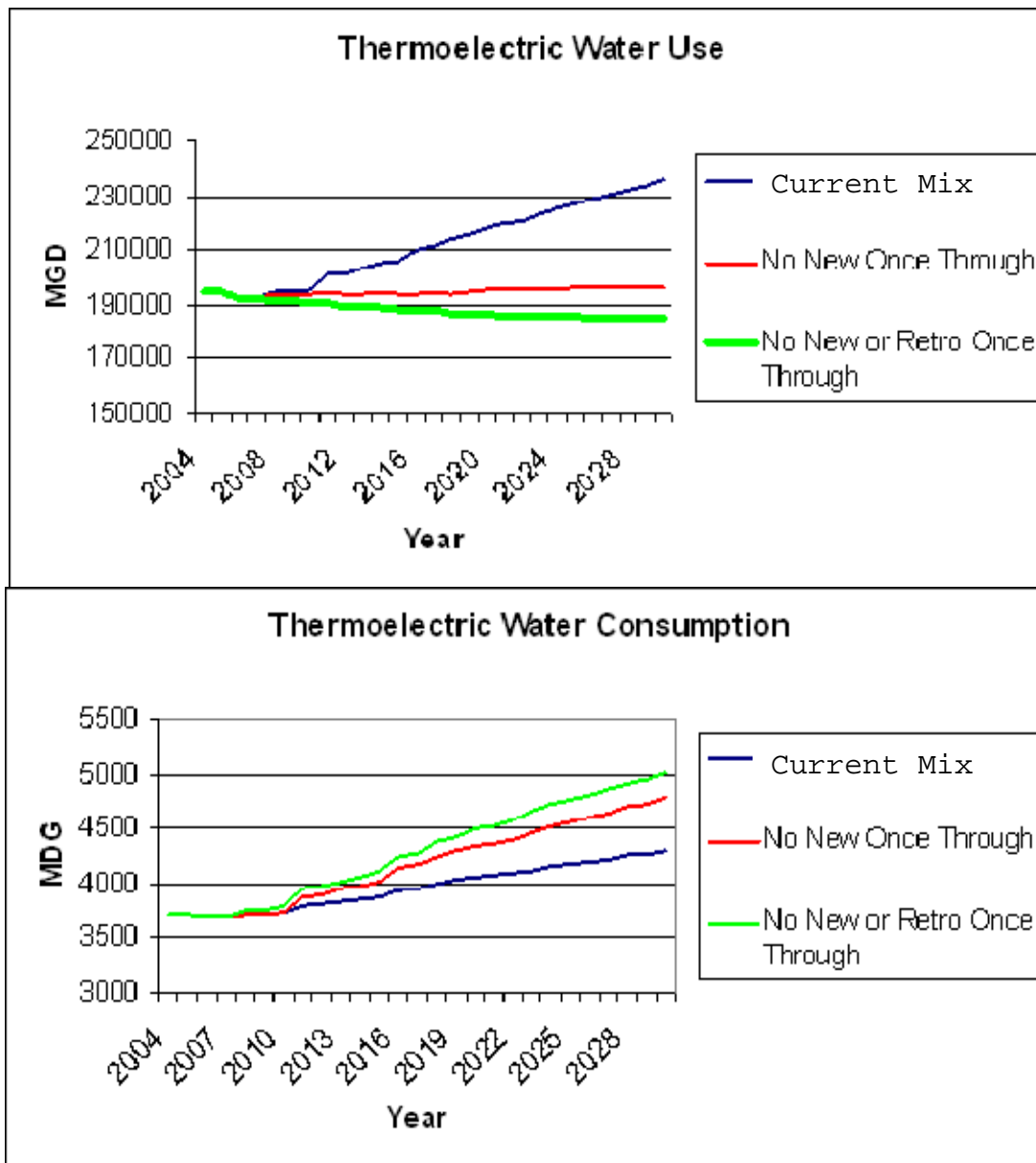


Figure 18. Thermoelectric water use and consumption aggregated at the national level for three different cooling technology mix scenarios.

With these three scenarios, rough upper and lower bounds for thermoelectric water use and consumption through 2030 can begin to be established. In terms of water use the current mix case defines the likely upper limit. This represents a 21% increase or 41,000 MGD of new withdrawals between 2004 and 2030. This would represent the largest increase across all water use sectors. This scenario is unlikely given the very small number of plants using once through technology that have been built since the 1980s, which environmental laws make difficult to permit. The push toward use of wet-recirculating cooling technology suggests the scenario

involving use of such technology in both newly constructed and recommissioned plants is a reasonable bet. This would involve a 5.5% decrease in water use (10 BGD savings) but a 35% increase in water consumption (increase of 1.3 BGD). In terms of consumption, growth in this sector would outpace all others except municipal. Of course the lower bound would involve full deployment of air-cooled systems which effectively use and consume no water. Another consideration is the impact of fuel mix on water use and consumption, a subject considered in the next set of scenarios (see below).

Of interest is the impact of the cooling technology mix on the competition for water at the regional scale. Figure 19 shows the increase in thermoelectric water consumption at the county level from 2004 to 2030 for the three different scenarios. The current mix having the lowest overall water consumption and the cooling towers in new and recommissioned plant construction has the highest. Overall it is difficult to detect strong differences between the three scenarios. The only real clear change occurs in southern California. This is not terribly surprising given that the total difference in consumption between the high and low scenario is only 715 MGD, which is distributed over approximately 1200 power plants sited in 1000 counties (see siting rules above). In other words, cooling technology decisions will only have very localized effects.

Another way of interpreting the results of Figure 19 is the far reaching effects of thermoelectric power on overall water consumption in the United States. Here we see how the extra 0.6 to 1.3 BGD of new water consumption due to thermoelectric power generation is spread across the nation. More important is the recognition that the siting and recommissioning of power plants has the potential to impact water supply decisions in over a thousand counties nation wide. Further, consider that one of these plants (assume of 500 MW coal fired plant with cooling towers) consumes the equivalent amount of water as 528 people (assuming a 100 gallons per capita per day).

How cooling mix decisions might impact regional water stress can be investigated by exploring changes in the water supply-demand ratio. Figure 20 shows the change in the ratio between 2004 and 2030 (calculated by subtracting the ratio in 2030 from that in 2004) for the current mix and cooling tower in new and recommissioned plant scenarios. While there are apparent changes across the two scenarios, there is no clear improvement for one case over the other. The reason being that there are two competing forces at work. The demand is calculated as total water use while supply is influenced by changes in water consumption. Because the impacts on thermoelectric water use and consumption have a reciprocal relation in the two scenarios, their influence effectively offsets each other in the supply-demand ratio. Thus, the cooling mix decision, at least for these scenarios, is not seen to be a significant factor.

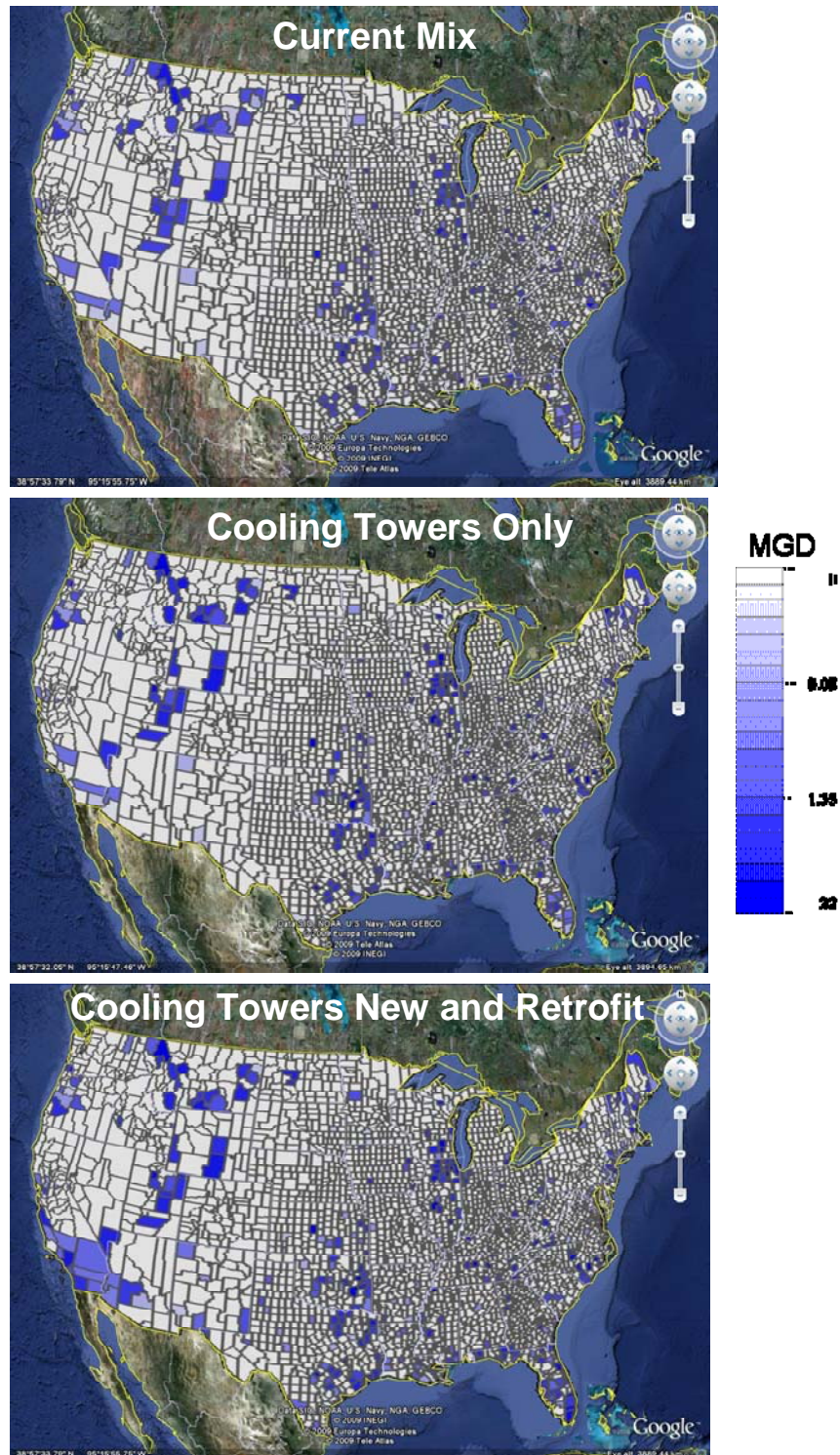


Figure 19. Change in thermoelectric water consumption by county from 2004 to 2030.

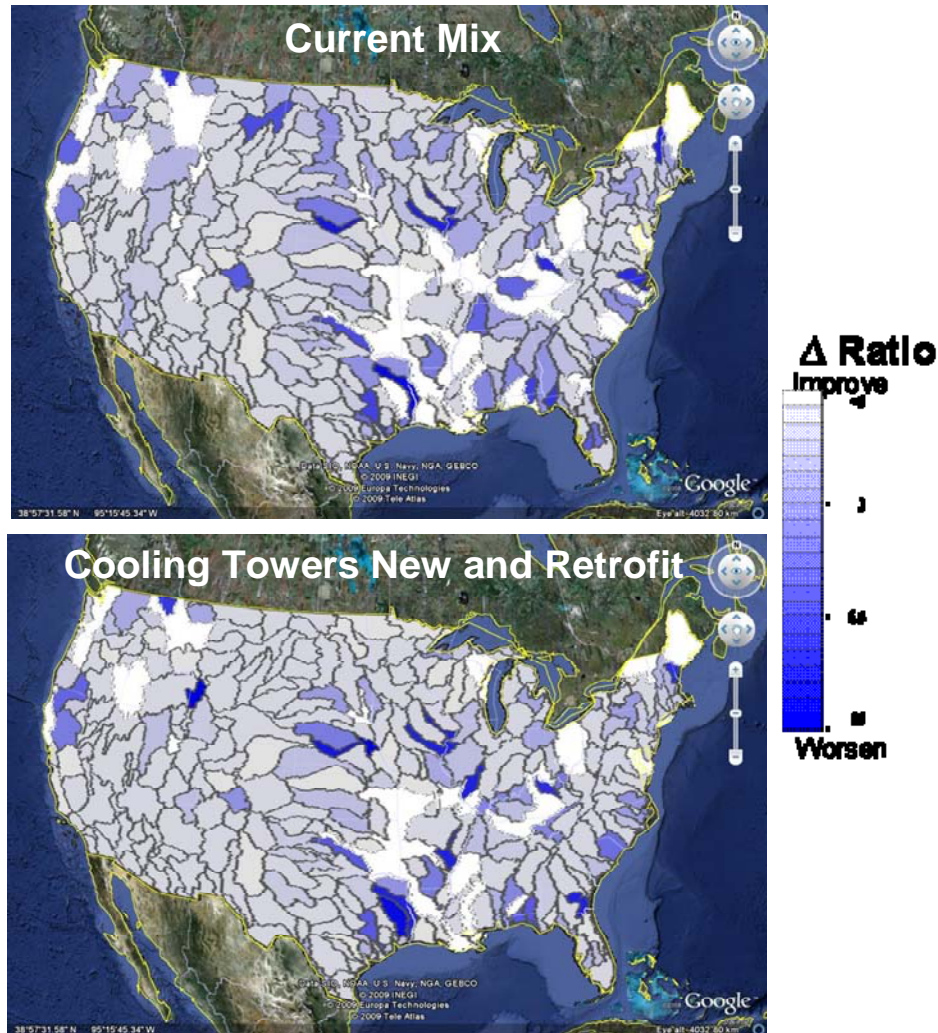


Figure 20. Change in the water supply to demand ratio in 2030 given two different mixes of cooling types employed for future electric power generation.

3.3 Fuel Type Mix

A second set of scenarios is explored that consider changes to the mix of fuel types used in future electrical power production. These scenarios deal only with the siting of new power plants. All recommissioned plants are assumed to remain unchanged in terms of fuel type. Again, all other factors remain unchanged, only fuel mix is varied (except case 4). Scenarios investigated include:

1. Current mix of fuel types is maintained into the future.
2. Renewable Portfolio Standard (RPS) scenario, which involves 25% power generation by renewables by 2030, all other fuel types are reduced in proportion to 2004 levels.

3. Pro Nuclear Standard in which 25% of future power generation is by nuclear, all other fuel types are reduced in proportion to 2004 levels.
4. High GDP Scenario following the BEA “high case” which corresponds to a 6% increase in electricity demand over the reference case. For this case the current mix of fuel types is used.

Changes to the fuel mix have a broad impact on the model, influencing total built capacity, thermoelectric water use/consumption, green-house gas emissions, and competition for power plant siting locations.

Figure 21 displays differences in built capacity across the four different scenarios. Differences among the first three cases reflect variability in the capacity factors (i.e., percent of time a plant generates power) for the different fuel types. Specifically, renewables currently have a relatively low capacity factor, while nuclear has the highest capacity factor. In other words, it takes more built capacity to produce the same amount of power in the case of a low capacity factor as a higher one. In terms of the increased GDP, increased capacity simply reflects increased demand. The highest capacities are attained for the RPS case, 1,404,700 MW, while the lowest is for the Pro Nuclear case, 1,276,200 MW, representing a 10% difference (or 57% in terms of new capacity).

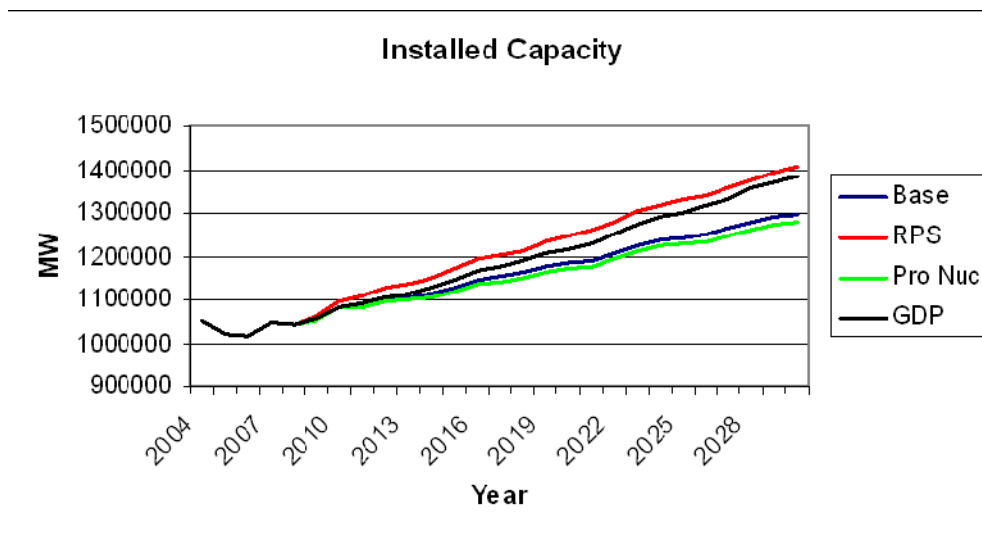


Figure 21. Comparison of built capacity out to the year 2030 for the four different fuel mix scenarios.

Changing the fuel mix also impacts the resulting CO₂ emissions (Figure 22). Fuel mixes favoring fossil based systems result in higher CO₂ emissions; however, all four scenarios result in increased emissions over the 2004 levels (since new fossil based power plants are being constructed in all cases). The high GDP scenario (current fuel mix with accelerated demand) has the highest emissions, 3184 tonnes/yr, while the RPS case has the lowest, 2810 tonnes/yr. This change in power production has the potential to reduce CO₂ emissions by 5% over the business as usual case (i.e., current mix).

