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Institutional Transformation Version 2.5 Modeling and Planning

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Abstract

Reducing the resource consumption and emissions of large institutions is an important step toward a sustainable future. Sandia National Laboratories' (SNL) Institutional Transformation (IX) project vision is to provide tools that enable planners to make well-informed decisions concerning sustainability, resource conservation, and emissions reduction across multiple sectors. The building sector has been the primary focus so far because it is the largest consumer of resources for SNL.

The IX building module allows users to define the evolution of many buildings over time. The module has been created so that it can be generally applied to any set of DOE-2 (http://doe2.com) building models that have been altered to include parameters and expressions required by energy conservation measures (ECM). Once building models have been appropriately prepared, they are checked into a Microsoft Access® database. Each building can be represented by many models. This enables the capability to keep a continuous record of models in the past, which are replaced with different models as changes occur to the building. In addition to this, the building module has the capability to apply climate scenarios through applying different weather files to each simulation year. Once the database has been configured, a user interface in Microsoft Excel® is used to create scenarios with one or more ECMs.

The capability to include central utility buildings (CUBs) that service more than one building with chilled water has been developed. A utility has been created that joins multiple building models into a single model. After using the utility, several manual steps are required to complete the process. Once this CUB model has been created, the individual contributions of each building are still tracked through meters.

Currently, 120 building models from SNL's New Mexico and California campuses have been created. This includes all buildings at SNL greater than 10,000 sq. ft., representing 80% of the energy consumption at SNL. SNL has been able to leverage this model to estimate energy savings potential of many competing ECMs. The results helped high level decision makers to create energy reduction goals for SNL. These resources also have multiple applications for use of the models as individual buildings.

In addition to the building module, a solar module built in Powersim Studio® allows planners to evaluate the potential photovoltaic (PV) energy generation potential for flat plate PV, concentrating solar PV, and concentration solar thermal technologies at multiple sites across SNL's New Mexico campus.

Development of the IX modeling framework was a unique collaborative effort among planners and engineers in SNL's facilities division; scientists and computer modelers in SNL's research and development division; faculty from Arizona State University; and energy modelers from Bridger and Paxton Consulting Engineers Incorporated.

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NOMENCLATURE

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BDL	Building Design Language
BEM	Building Energy Model
BEND	Building ENergy Demand model (PNNL)
BTU	British Thermal Unit (1kWh = 3412BTU)
CPV	Concentrating PV
CST	Concentrating solar thermal
CUB	Central Utility Building
CV(RMSE)	Coefficient of Variation of Root Mean Square Error
DOE	Department of Energy
DOE-2	Building modeling environment created by the DOE
ECM	Energy conservation measures
GPM	Gallon per minute
GPV	Ground PV
HADCM3	Hadley Centre Coupled Model version 3
HVAC	Heating, ventilation, and air conditioning
IPCC	International Panel on Climate Change
ITC	Investment Tax Credit
IX	Institutional Transformation
kW	kilowatt (1,000 Watts)
LCOE	Levelized Cost of Electricity
MIT	Massachusetts Institute of Technology
MW	Mega-Watts (1,000,000 Watts)
NMBE	Normalized Mean Bias Error
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PNM	Public Service Company of New Mexico
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
REC	Renewable Energy