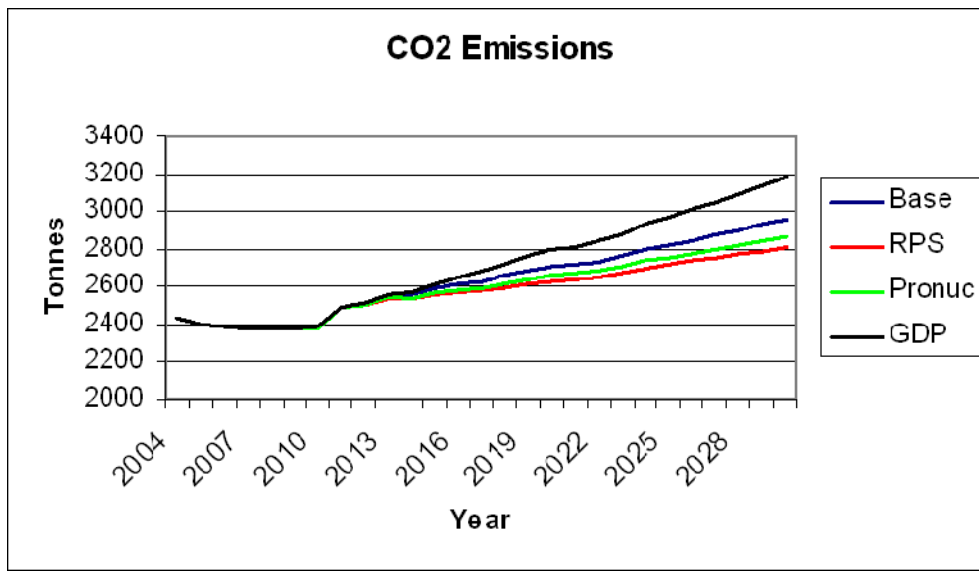


Figure 22. Comparison of CO2 emissions out to the year 2030 for the four different fuel mix scenarios.

While fuel mix has a measurable influence on thermoelectric water consumption, no real difference is seen for the case of water use (Figure 23). As we have assumed that all new construction utilizes recirculating wet cooling, water use and water consumption values are essentially identical, hence the perceived difference between use and consumption is simply a matter of the significant difference in absolute scales (water use being 40 times greater). The GDP case yields the highest water consumption at 5185 MGD, while the RPS yields the least at 4634 MGD. It is important to note that a shift toward a richer renewables mix is capable of reducing overall thermoelectric water consumption by 5%, or 23% in terms of post 2004 water consumption.

As we have already seen, decisions concerning the mix of fuel types effects both the built capacity, and hence the number of plants constructed, as well as thermoelectric water consumption. Both of these factors have implications for future competition between the energy sector and other water use sectors. To help visualize this potential competition the counties meeting power plant siting criteria in 2030 are shown in Figure 24 for both the Pro Nuclear and RPS cases. These cases were selected because they represent the end points in terms of new plants constructed, Pro Nuclear requiring 958 new plants, while RPS requires 2468. As noted above, the siting criteria used include a water supply/demand ratio >5 and that the county had at least 1 power plant in 2004. An additional criterion was added that no more than 5 new power plants would be constructed in any single county—this assumes that there is a limit to how many power plants a county would permit. A review of the maps show a visible decline in the number of counties meeting siting criteria in 2030 (Figure 24) relative to that in 2004 (see Figure 17). For the Pro Nuclear case counties meeting the criteria number 1187 in 2004 and only 707 in 2030, a loss of 480. The RPS case is more severe with only 609 viable counties nation wide remaining in 2030. When viewed at the NERC region level, this issue is even more concerning; specifically, the Florida Reliability Coordinating Council (FRCC) and Texas Regional Entity (TRE) have

effectively exhausted all suitable siting counties by 2030. There are also large areas of the country with few or no suitable sites, Southwest, Interior West, Great Plains and the Atlantic Coast. While this does not suggest there is nowhere to place a new plant, it does suggest that new sitings will need to consider successively less attractive construction locations. Of course different selection criteria could lead to both more restrictive and less restrictive siting scenarios.

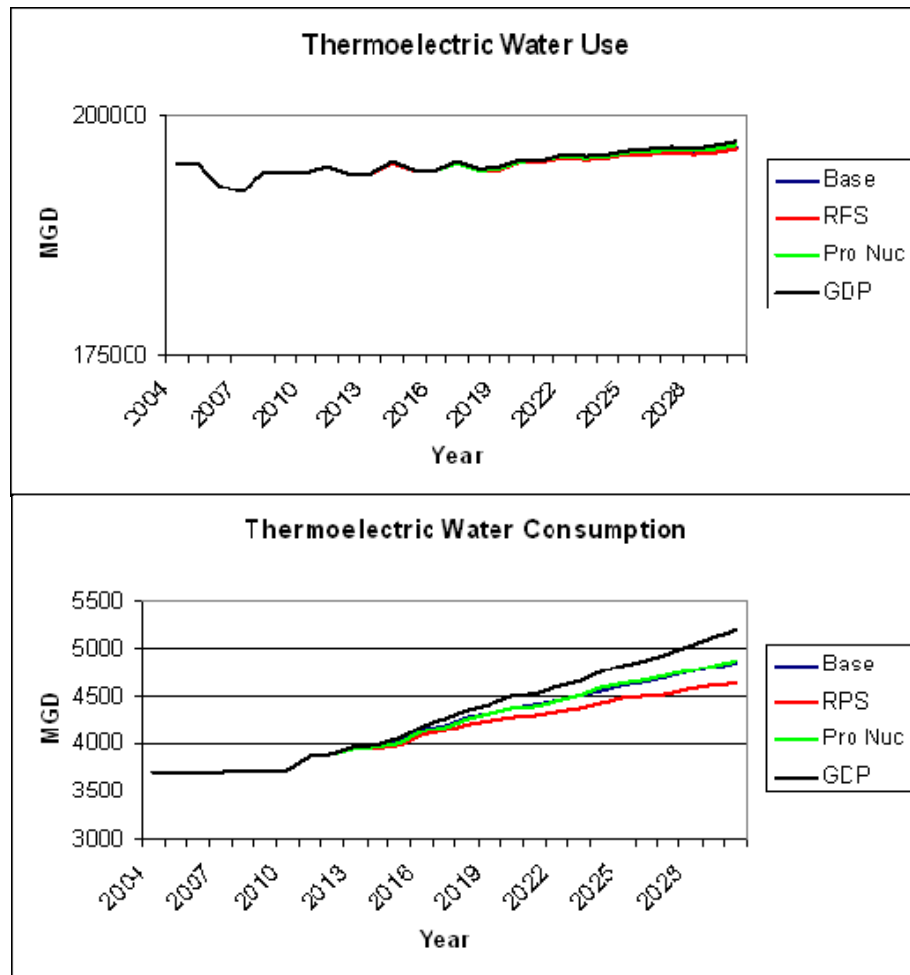


Figure 23. Comparison of thermoelectric water use and consumption out to the year 2030 for the four different fuel mix scenarios.

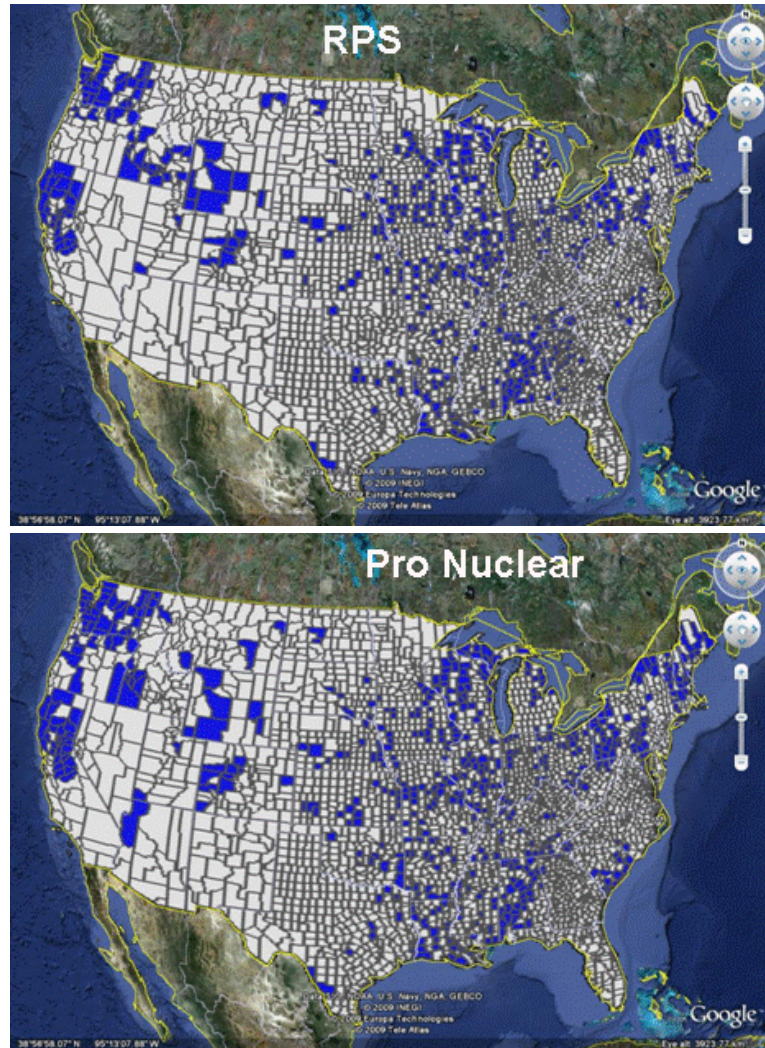


Figure 24. Counties that meet power plant siting requirements in 2030 for two different fuel mix scenarios, RPS and Pro Nuclear cases.

4. Summary

The primary goal of this research was to develop a decision support framework for integrated energy-water planning and management. The model targets the needs of energy and water producers, resource managers, regulators, and decision makers at the federal, state and local levels. The framework integrates analysis and optimization capabilities to identify trade-offs, and “best” alternatives among a broad list of energy/water options and objectives. The decision support framework is formulated in a modular architecture that facilitates tailored analyses over different geographical regions and scales (e.g., national, state, county, watershed, NERC region). An interactive interface allows direct control of the model and access to real-time results displayed as charts, graphs and maps. Ultimately, this open and interactive modeling framework provides a tool for evaluating competing policy and technical options relevant to the energy-water nexus.

The integrated energy-water planning model is formulated within a system dynamics architecture, designed to operate on an annual time step. The spatial extent of the model includes the continental United States, Alaska and Hawaii. At its highest level, the model is organized according to three primary sectors, demography, electric power, and water. The demographic sector simulates changes in population and gross state product, which in turn drives the demand for electric power and water.

Electric power generation is modeled at the power plant scale with 4841 individual plants simulated. Plants are distinguished by fuel type; utility vs. non-utility designation; geographic location; installed capacity and annual power output; build date; and, cooling type. To the extent of the available data, we characterize the inputs and outputs for the various plants in terms of fuel and water consumption, power generation, and resulting greenhouse gas emissions. A power plant replacement module tracks the aging of plants and replaces them once they exceed their life expectancy. Also within the electric power sector, the growing demand for power is simulated along with the accompanying construction of new power plants. The analyst has control of the type of plant (i.e., coal, oil, natural gas, nuclear, hydroelectric, geothermal, wind, and other) as well as the type of cooling system (i.e., once through, recirculating cooling tower, recirculating cooling pond, or air cooled) employed in the new construction.

The corresponding water model is implemented at the county or watershed (USGS six-digit hydrologic unit classification) level. Water use is tracked according to domestic, public supply, industrial, energy, agricultural and environmental demands. Future demands are projected according to historical trends as modified by population pressure and economic forcings. Water supply data are more difficult to come by. Rather a series of supply indicators have been developed according to groundwater baseflow, mean surface water flow, and drought flows. Growth in the water sector feeds back to the energy sector in terms of increased electricity demand and vice versa. That is, in addition to the water used in thermoelectric power generation, the energy used to move and treat primary and waste water is simulated by the model.

To aid in visualization of model simulation results a link to Google Earth™ has been developed. Spatial variations in water use, electrical power demand/production, etc. can be viewed at the

county, watershed, state, and NERC region levels. This simple linkage allows broad use of the model without the need to purchase costly GIS software.

Also developed are integer programming (IP) models that can integrate with data generated by the system dynamics model. These IP models minimize population density, while constraining power plant construction based on the availability of potential sites, the availability of water resources and required power demand. Predictions from the system dynamics model for future water and energy demands are used to define the constraints. To solve these IP models, we are using Pyomo, a new modeling tool developed by Sandia's discrete math group, which can work directly with MS Windows applications.

Once assembled the modeling framework was calibrated according to a variety of leading projections relevant to water and electricity. Specifically, population projections were calibrated to the Census Bureau, Bureau of Economic Analysis projections were mimicked for GSP projections, future electricity demands and green house gas emissions were obtained from the Energy Information Administration, while energy use projections by water and waste water utilities were matched from the American Water Works Research Foundation and the Electric Power Research Institute.

The calibrated model has been subsequently exercised. Specifically, a business as usual baseline case was developed along with two policy scenarios, one involving different mixes of cooling technology in new and retrofitted power plants while the second involves different fuel mixes to meet future electricity generation demands. Key findings of this analysis are as follows:

1. Under the baseline case for future electricity production (maintain current fuel mix and cooling mix with the exception of no new once through cooling) water withdrawals are projected to increase from 194.5 to 204.0 BGD (a 5% increase) with a more significant increase in water consumption 3.7 to 4.7 BGD (a 27% increase).
2. Relative to the cooling mix scenario, the case utilizing the current mix of technology is seen to have the highest water use, 236.1 BGD in 2030 and lowest water consumption, 4.3 BGD, while the scenario utilizing recirculating cooling towers in all new construction and recommissioned plants has the lowest water use, 184.8 BGD but highest consumption, 5.0 BGD.
3. Altering the fuel mix has a notable influence on thermoelectric water consumption. The GDP case (increase of 6% in electricity demand) yields the highest water consumption at 5.2 BGD, while the RPS case (25% national RPS standard) yields the least at 4.6 BGD. It is important to note that a shift toward a richer renewables mix is capable of reducing overall thermoelectric water consumption by 5% in 2030, or 23% in terms of total post 2004 water consumption.
4. For most scenarios, growth in thermoelectric water use and consumption outpaces that of the industrial sector but is less than that of municipal. Industrial use grows from 17.7 to 22.5 BGD (27% increase) and consumption 2.1 to 2.9 BGD (38% increase), while municipal use grows from 49.8 to 63.4 BGD (27% increase) and consumption 8.6 to 11.0 BGD (28% increase).
5. Efforts were made to identify locations where electrical power production is likely to compete with other water use sector demands for limited resources. To aid in this effort

maps were constructed showing the ratio of water supply to water demand. Where this ratio is large, shortages of water are unlikely, where the ratio is small supply is on the order of demand thus there is little room for new growth. Three different ratios have been formulated one for surface water supply, another for drought supply and a third for groundwater. A review of the mean surface water supply and sustainable groundwater recharge ratios clearly reveals that ratios tend to be higher in the East and far Northwest, while the greatest opportunity for water stress is in the Southwest. The drought ratio indicates that most all of the continental United States is susceptible to the effects of short term drought. However, it is important to recognize that these three metrics are not perfect indicators of useable water supply. In each case the metric only provides a measure of the amount of water present in the basin, but this says nothing as to whether that basin can use the water.

6. Supply/demand ratios were calculated for each of the aforementioned scenarios. Overall it was difficult to detect strong differences between the different cases. This is not terribly surprising given that the total difference in consumption between the high and low scenario is only 715 MGD, which is distributed over approximately 1200 power plants sited in 1000 counties.
7. Another measure of competition is through the number of counties meeting power plant siting criteria. Siting criteria for this analysis included a water supply/demand ratio >5 , the county had at least 1 power plant in 2004, and no more than 5 new power plants would be constructed in any single county. The analysis showed a marked decline in the number of counties meeting the siting criteria in 2030. When viewed at the NERC region level, this issue is more concerning; specifically, the Florida Reliability Coordinating Council (FRCC) and Texas Regional Entity (TRE) have effectively exhausted all suitable siting counties by 2030. There are also large areas of the country with few or no suitable sites, Southwest, Interior West, Great Plains and the Atlantic Coast. While this does not suggest there is nowhere to place a new plant, it does suggest that new sitings will need to consider successively less attractive construction locations.

Other results are discussed in the section above. Of course, many other scenarios can be simulated and analyzed with this tool—that being its purpose. As such, the model is available from the lead author. No specialized software is necessary to operate the model. A PowerPoint slide user's manual to assist with navigating the user interface is included as an appendix (Appendix C).

5. References

- AWWARf (American Water Works Association research foundation), 2007. Energy Index Development for Benchmarking Water and Wastewater Utilities. AWWARf, Denver, Colorado.
- Brown, T.C., 1999. Past and Future Freshwater Use in the United States: A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment. Gen. Tech. Rep. RMRS-FTR-39, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 47pp.
- BEA (Bureau of Economic Analysis), 2007. Gross Domestic Product by State. U.S. Department of Commerce, <http://www.bea.gov/regional/gsp/> As of December 10, 2007.
- CEC (California Energy Commission), 2005. 2005 Integrated Energy Policy Report: Committee Draft Report. CEC-100-2005-007-CTD.
- Curlee, T.R. and M.J. Sale, 2003. Water and energy security, in proceedings Universities Council on Water Resources. 2003 UCOWR Annual Conference, Water Security in the 21st Century, Washington, D.C.
- E-Gov, 2008. geodata.gov. available at <http://gos2.geodata.gov/wps/portal/gos>, accesses in September 2008.
- EIA (Energy Information Administration), 2003. 1990-2003 Net Generation by State by Type of Producer by Energy Source (EIA-906). Available at <http://www.eia.doe.gov/cneaf/electricity/>. As of September 13, 2008.
- EPA (U.S. Environmental Protection Agency), 2004. Clean Watersheds Need Survey, Available at <http://www.epa.gov/cwns/>. Accessed in June, 2008
- EPA (U.S. Environmental Protection Agency), 2007. Emissions & Generation Resource Integrated Database (eGRID), version 1.0. Available at: 9. <http://www.epa.gov/cleanenergy/energyresources/egrid/index.html>. As of February 20, 2009.
- EPRI (Electric Power Research Institute), 2003. A Survey of Water Use and Sustainability in the United States With a Focus on Power Generation. EPRI Topical Report 1005474, Palo Alto, California.
- EPRI (Electric Power Research Institute), 2005. Framework to Evaluate Water Demands and Availability for Electrical Power Production within Watersheds Across the United States: Development and Applications. EPRI, Palo Alto, California.
- Forrester, J. W., 1990. Principles of Systems. Productivity Press, Portland, Oregon.

GAO (General Accounting Office), 2003. Freshwater supply: States' views on how federal agencies could help them meet challenge of expected shortages. GAO-03-514, Washington, D.C. available at <http://www.gao.gov/new.items/d03514.pdf>.

Guldin, R.W., 1989. An Analysis of the Water Situation in the United States: 1989-2040. Gen. Tech. Rep. RMRS-FTR-177, U.S. Department of Agriculture, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, 178 pp..

National Research Council, 2004. Confronting the Nation's Water Problems: The Role of Research. Committee on Assessment of Water Resources Research, National Academies Press.

NDMC (National Drought Mitigation Center), 2008. Understanding Your Risk and Impacts. available at <http://www.drought.unl.edu/risk/us/compare.htm#costs>, accessed September 2009.

NextGen Energy Council, 2008. Lights Out In 2009? Available on the web at www.nextgenenergy.org, accessed in September 2009.

Platts, 2006. North American Electric Reliability Council (NERC) Regions geospatial data layer. Available at <http://www.gisdata.platts.com/>.

Roy, S.B., Ricci, P.F., Summers, K.V., Chung, C.-F., and Goldstein, R.A., 2005. Evaluation of the sustainability of water withdrawals in the United States, 1995 to 2025, Journal of the American Water Resources Association, 1091-1108.

Reeley, T.J., T.J. Skone, G.J. Stiegel, A McNemar, M. Nemeth, B. Schimmoller, J.T. Murphy, L. Manfredo, 2007. Water: A critical resource in the thermoelectric power industry. Energy, doi: 10.1016/j.energy.2007.08.007.

Reno Gazette-Journal and Associated Press, 2006. Sempra energy halts Gerlach project study. Published March 8, 2006.

Reuters News Service, 2006. Idaho committee adopts moratorium on coal power. Published March 14, 2006.

Silk, J.I. and F. L. Joutz, 1997. Short and long-run elasticities in US residential electricity demand: a co-integration approach. Energy Economics 19, pp. 493-513.

Sovacool, B.K., 2009. Nexus and the U.S. electric utility sector, Energy Law Journal, 30(11), 11-51.

Sovacool, B.K. and K.E. Sovacool, 2009a. Preventing National Electricity-Water Crisis Areas in the United States, Columbia Journal of Environmental Law. 34(2), 333-393.

Sovacool, B.K. and K.E. Sovacool, 2009b. Identifying future electricity-water tradeoffs in the United States, Energy Policy. 37, 2763-2773.

Simonovic, S. P. and H. Fahmy, 1999. A new modeling approach for water resources policy analysis. *Water Resources Research* 35(1):295-304.

Sterman, J. D., 2000. *Business Dynamics, Systems Thinking and Modeling for a Complex World*. McGraw-Hill, Boston. 982 pp.

Stewart, D.W., A. Rea and D.M Wolock, 2006. USGS Streamgages Linked to the Medium Resolution NHD Geospatial Data Presentation Form: Vector Digital Data. US Geological Survey DS-195, data available at:
<http://water.usgs.gov/GIS/metadata/usgswrd/XML/streamgages.xml#stdorder>, accessed April 2007.

Tucson Citizen, 2002. Tucson, AZ, published January 31, 2002.

U.S. Census Bureau, 2004. Statistical Abstract of the United States: 2004-2005. Available at <http://www.census.gov/prod/2004pubs/o4statab/pop.pdf>. Accessed in August, 2008.

U.S.G.S. (U.S. Geological Survey), 1985, 1990, 1995. *Water Use in the United States*, Available at <http://water.usgs.gov/watuse/> Accessed in November, 2008.

U.S. Water News Online, 2002. Idaho denies water rights request for power plants. Published August 2002.

U.S. Water News Online, 2003. South Dakota governor calls for Missouri River meeting. Published August, 2003.

Webber, M.E., 2008. Catch-22: Water vs. energy. *Scientific American Earth* 3.0, 18(4)34-41.

Appendix A: Analysis of Current Power Plant Water Use

The purpose of this analysis is to rectify statistics for thermoelectric power plant water use as prepared by the Energy Information Administration (EIA) the Emissions and Generation Resource Integrated Database (eGRID) and the U.S. Geological Survey. The data of most interest was power production (from eGRID) and water use for cooling purposes (from EIA). The power plant water use data was directly compared to estimated thermoelectric water use data from the United States Geological Survey (USGS). Water use can be broken down into a number of different categories. The two main categories of interest in this work are thermoelectric water withdrawals and consumption.

On a lesser note, this work will try to analyze how water use has changed with respect to energy production from 2000 (the last year for which water use data is available from the USGS) to 2004. It is inferred that water use will increase as energy generation increases. Changes in capacity factors of power plants will be used to model the change in energy production because name plate capacities do not change often.

2004 Power Plant Data

EIA/eGRID data

Analysis was initiated with the dataset consisting of 2004 thermoelectric power plant data for the United States from eGRID and the EIA. After examination, the dataset was found to include:

- A total of 2867 thermoelectric power plants. The dataset includes coal, gas, oil, and nuclear power plants. (There was many more power plants but this analysis only concentrated on fossil fuels and nuclear power)
- 645 coal fired plants with a range of name plate capacities from 1.0 to 3969.0 megawatts (MW).
- 1416 gas fired plants with a range of name plate capacities from 1.0 to 2876.4 MW.
- 746 oil fired plants with a range of name plate capacities from 0.7 to 4175.1 MW.
- 60 nuclear power plants with a range of name plate capacities from 502.0 to 5209.3 MW.
- 294 out of the 2867 plants have reported water use and details about the cooling system.
- 144 out of the 644 coal fired plants have a reported boiler criticality.

At the national level the EIA reported water withdrawals are ~40.8 billion gallons per day (BGD) and consumption is ~1.6 BGD. To analyze the accuracy of the water use plant data, the data needed to be compared to USGS thermoelectric water use estimates for 1995 and 2000.

1995 and 2000 USGS data

The USGS tracks water use for fossil fuel plants, nuclear plants, and geothermal plants. For 1995, the USGS total water withdrawals are ~187.2 BGD with a water consumption of ~3.7 BGD. As for 2000, the USGS reported total water withdrawals of ~192.9 BGD. A few issues with the USGS data had to be rectified before it could be used in the analysis. The following are these issues and how they affected the analysis:

- The 2000 USGS water use estimates do not include consumptive water use for any category. A ratio was calculated between water withdrawals and consumption from the 1995 USGS data. This ratio was used to infer water consumption for 2000 USGS data. The estimated total water consumption for 2000 is ~8.4 BGD.
- Manassas City and Manassas Park City are two counties in Virginia that had to be grouped into one.

- Yellowstone and Yellowstone Nat'l Park are two counties in Montana that had to be grouped into one.
- Dale County in Florida was reported in 1995 and not in 2000.
- The two datasets had different methods of reporting the identity of counties. This made it cumbersome to bring the two datasets together because the 2000 data used full FIPS numbers and the 1995 data used county names.

EIA/eGRID Aggregates

The plant level cooling water use and power production data was aggregated to the county level using the full FIPS numbers from the eGRID data. The aggregates were done in order to compare the plant water use data to USGS thermoelectric water use data that is at the county level. Power plants built after 1995 were not included in the direct comparison with the 1995 USGS data and no power plants built after 2000 were included in the direct comparison with the 2000 USGS data. The aggregate data had:

- 1339 out of 3141 counties have a power plant within their limits. Of these 1339 counties, only 262 have a reported EIA water use of greater than zero.
- The 1995 USGS thermoelectric data has 637 counties with a reported water withdrawal of greater than zero.
- The 2000 USGS thermoelectric data has 644 counties with a reported water withdrawal of greater than zero.

When comparing the data sets, it was very clear that the water use values from the EIA and USGS were very different. When an aggregate to the national level is done, the data exhibits rather large differences between the USGS and EIA water use values. For 1995, reported EIA withdrawals are ~79% short with consumption ~58% short of the USGS values. The difference between total withdrawals is ~146.4 BGD with a consumption difference of ~2.1 BGD for 1995. As for 2000, reported EIA withdrawals are ~79% short with consumption ~82% short of USGS values. The difference between withdrawals was ~152.1 BGD with a consumption difference of ~6.9 BGD. The large difference in values is largely due to the sheer lack of reported water use for individual power plants. It was concluded that water use estimates for each power plant were needed in order to properly model water use.

NETL Estimates

Reported power generation for individual power plants was a far more reliable field than reported water use. A study by Feeley et al. (2007) assigned water use factors to power plants that modeled water use according to power generation. The amount of water a power plant uses depends on the technology used for power generation and cooling purposes. A hierarchical approach was used by Feeley et al. (2007) that assigned plant profiles according to generation type, cooling water type, cooling water system type, boiler type (for coal only), and flue gas desulfurization (FGD) type (for coal only). Using this approach averages of water withdrawal and consumption factors were calculated that can be assigned to individual power plants. The Feeley et al. (2007) study examined six different fuel types (coal, nuclear, oil, gas, NGCC, and IGCC), but limited its analysis to fresh water.

The decision was made to assign a withdrawal and consumption factor to every power plant in the dataset. A slightly modified version of the Feeley et al. (2007) approach was used in assigning power plants with their respective water use factors. In this analysis only four fuel types (coal, gas, oil, nuclear) were examined. The FGD type of each plant was ignored and an average between FGD profiles was used for the water use factors. The hierarchical approach (Table A1) in this analysis assigned plant profiles according to primary fuel, primary cooling system design, cooling system specifications, and boiler type (for coal only). Also, this analysis included fresh and saline water, but the water type did not affect the

respective plant profiles. Several assumptions were made in the assignment of water use factors and they are listed below:

- Numerous power plants had a primary fuel type of “Gas S”, these power plants were assumed to be “Gas” plants.
- 2573 power plants did not have a reported primary cooling system design. To correct for this, plants that did not report a primary cooling system design were assigned one. It is assumed that all power plants built after 1980 have a recirculating primary cooling system design. With this in mind, power plants built after 1980 are categorized as recirculating and those built before are categorized as once-through.
- 2635 power plants did not report cooling system specifications. When this was the case an average of water use factors between profiles was used.
- The dataset has three different types of cooling towers. The different cooling towers were aggregated into one cooling tower category.
- Several power plants report a primary cooling system of once-through with cooling ponds. Feeley et al. (2007) does not have water use factors for this type of cooling system. This type of power plant was assigned the water use factors of a once-through power plant.
- 501 coal fired plants did not have a reported boiler criticality. Reports by the NETL (2008) states that most supercritical coal fired plants have a name plate capacity greater than 500 MW. If a coal fired plant did not have a reported criticality, it was categorized as supercritical if it had a name plate capacity greater than 500 MW and all others were categorized as subcritical.
- All power plants with a capacity factor less than zero were assumed to be zero.

Comparison of Estimated Values and EIA Values

Assigned water use factors and power production from each plant were used to estimate plant water use for the 2004 dataset. The estimates were calculated by multiplying the water use factors with power generation for a specified amount of time (one day, to match USGS units). These estimates produced a more robust dataset with water use values for every power plant in the 2004 dataset. At the national level the estimated water withdrawals were ~135.4 BGD and a consumption of ~2.5 BGD. When compared to the EIA reported values, estimated withdrawals are ~70% greater and estimated consumption is ~38% greater. There is a difference in withdrawals of ~94.6 BGD and a difference in consumption of ~1.0 BGD.

Comparison of Estimated Values and USGS Values

An aggregate to the county level was done to the water use estimates in order to compare them with the USGS data. As before, plants built after 1995 were not included in the 1995 comparison and plants built after 2000 were not included in the 2000 comparison. The estimates display rather large differences when compared to the USGS data. At the national level, the 1995 withdrawals are ~31% less than the USGS values with consumption ~36% short. There is a difference in withdrawals of ~60.5 BGD and a difference in consumption of ~1.3 BGD. The national 2000 withdrawals are ~31% short and consumption is ~71% short of the 2000 USGS values. There is a withdrawal difference of ~64.2 BGD and a difference in consumption of ~5.9 BGD.

Evaluation of Water Use Factors

A new approach was needed because the reported and estimated water use values were much lower than the USGS water use values. The Feeley et al. (2007) water use factors were based on a very coarse analysis. It was decided to attempt to formulate our own water use factors. Before this could be done, data had to be plotted and analyzed.

Table A1: Profiles for Water Use Factors

Primary Fuel	Primary Cooling System Design	Cooling System Specifications	Boiler Type	Withdrawal Factor (gal/kWh)	Consumption Factor (gal/kWh)
Coal	Once-through	Local water body	Subcritical	27.082	0.107
Coal	Once-through	Local water body	Super-critical	22.584	0.097
Coal	Once-through	Cooling pond	Subcritical	27.082	0.107
Coal	Once-through	Cooling pond	Super-critical	22.584	0.097
Coal	Once-through	NA	Subcritical	24.786	0.274
Coal	Once-through	NA	Super-critical	19.945	0.082
Coal	Recirculating	Cooling tower	Subcritical	0.500	0.431
Coal	Recirculating	Cooling tower	Super-critical	0.642	0.491
Coal	Recirculating	Cooling pond	Subcritical	17.896	0.773
Coal	Recirculating	Cooling pond	Super-critical	15.029	0.037
Coal	Recirculating	NA	Subcritical	9.198	0.602
Coal	Recirculating	NA	Super-critical	7.836	0.264
Gas	Once-through	Local water body	NA	22.740	0.090
Gas	Once-through	Cooling pond	NA	22.740	0.090
Gas	Recirculating	Cooling tower	NA	0.250	0.160
Gas	Recirculating	Cooling pond	NA	7.890	0.110
Gas	Recirculating	NA	NA	4.070	0.135
Nuclear	Once-through	Local water body	NA	31.497	0.137
Nuclear	Once-through	Cooling pond	NA	31.497	0.137
Nuclear	Recirculating	Cooling tower	NA	1.101	0.624
Oil	Once-through	Local water body	NA	22.740	0.090
Oil	Once-through	Cooling pond	NA	22.740	0.090
Oil	Recirculating	Cooling tower	NA	0.250	0.160
Oil	Recirculating	Cooling pond	NA	7.890	0.110
Oil	Recirculating	NA	NA	4.070	0.135

Note: Values and profiling scheme are mostly from averages of Table 2 of Feeley et al. (2007), “Water: A critical resource in the thermoelectric power industry.”

The data was plotted in an x-y scatter scheme. The x-axis consisted of plant power production and the y-axis consisted of reported water withdrawals. The different power plants were grouped using the hierarchal approach that was used in assigning water use factors. Once again, the lack of data posed many problems. For the most part, the plotting of data was limited to coal fired power plants. This was because all other fuels had very few or no reported water withdrawals (oil: 2, gas: 1, nuclear: 0). Plots of the power plants showed no linear relationship. The plots exhibited large amounts of variability and they contained many outliers. It was even attempted to add a regional aspect to the hierarchal approach. Data

was grouped like before with respective NERC regions as one of the criteria, but the data still displayed no trend.

It was decided to not attempt to formulate new water use factors and to continue using the Feeley et al. (2007) factors. The data and analysis steps were checked to ensure that the large differences between data were not a mistake. It was also attempted to only analyze fresh water in the analysis. This could not be done because the source of cooling water for most power plants could not be determined.

2000 Power Plant Data

EIA/eGRID data

The decision was made to build a new power plant database with values from 2000. A database for 1995 could not be made because the data for that year is incomplete. The data for 2000 came from the same sources as the previous dataset (eGRID and the EIA).

The power generation and plant location data is from the eGRID online database. This data needed some processing before it could be used. Below are the processing steps:

- 16 power plants did not report a capacity factor. Power generation could not be calculated for these plants. Power generations from 2004 EIA data and capacity factors for 2004 were used to estimate power production for the respective plants.
- Power plants with a capacity factor less than zero were assumed to be zero.
- The data lacked full FIPS numbers for the county that each power plant fell within. Power plants were assigned full FIPS numbers using the 2004 dataset and by using the state and county FIPS codes.
- The dates of when each plant came online were not listed at the plant level. Power plants were assigned a start date using the 2004 dataset and eGRID generator data. The generator data listed the generators in each power plant and their respective start date. Generators have come online at different points throughout a power plant's history and the earliest date was assigned to each power plant.

The cooling system and water use data is from the EIA-767 online database. The data needed some processing before it could be used. Below is the processing that was needed:

- The data was listed at the generator and boiler level. Aggregates had to be done on all data in order to have it at the plant level. With this in mind, several plants reported having several different types of cooling systems. The "primary" cooling system type was assigned to each power plant.
- This dataset contains information on a much smaller number of power plants than the eGRID dataset.

Bringing both datasets together into one was quite cumbersome. The ORISPL number provided by both data sets was used to combine them. A problem with this method of combining the data is that there are 46 power plants from the EIA that eGRID did not include in their dataset. These power plants had only an ORISPL number with no information about their location. Most of the full FIPS numbers were found in the 2004 dataset, but a number were found through research on the Internet.

Once the dataset was compiled, the same analysis could be done on the 2000 power plant data as was done on the 2004 dataset. The dataset has a smaller number of power plants, but it also has plants that the 2004 dataset does not have. An examination of the dataset revealed:

- A total of 2535 power plants. Only 660 of these plants have a reported water use and details about the cooling system.

- 623 coal fired plants are included in the dataset. The name plate capacities range from 0.0 to 3969.1 MW.
- 1229 gas fired plants are included in the dataset. The name plate capacities range from 0.6 to 2650.3 MW.
- 620 oil fired plants are included in the dataset. The name plate capacities range from 0.105 to 2950.6 MW.
- 61 nuclear plants are included in the dataset. The name plate capacities range from 105 to 4209.57 MW.
- A boiler criticality for the coal fired plants could not be found for any of the power plants.

Comparison between EIA and USGS data

At the national level the reported water withdrawals were ~212.4 BGD with a consumption of ~6.3 BGD. After the data was aggregated to the county level it could be directly compared to the 2000 USGS data. The values between the data still displayed differences, but the withdrawal and consumption values are much closer than they were before. Many of the reported water withdrawals fall very close to the 2000 USGS value. When all data is aggregated to the national level, EIA withdrawals are ~9% greater than USGS withdrawals and EIA consumption is ~25% less than USGS consumption. There is a difference between EIA and USGS withdrawals of ~19.4 BGD with a consumption difference of ~2.1 BGD. It is of interest that the EIA reported water withdrawals are greater than the USGS water withdrawals. This new dataset has more reliable numbers but it still is missing water use for most power plants in the eGRID data.

Water Use Estimates

In order to have water use values for every power plant, water use estimates were assigned to all power plants in the 2000 dataset. The Feeley et al. (2007) water use factors and the approach from before were used again. The following assumptions were made:

- 51 of the nuclear power plants did not have a specified primary fuel. The primary fuel of these plants was inferred using the 2004 dataset.
- Only 658 power plants had a reported primary cooling system design. Primary cooling system designs were assigned to all other power plants using the Tidwell (2008) assumption. All power plants built after 1980 are inferred to be recirculating and all others are inferred to be once-through.
- The coal fired plants did not have a reported boiler criticality. Criticality was assigned using the 2004 dataset and with the NETL (2008) assumption. When the NETL (2008) assumption is used, all plants with name plate capacity greater than 500 MW were inferred to be supercritical and all others were inferred to be subcritical.
- Three different kinds of cooling towers are included in the dataset. These different cooling towers types are aggregated into one cooling tower category.
- Power plants that did not have a reported cooling system specifications were assigned averages of water use factors between profiles.
- All power plants with a capacity factor less than zero were assumed to be zero.

Comparison between Estimated Values and EIA Values

The water use estimates were calculated by multiplying the water use factor by the energy generated over a day. These estimates assigned a water use value to all reported power plants in the dataset. Estimates for individual power plants are generally smaller than the reported value. When the estimated values are aggregated to the national level there is a total withdrawal of ~118.3 BGD with a total consumption of ~2.4 BGD. At the national level, estimated withdrawals are ~44% short and estimated consumption is

~62% short of the EIA values. The difference between the EIA reported and estimated withdrawals is ~104.8 BGD with a difference in consumption of ~4.1 BGD.

Comparison between Estimated Values and USGS Values

The 2000 estimated power plant water use values were then aggregated to the county level for comparison with the 2000 USGS data. All power plants were included in the direct comparison. At the national level, estimated withdrawals are ~39% short and estimated consumption is ~71% short of the USGS values. There is a withdrawal difference of ~74.6 BGD and a consumption difference of ~6.0 BGD.

Summary of Water Use Data

Most of the problems that arose in the analysis were largely due to the lack of reliable data. There is little data about the technology that individual power plants use for 2000 through 2004. Estimates and assumptions have to be used in order to have water use values for each power plant.

The Feeley et al. (2007) water use factors seem to significantly underestimate the amount of water a power plant needs according to the amount of power it generated. This is because the total withdrawals and consumption at the national level are significantly less than the reported withdrawals for the 2000 data. The reported EIA values only account for 660 of the 2535 reported power plants. The estimated values are larger than the reported values at the national level in the 2004 dataset, but this is because only 294 power plants reported water use for that year. As for the USGS data, it is considered the most reliable water use data in the United States. This brings to question the reliability of the USGS data because reported EIA water withdrawals for 2000 are greater with only 660 plants reporting withdrawals.

References

DOE/NETL-400/2008/1339, Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements; 2007 Update, pg C-1 to C-2.

Feeley TJ III, et al., Water: a critical resource in the thermoelectric power industry. Energy (2007), doi:10.1016/j.energy.2007.08.007.

Appendix B: Optimization

Integration of optimization tools into the energy-water model was complicated by the fact that Powersim's Studio Expert 2007 does not provide native support for optimization extensions. However, Studio Expert can execute Visual Basic functions, which can execute functions that are exposed by a COM object. The Component Object Model (COM) is an interface standard for software components that is used to enable inter-process communication and dynamic object creation between different programming languages. COM provides a language-neutral way of implementing objects that can be used in environments different from the one they were created in, even across machine boundaries.

We developed a COM interface for an optimization toolkit, Coopr. Coopr is a Python package developed at Sandia National Laboratories that provides generic optimization interfaces and Pythonic optimization modeling tools (see <https://software.sandia.gov/svn/public/coopr>). The COM interface was used to setup two different optimizers that can solve a power plant siting problem.

The power plant siting problem used in the energy-water model selects counties for placing power plants. The objective of this problem is to minimize the population affected by these plants, so counties with low population densities are preferred. Power plants siting is constrained by water resources. For each county, water availability and current water demands are used to determine if siting a power plant is feasible, given the water demands for that new plant.

Two different optimizers are supported by this COM interface. These optimizers determine the siting for a list of power plant types that need to be constructed in each year. An integer programming optimizer uses an algebraic model of this siting problem to guarantee the best possible locations for all power plants simultaneously, where best refers to the minimum exposure to human populations. The integer programming model is formulated with Coopr's Pyomo modeling tool (Hart, 2009), and optimization is performed using an external mixed-integer programming optimizer. For example, Sandia's PICO solver has been used, but other commercial and publicly available solvers can also be used.

A heuristic optimizer is also supported by this COM interface. This optimizer does not require an explicit model. Instead, it iteratively performs a greedy assignment of plants to sites. This optimizer is written in Python, and it does not depend on external solvers.

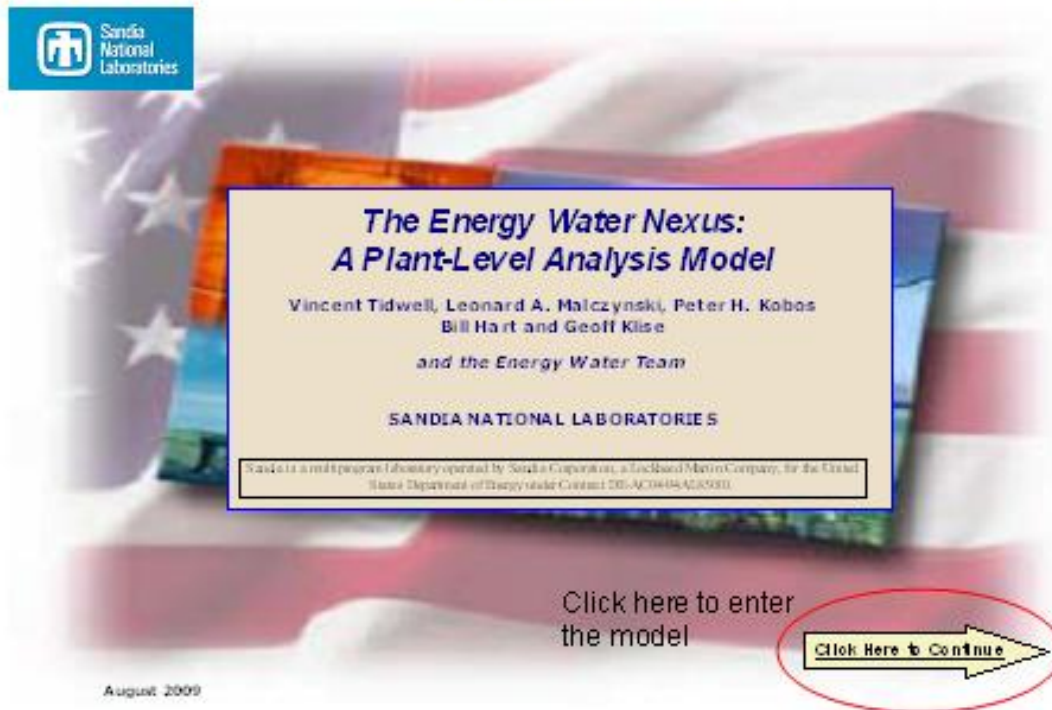
Note that in some cases it may not be possible to site all power plants given water resource availability and current demands. In these cases, the optimizers will indicate that no feasible site has been identified for a plant.

References

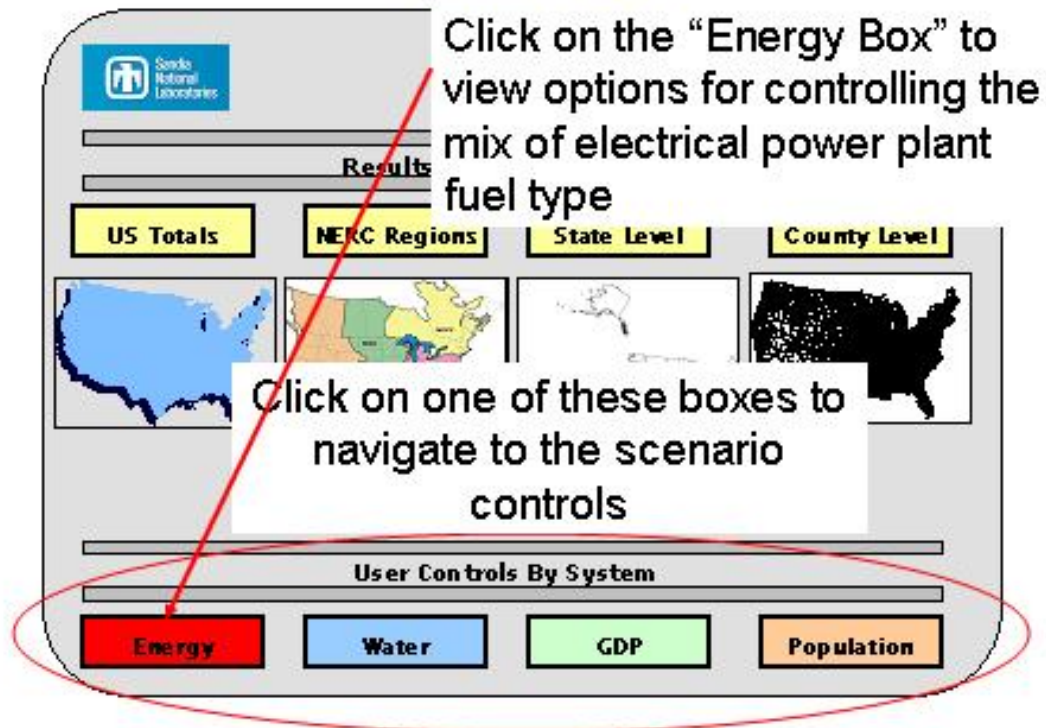
Hart, W. E., 2009. Python Optimization Modeling Objects (Pyomo), in Operations Research and Cyber-Infrastructure. Eds. J. W. Chinneck, B. Kristjansson and M. J. Salzman. pp. 3-19. Springer.

Appendix C: Model Interface Users Guide

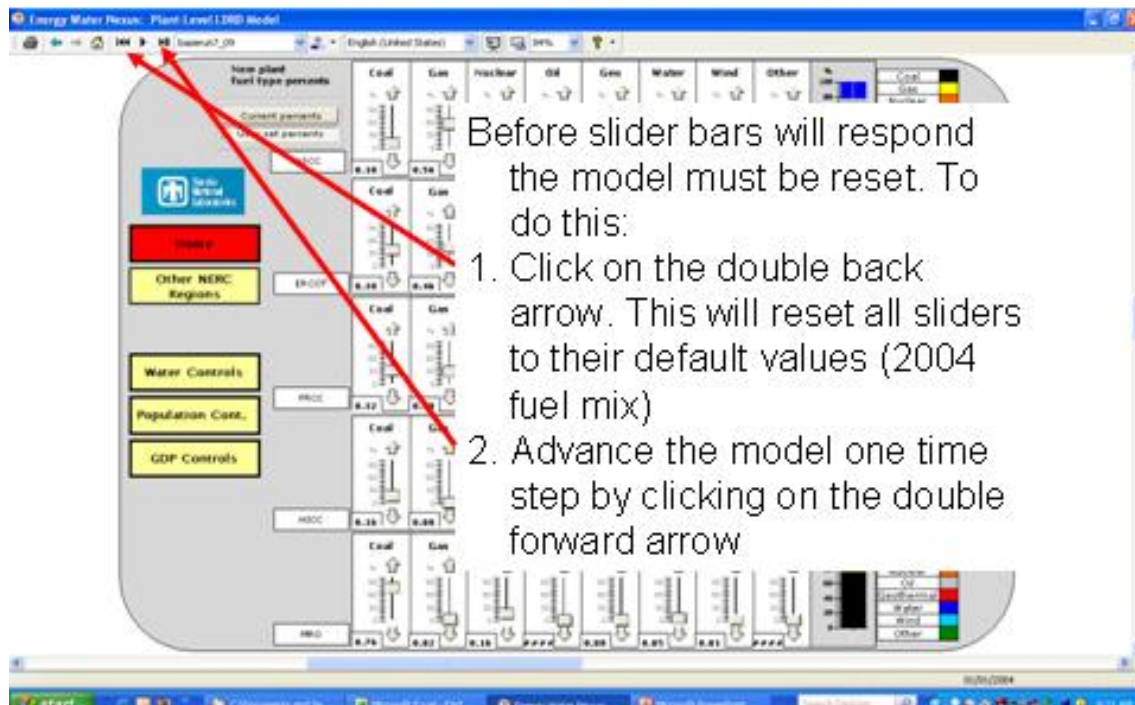
Splash Page



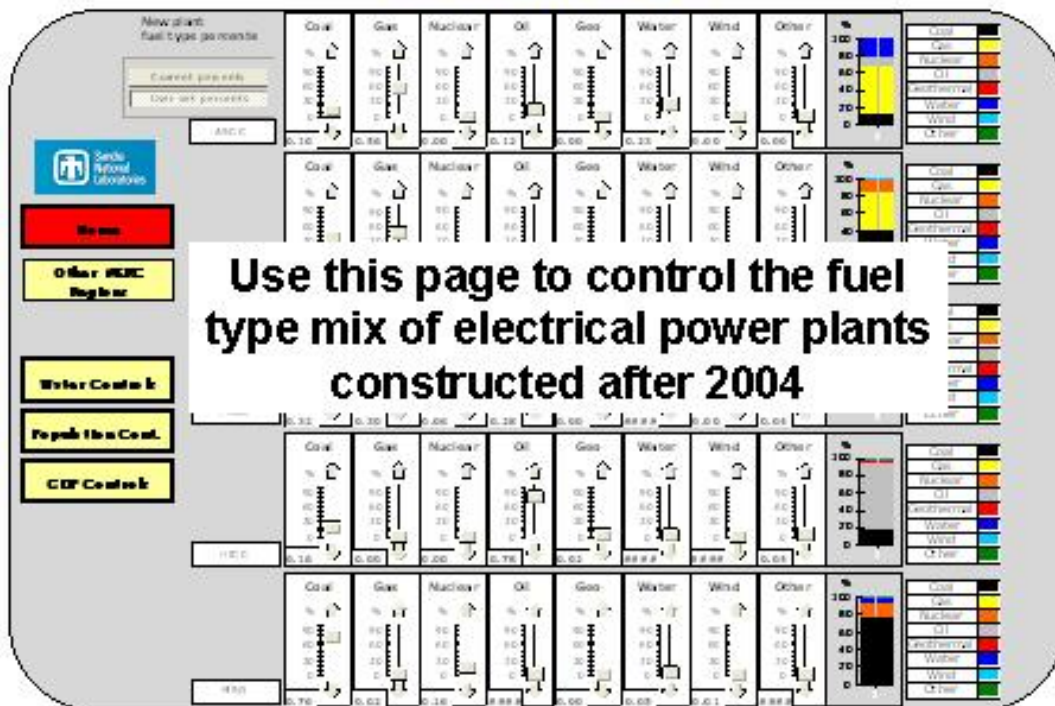
Home Page



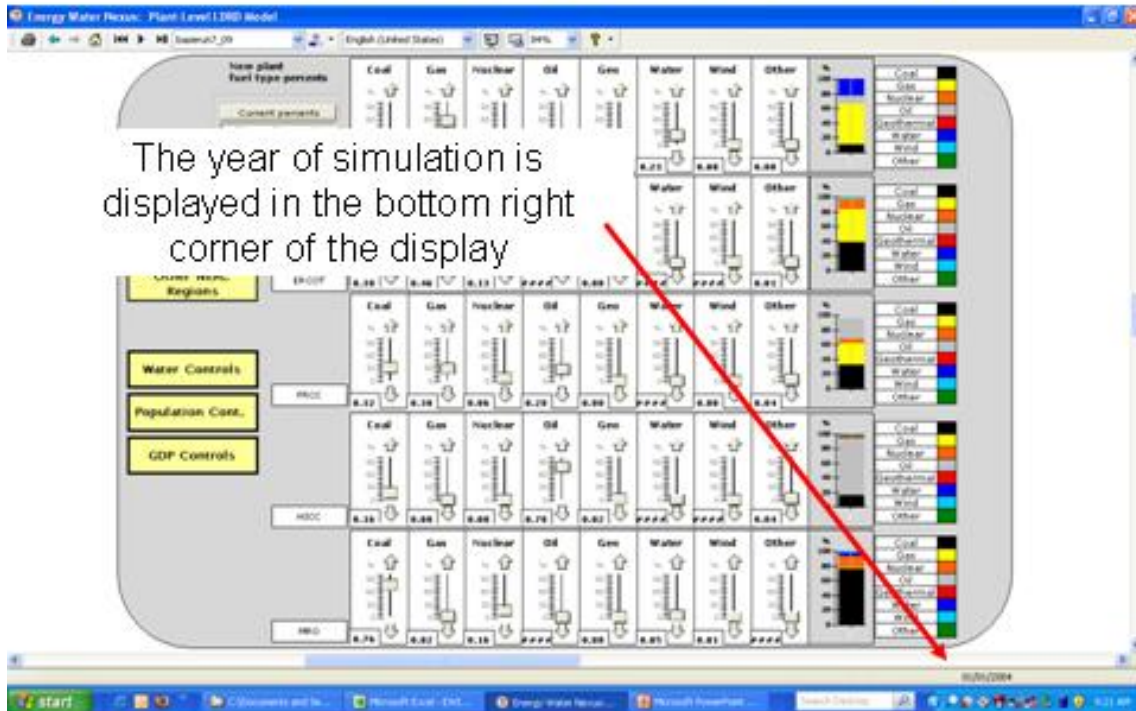
Control Page Operation



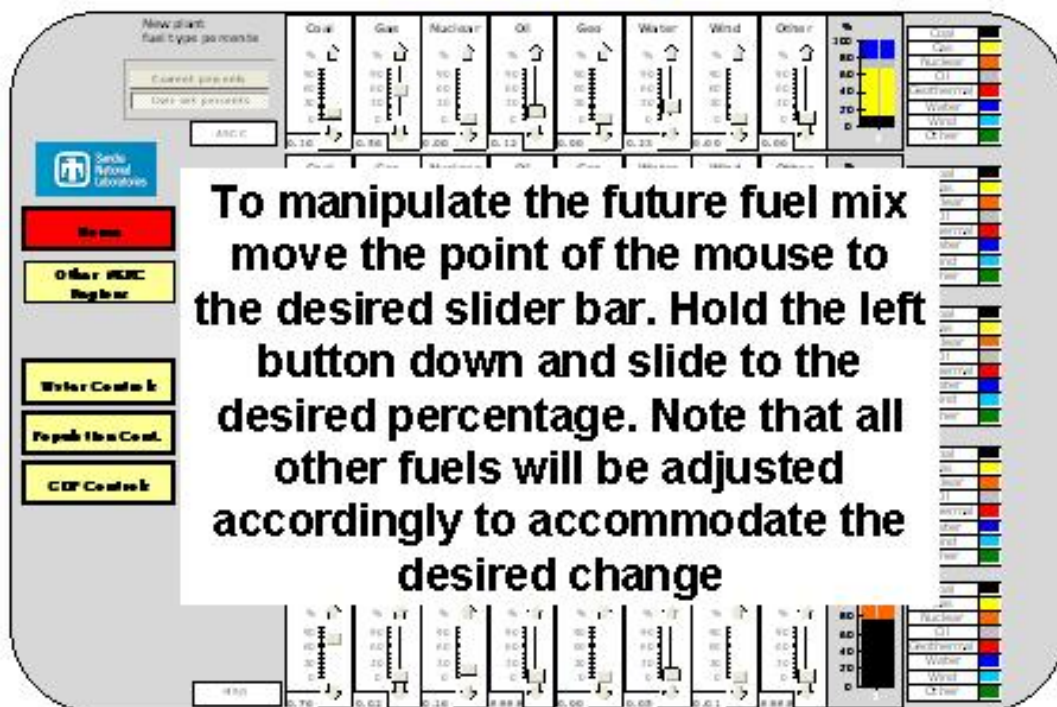
Energy Page



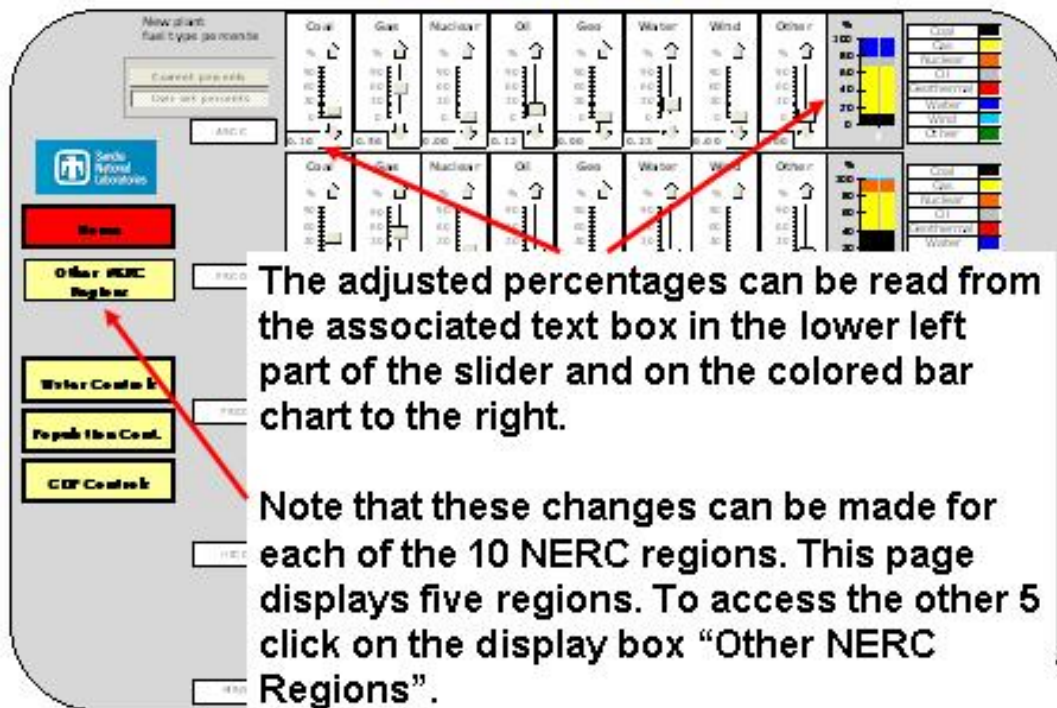
Observing Year of Simulation



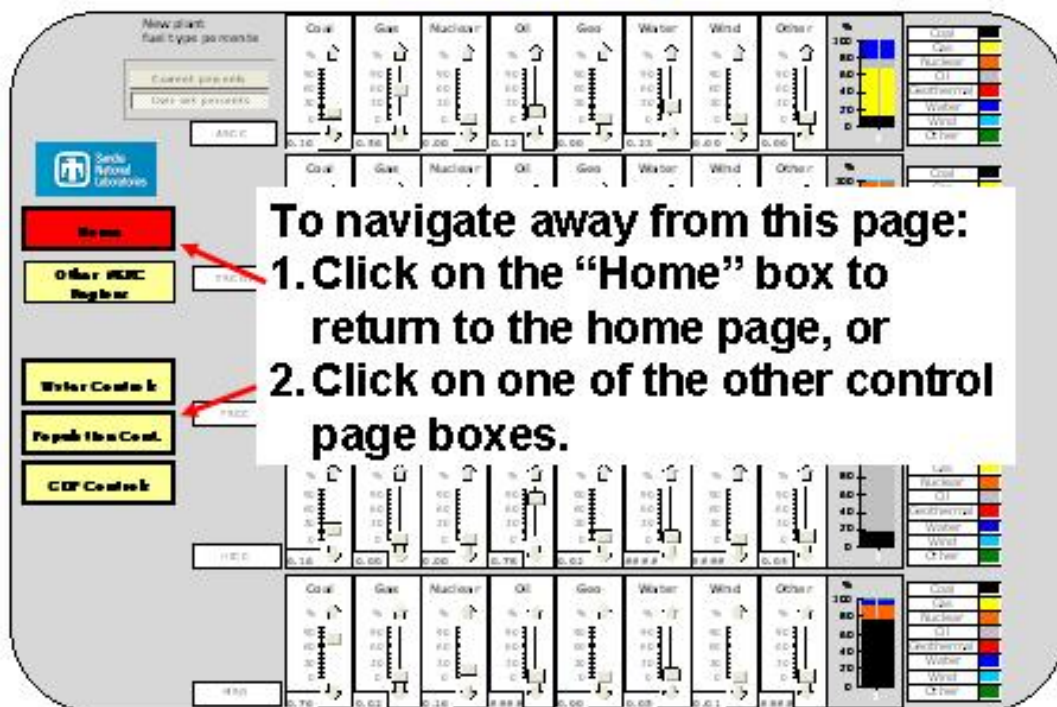
Energy Page



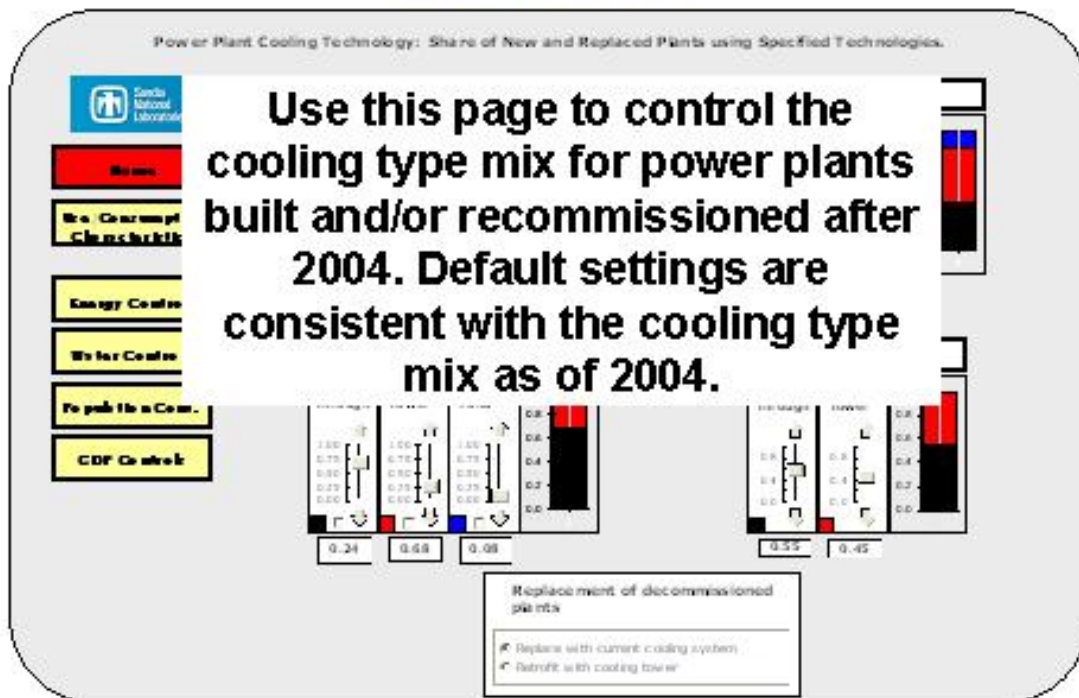
Energy Page



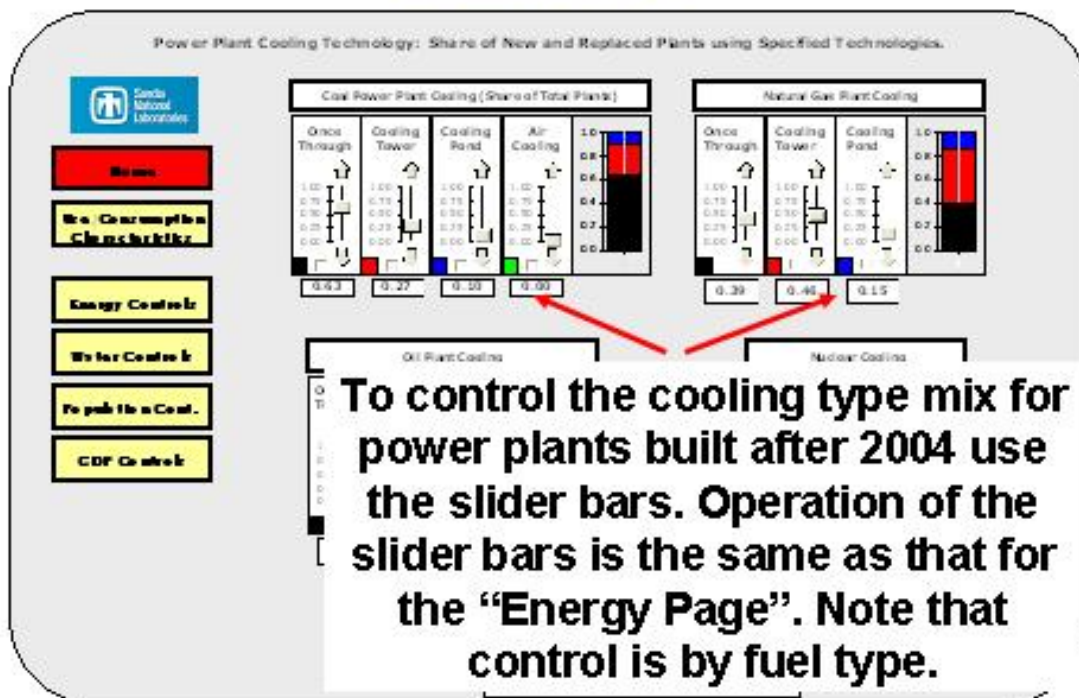
Energy Page



Water Page



Water Page



Water Page

To control the cooling type for power plants decommissioned and recommissioned after 2004 click the radio button below. When clicked all recommissioned power plants will be equipped with recirculating cooling towers. Default assumes recommissioned plants retain prior cooling system.

Replacement of decommissioned plants

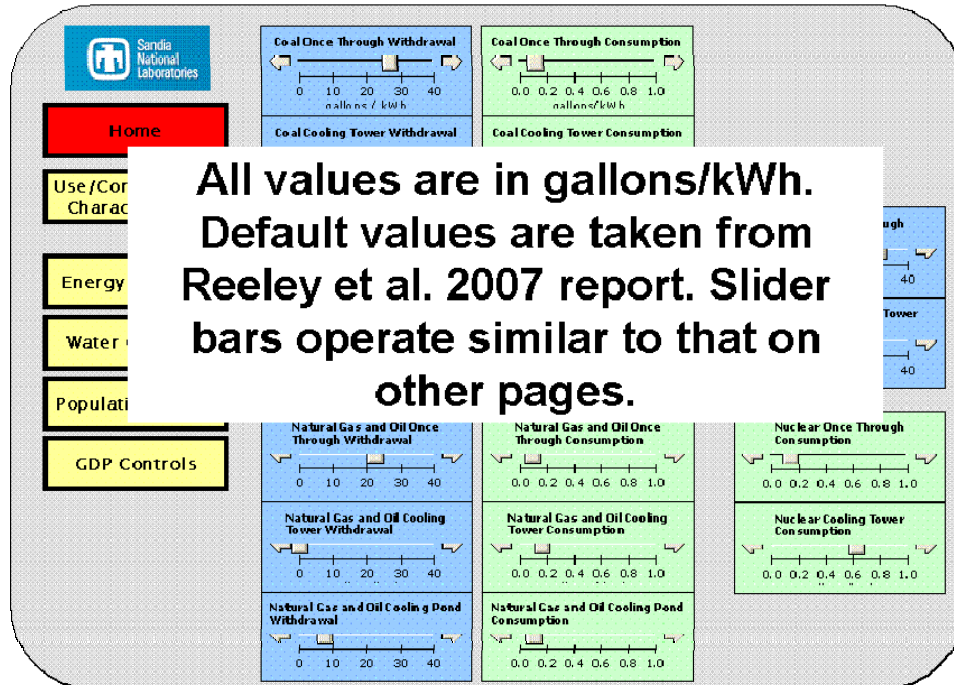
- ☒ Replace with current cooling system
- ☐ Retrofit with cooling tower

Water Page

Control of the use and consumption levels for the various cooling types (by fuel type) can be manipulated by clicking on the “Use/Consumption Characteristics” box.

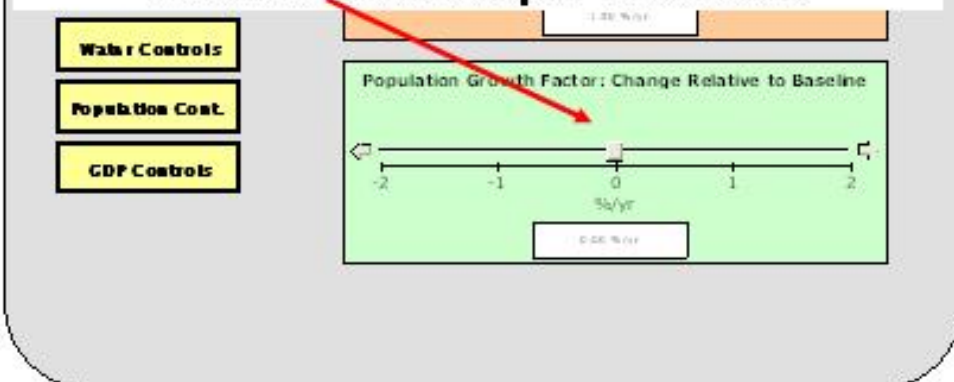
Control of the use and consumption levels for the various cooling types (by fuel type) can be manipulated by clicking on the “Use/Consumption Characteristics” box.

Water Use/Consumption Page

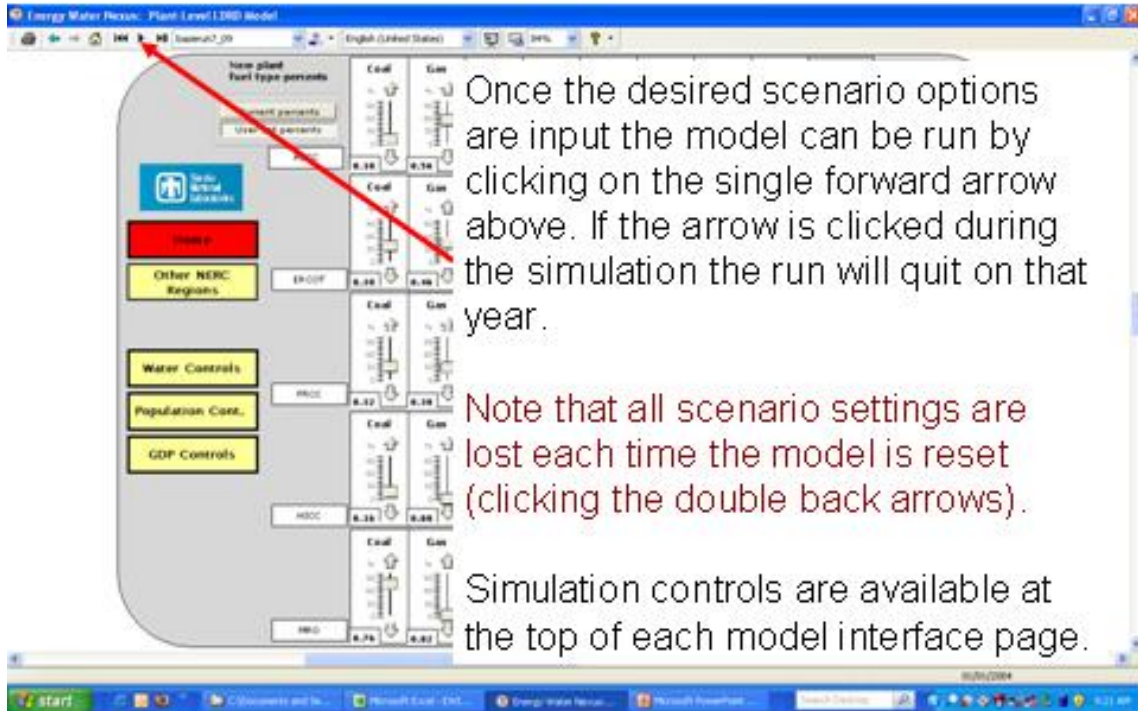


Population/Gross State Product Page

Control population growth rate relative to the 1990-2000 rate. Changes made here are in addition to the default growth rates used by the model. Population growth influences municipal water use.



Running the Model

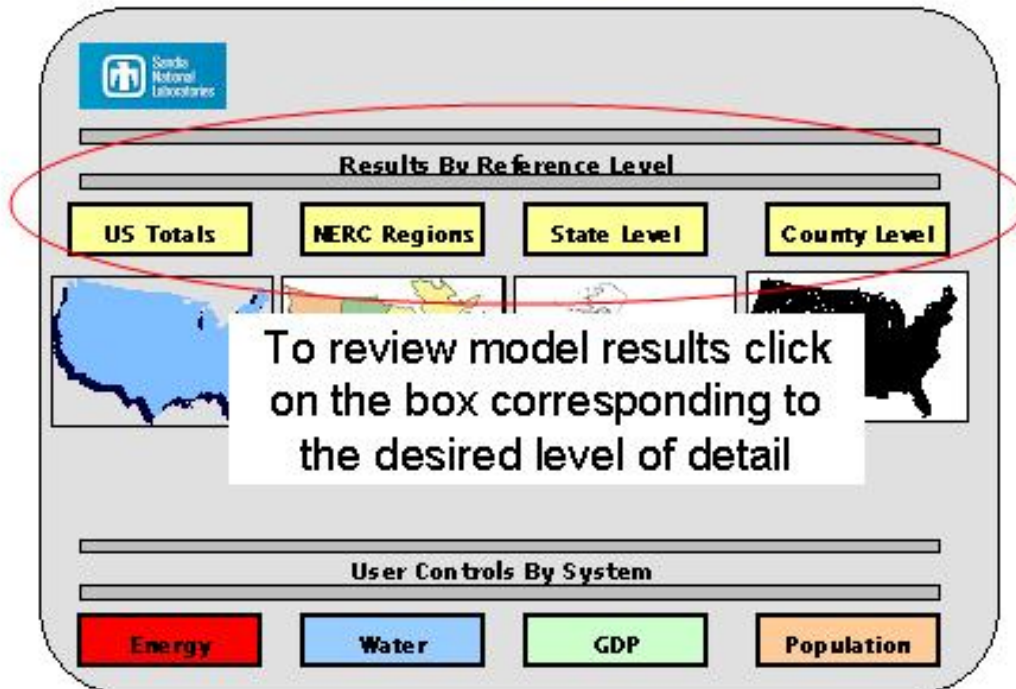


Once the desired scenario options are input the model can be run by clicking on the single forward arrow above. If the arrow is clicked during the simulation the run will quit on that year.

Note that all scenario settings are lost each time the model is reset (clicking the double back arrows).

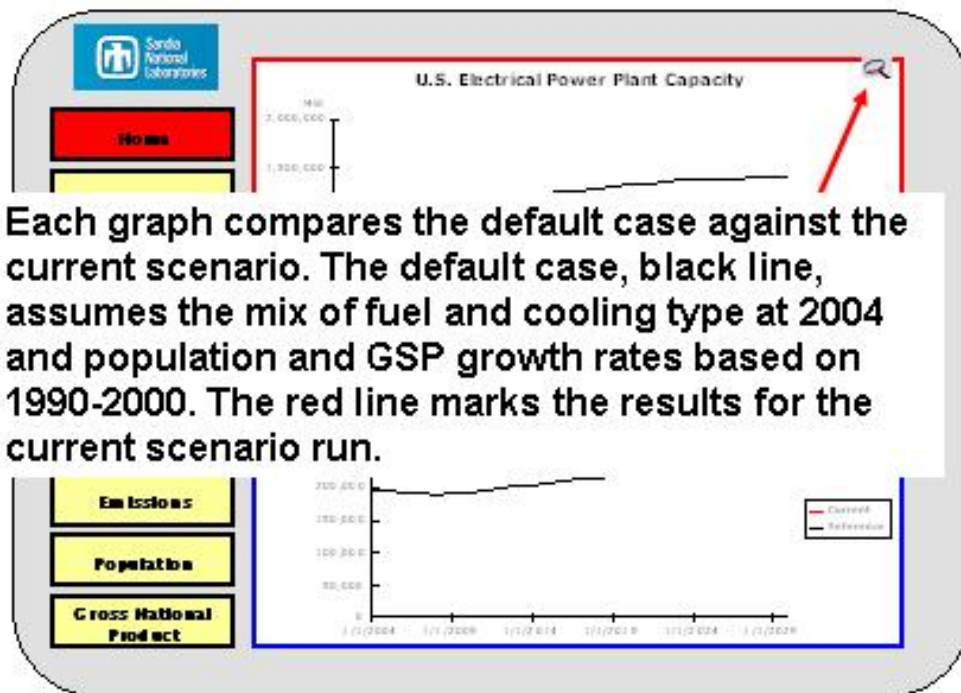
Simulation controls are available at the top of each model interface page.

Home Page

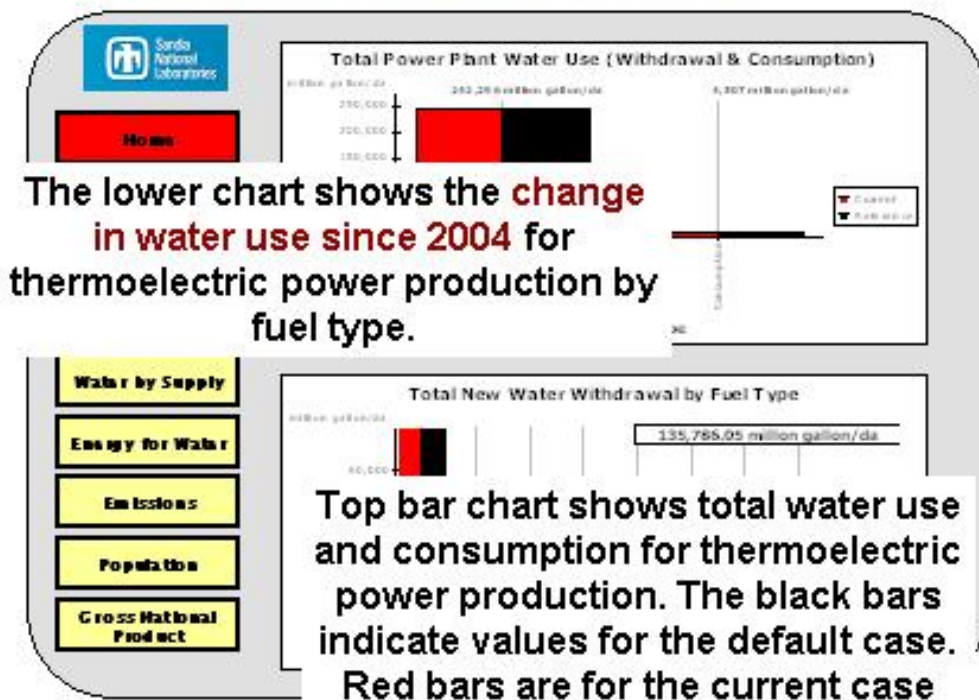


To review model results click on the box corresponding to the desired level of detail

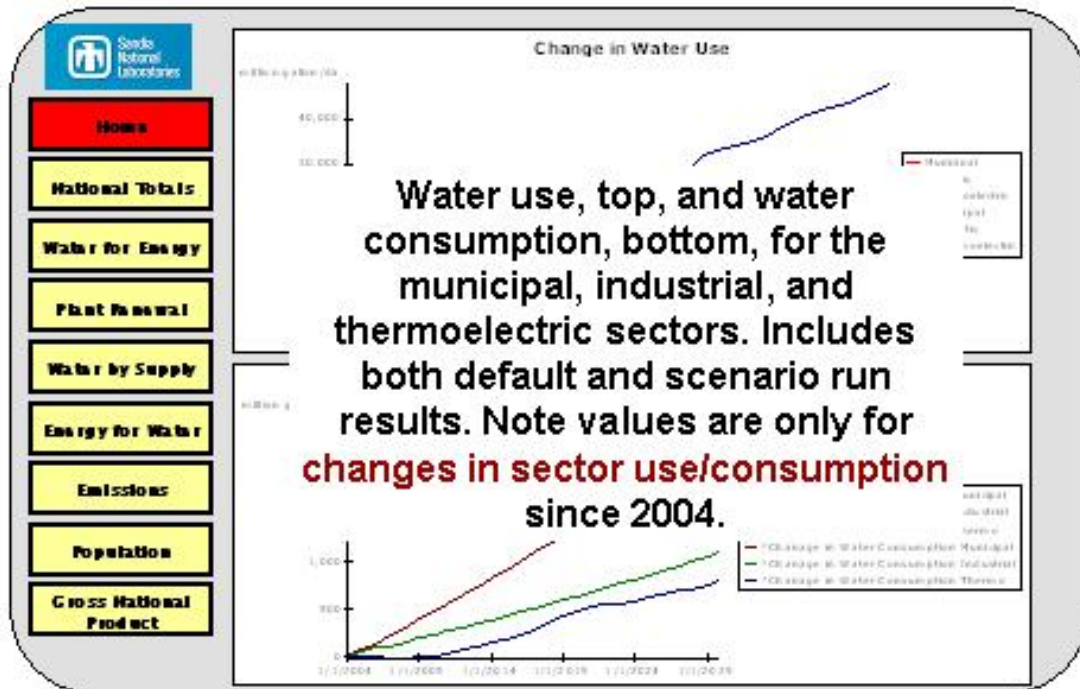
National Totals Page



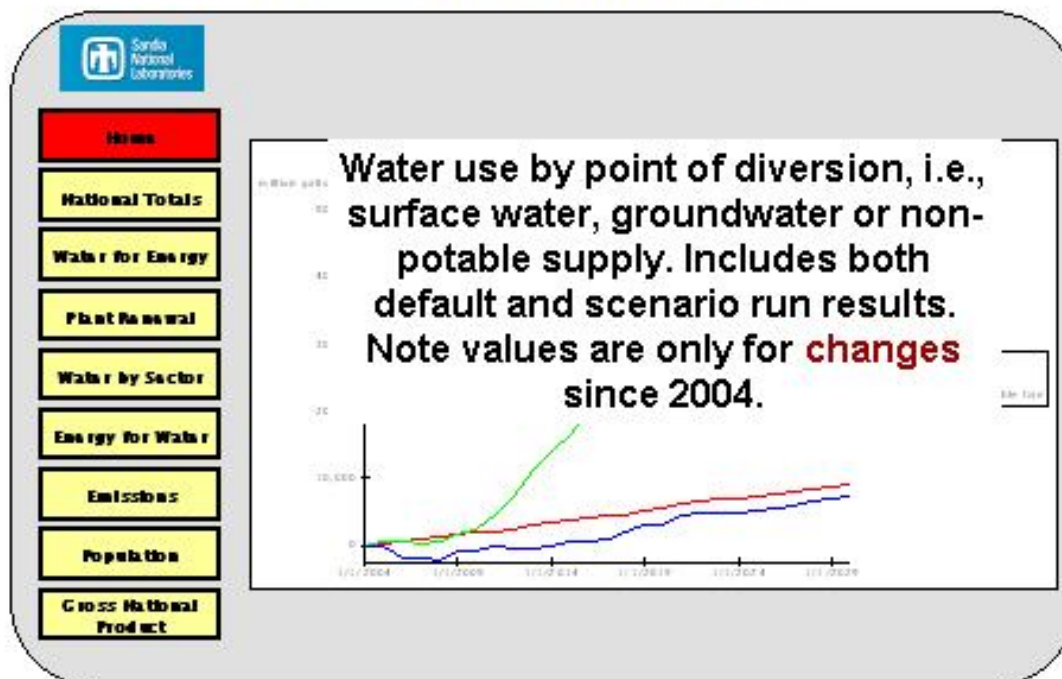
Water for Energy Page



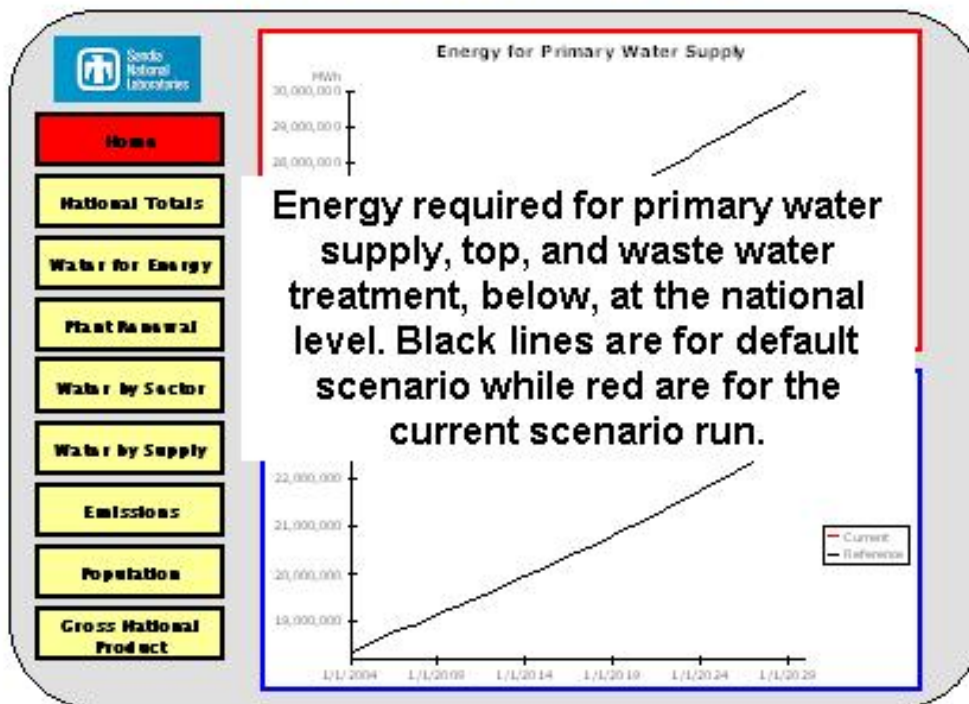
Water by Sector Page



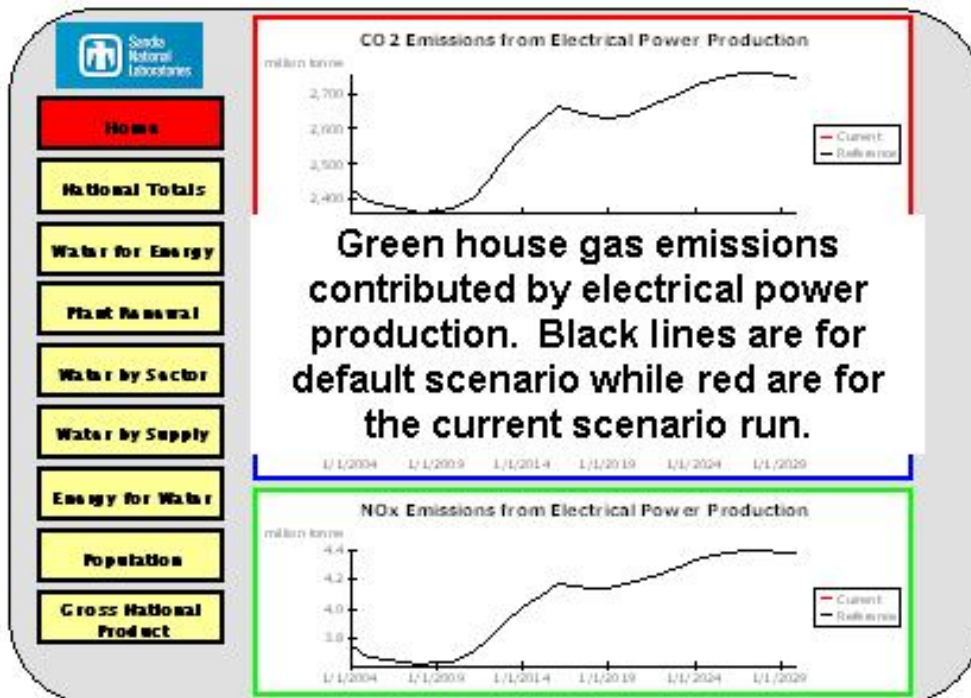
Water by Supply Page



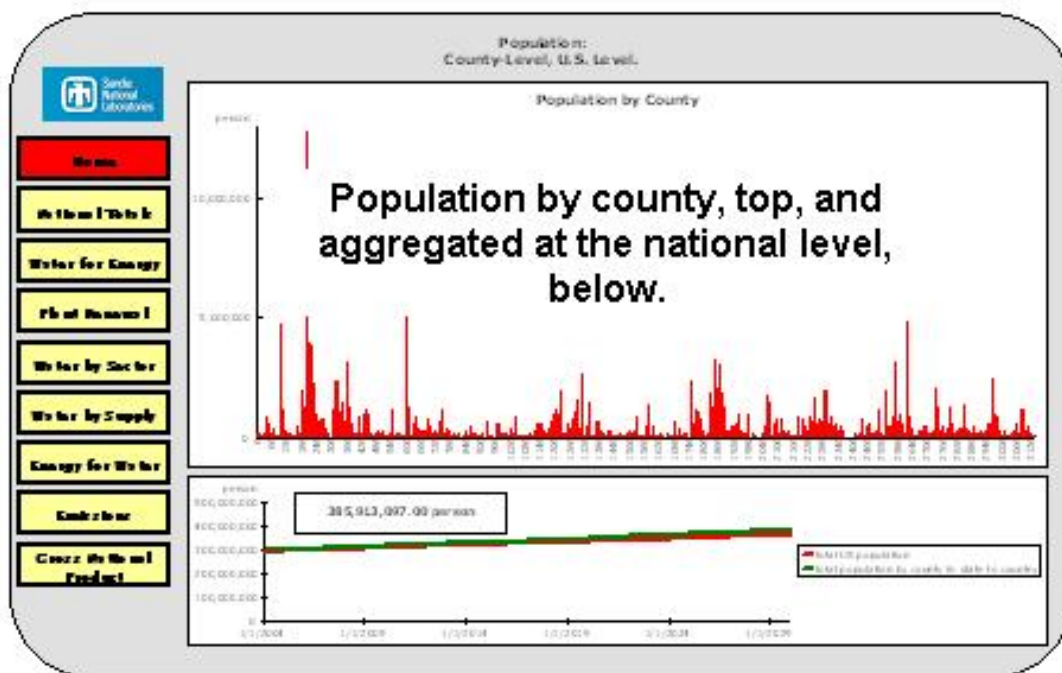
Energy for Water Page



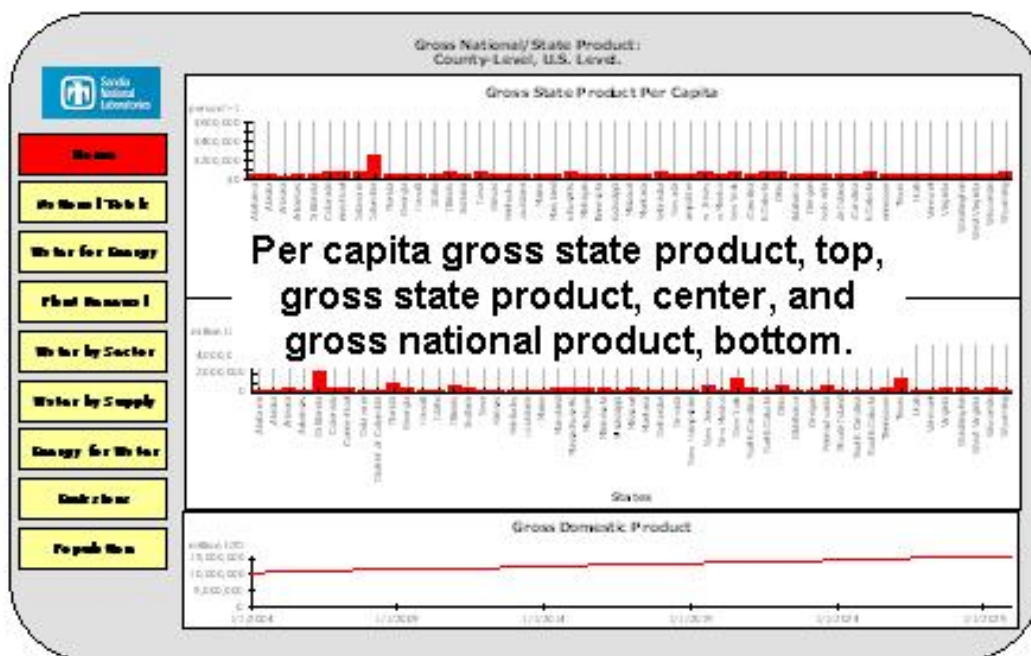
Emissions Page



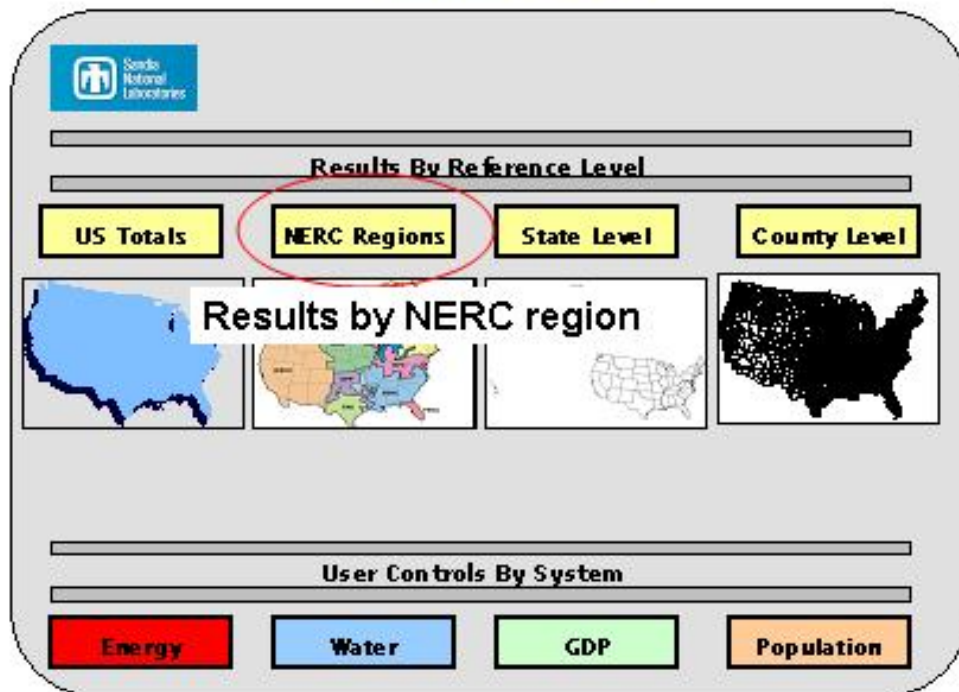
Population Page



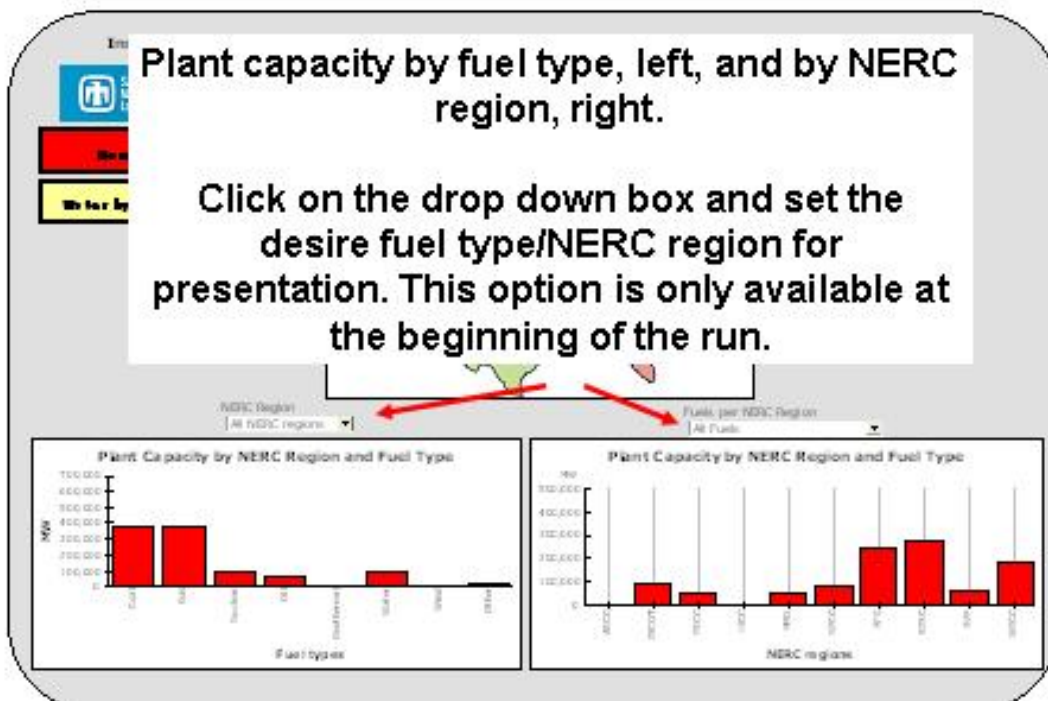
Gross State Product Page



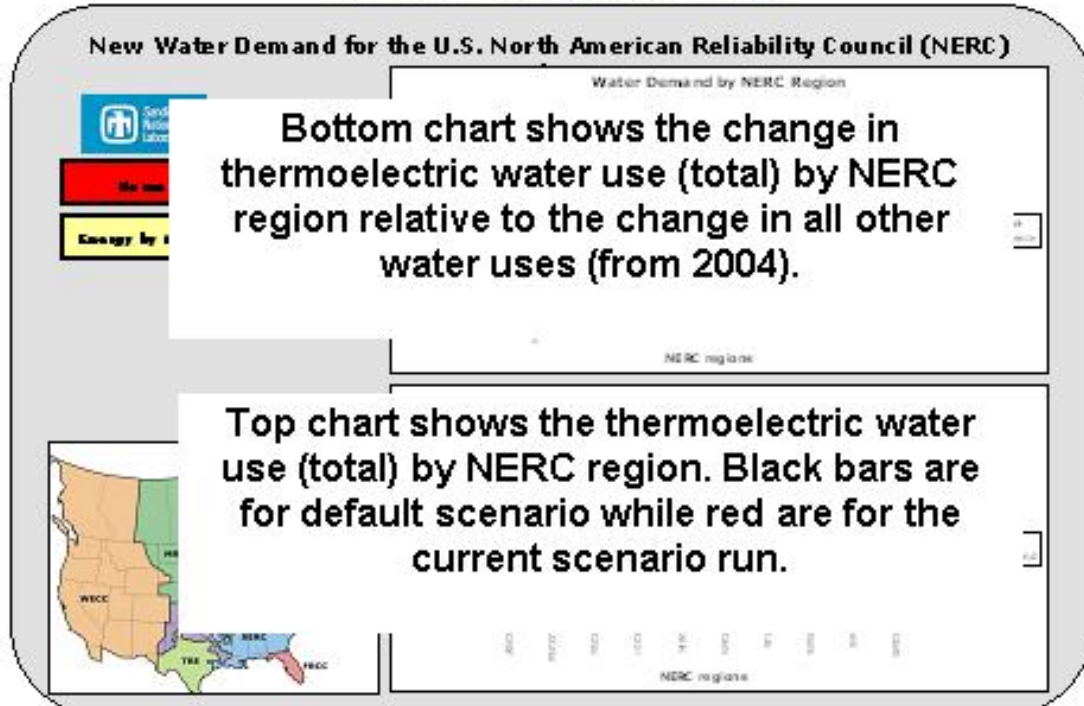
Home Page



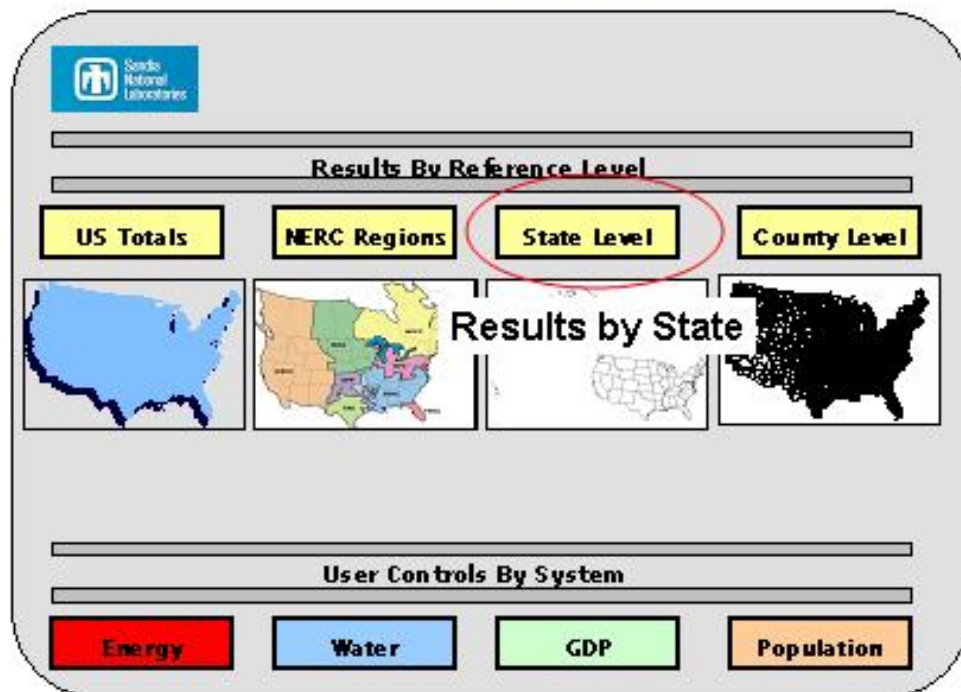
Electricity Production by NERC Region Page



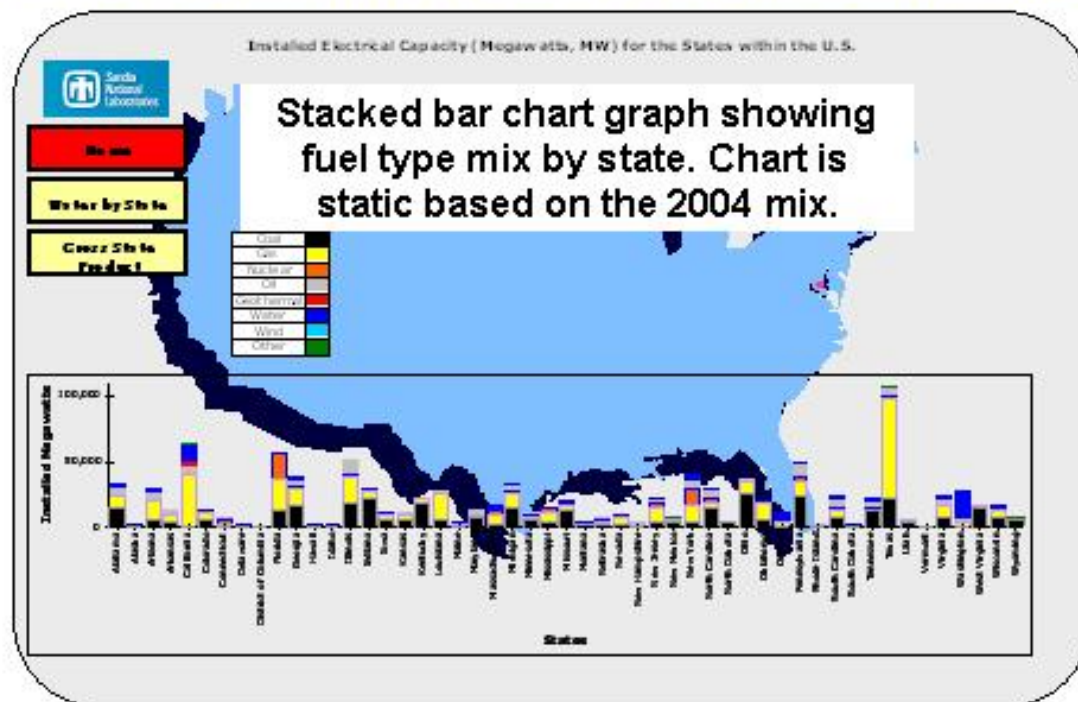
Thermoelectric Water Use by NERC Region Page



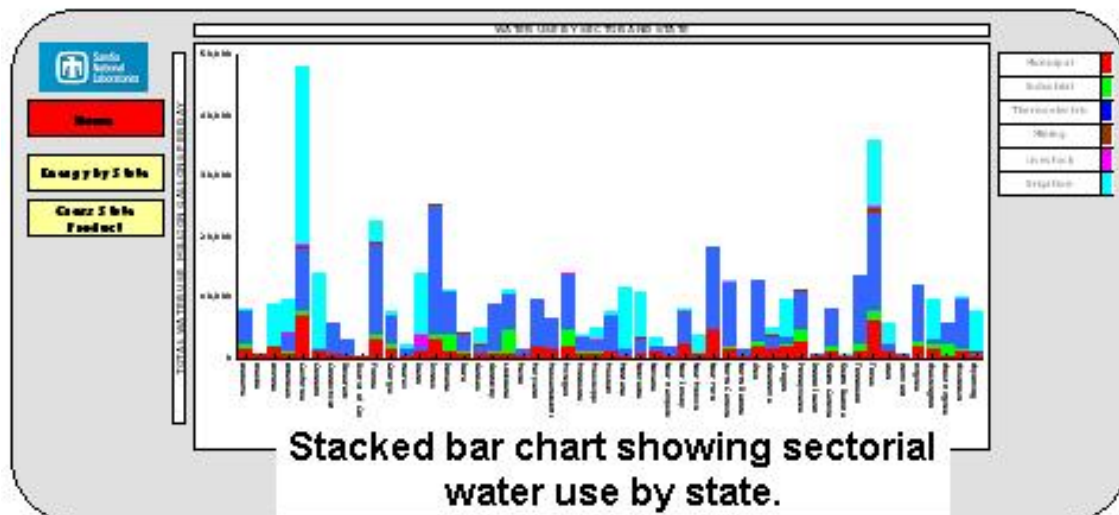
Home Page



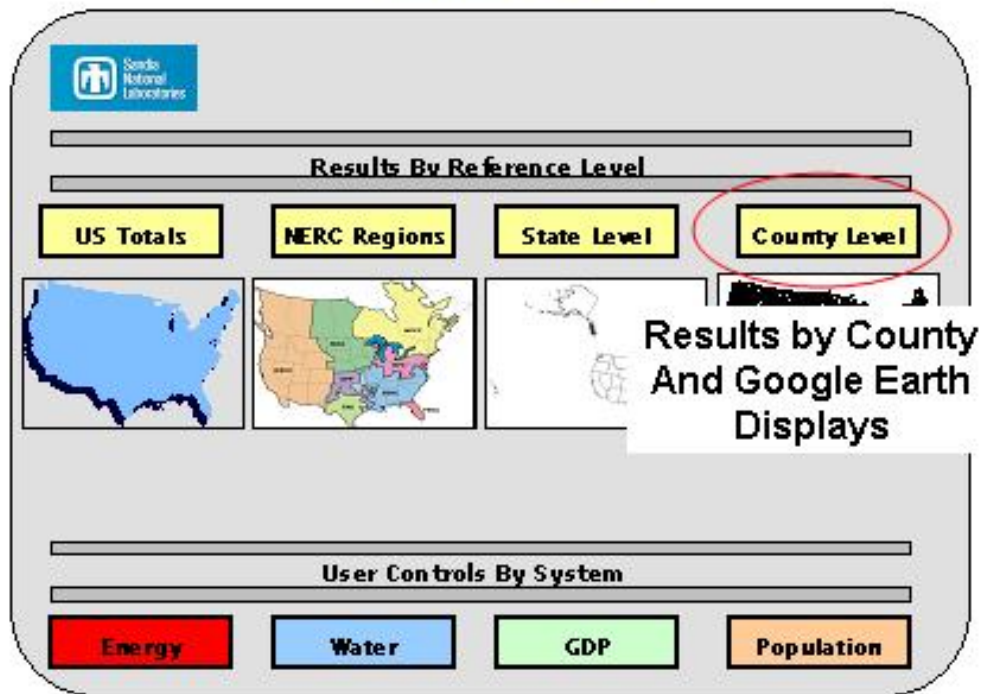
Power Capacity by Fuel Type and State Page



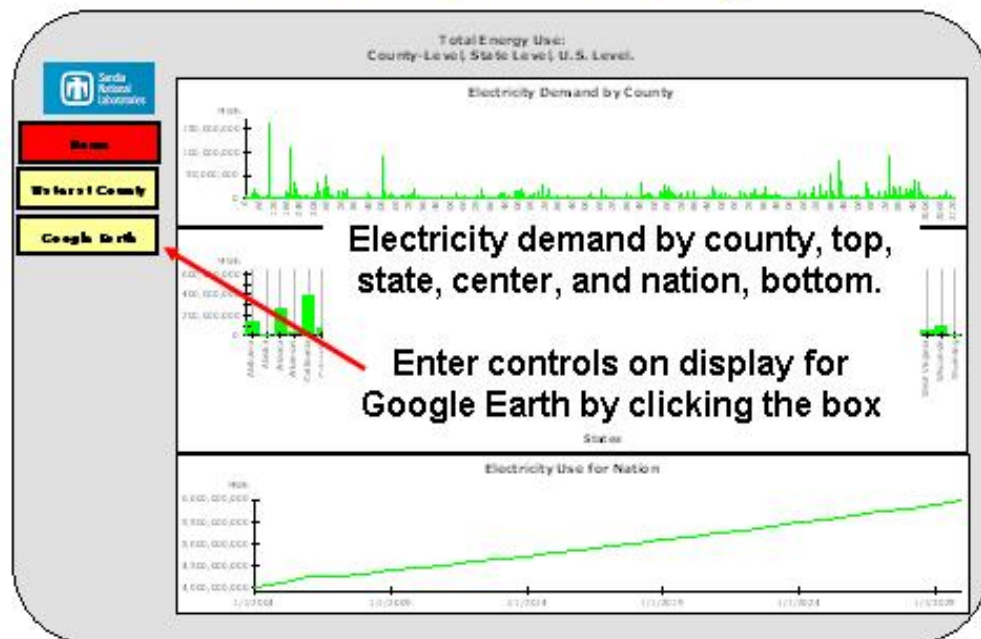
Water Use by Sector and State Page



Home Page



Electricity Demand Page



Google Earth Control Page: County Level

Check Which States to Simulate

<input type="checkbox"/> Alaska	<input type="checkbox"/> Hawaii	<input type="checkbox"/> Michigan	<input type="checkbox"/> Nevada	<input type="checkbox"/> Utah
<input type="checkbox"/> Arizona	<input type="checkbox"/> California	<input type="checkbox"/> Colorado	<input type="checkbox"/> Connecticut	<input type="checkbox"/> Delaware
<input type="checkbox"/> Florida	<input type="checkbox"/> Georgia	<input type="checkbox"/> Idaho	<input type="checkbox"/> Illinois	<input type="checkbox"/> Indiana
<input type="checkbox"/> Iowa	<input type="checkbox"/> Kansas	<input type="checkbox"/> Kentucky	<input type="checkbox"/> Louisiana	<input type="checkbox"/> Maine
<input type="checkbox"/> Maryland	<input type="checkbox"/> Massachusetts	<input type="checkbox"/> Minnesota	<input type="checkbox"/> Missouri	<input type="checkbox"/> Montana
<input type="checkbox"/> Nebraska	<input type="checkbox"/> New Hampshire	<input type="checkbox"/> New Jersey	<input type="checkbox"/> New Mexico	<input type="checkbox"/> New York
<input type="checkbox"/> North Carolina	<input type="checkbox"/> North Dakota	<input type="checkbox"/> Ohio	<input type="checkbox"/> Oklahoma	<input type="checkbox"/> Oregon
<input type="checkbox"/> Rhode Island	<input type="checkbox"/> South Carolina	<input type="checkbox"/> South Dakota	<input type="checkbox"/> Tennessee	<input type="checkbox"/> Texas
<input type="checkbox"/> Vermont	<input type="checkbox"/> Virginia	<input type="checkbox"/> Washington	<input type="checkbox"/> West Virginia	<input type="checkbox"/> Wisconsin
<input type="checkbox"/> Wyoming	<input type="checkbox"/> All States			

Control the variable displayed by clicking on the metric in the box below. Note that selections can only be made at the beginning of the simulation

Click in the box next to the state to select that state for display.

Google County Switch

- ☐ Population
- ☐ Total Water Use
- ☐ Thermal Water Use
- ☐ Electricity Demand
- ☐ Electricity Production
- ☐ Electricity Production/Demand Ratio
- ☐ Water-Use Metric
- ☐ Available Storage Counters
- ☐ Change in CO2 Emissions

Home

View Watershed Data

Google Earth Control Page: Watershed Level

Google watershed switch

- ☐ Mean River Flow
- ☐ Low River Flow
- ☐ Groundwater Base Flow

UPDATE KML

- ☐ Update KML File
- ☐ Don't Update KML File

Beginning Watershed

0

Select the supply metric by clicking in the box in the upper left side of the page

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310

Output Interval

1.00 yr

Years

Home

View County Data

Google Earth Control Page: Watershed Level

Google watershed switch:
☐ Mean River Flow
☐ Low River Flow
☐ Groundwater Base Flow

UPDATE KML:
☐ Update KML File
☒ Don't Update KML File

Beginning Watershed

Ending Watershed

Output Interval

Home
View County Data

Select the range of watersheds to be displayed by setting the beginning and ending watershed. Number is related to the increasing rank of the 5th level HUC designation

Google Earth Control Page: Watershed Level

Google watershed switch:
☐ Mean River Flow
☐ Low River Flow
☐ Groundwater Base Flow

UPDATE KML:
☐ Update KML File
☒ Don't Update KML File

Beginning Watershed

Ending Watershed

Output Interval

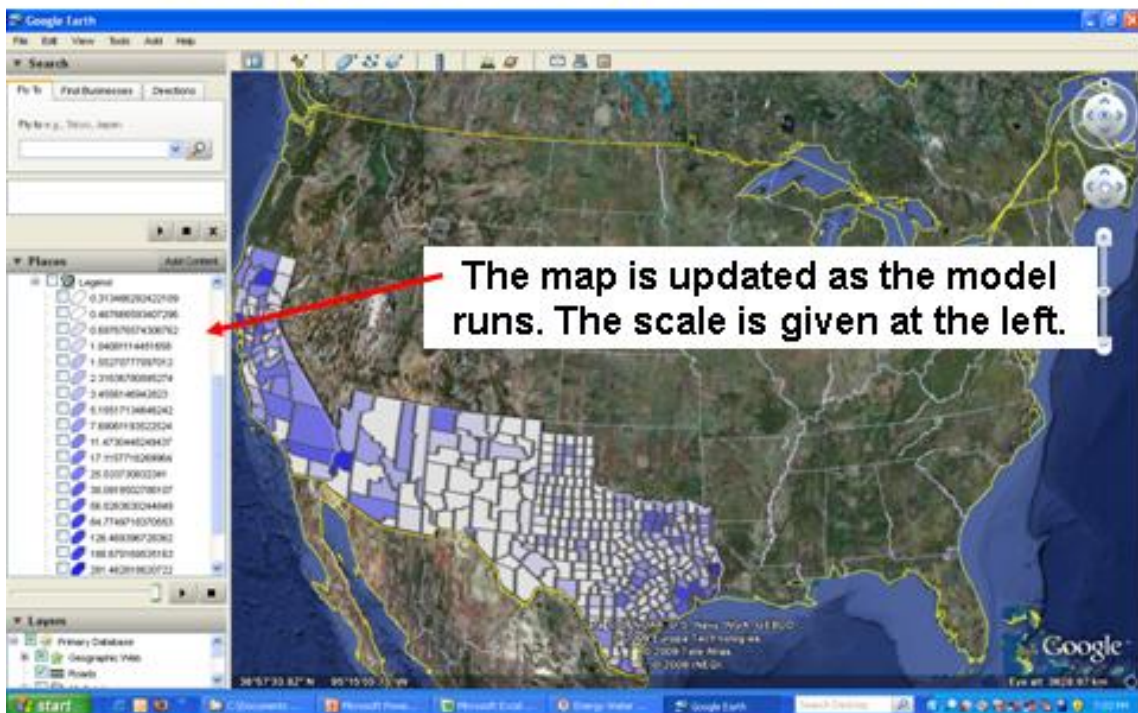
Home
View County Data

Once you have selected the watersheds of interest. Finally click to update the KML file.

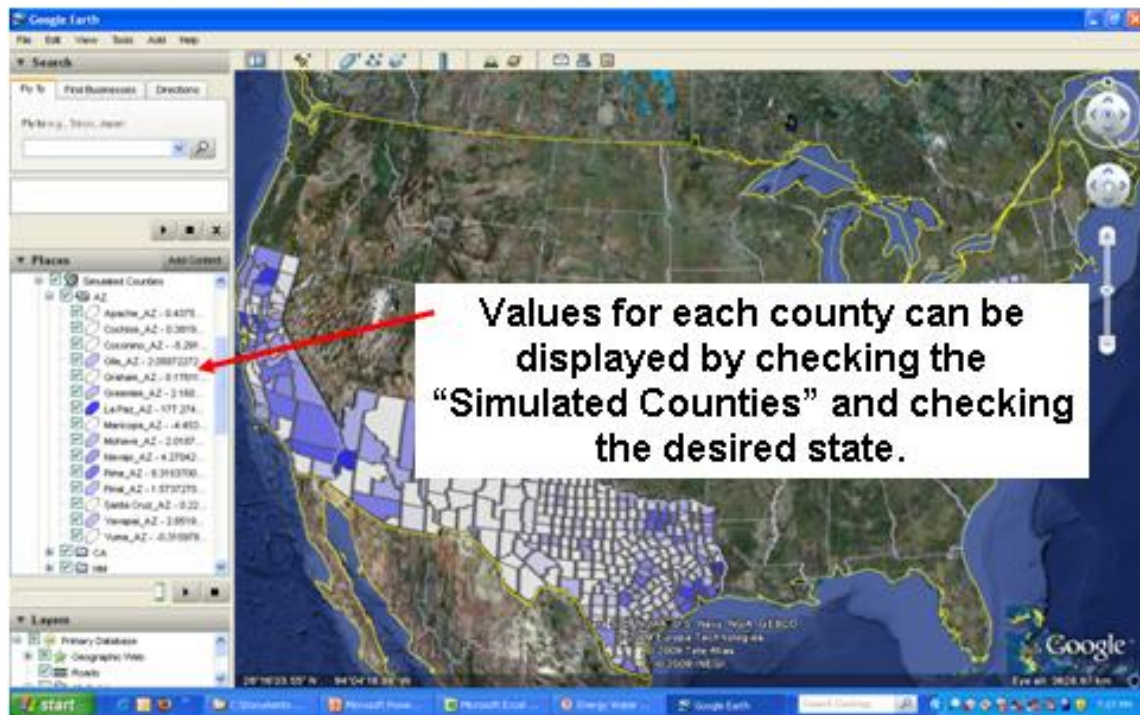
Setting Up the Google Earth Display



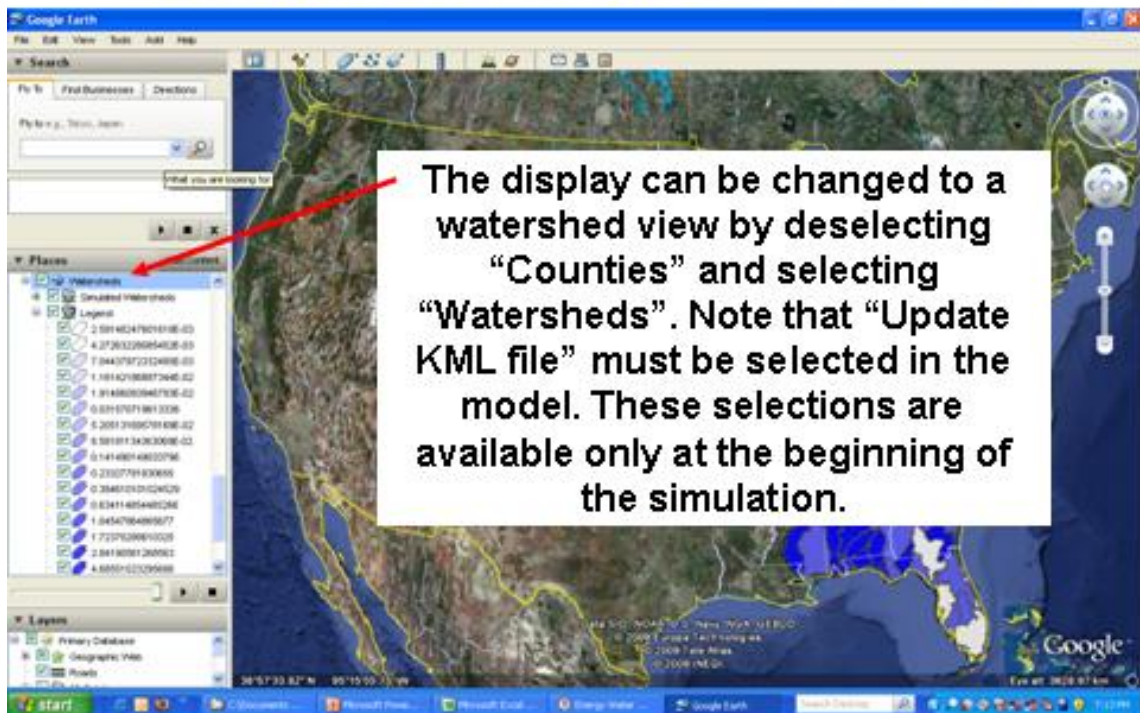
Setting Up the Google Earth Display



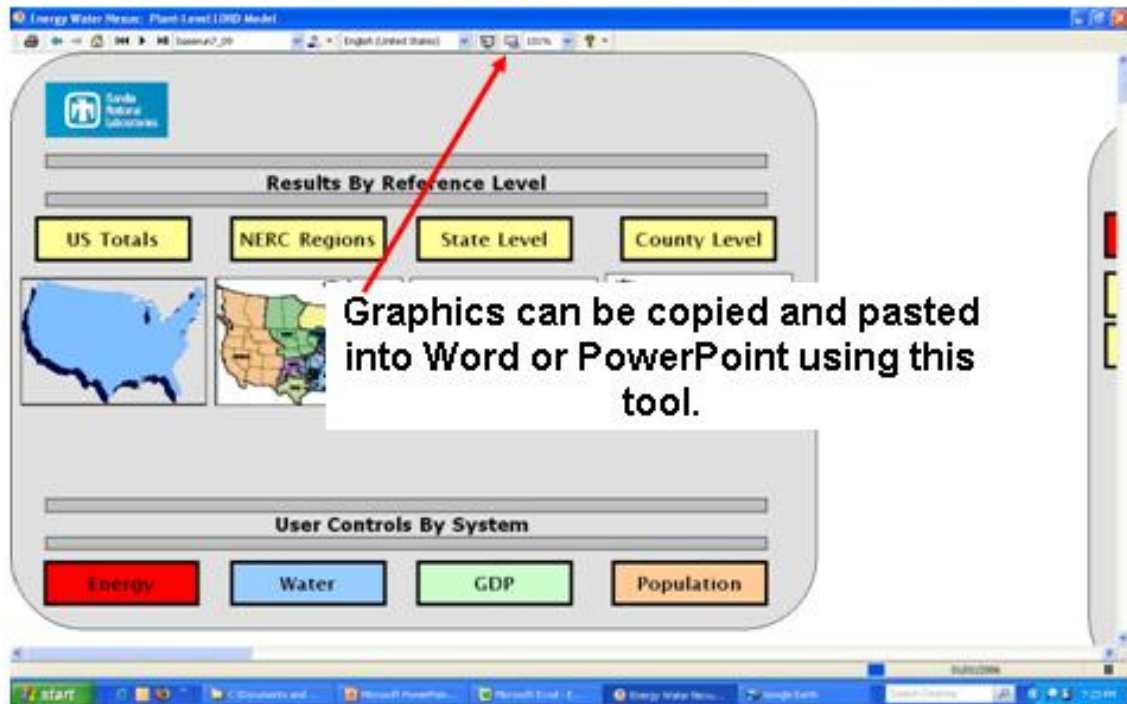
Setting Up the Google Earth Display



Setting Up the Google Earth Display



Pasting Results into Word or PowerPoint



Distribution

MS0123	LDRD Office	1011 (electronic copy)
MS0899	Technical Library	9536 (electronic copy)
MS1137	Vince Tidwell	6313 (electronic copy)
MS0706	Dave Borns	6312 (electronic copy)
MS0735	Amy Sun	6311 (electronic copy)
MS0735	Geoff Klise	6313 (electronic copy)
MS0735	John Merson	6310 (electronic copy)
MS0735	Peter Kobos	6313 (electronic copy)
MS0751	James Brainard	6311 (electronic copy)
MS1104	Majorie Tatro	6200 (electronic copy)
MS1104	Rush Robinette III	6330 (electronic copy)
MS1108	Mike Hightower	6332 (electronic copy)
MS1137	Elizabeth Richards	6313 (electronic copy)
MS1137	Howard Passell	6313 (electronic copy)
MS1137	Jesse Roach	6313 (electronic copy)
MS1137	Len Malczynski	6313 (electronic copy)
MS1137	Marissa Reno	6313 (electronic copy)
MS1137	Ray Finley	6313 (electronic copy)
MS1137	Thomas Lowry	6313 (electronic copy)
MS1137	Will Peplinski	6313 (electronic copy)
MS1318	Jean-Paul Watson	1412 (electronic copy)
MS1318	Mark D. Rintoul	1412 (electronic copy)
MS1318	William Hart	1412 (electronic copy)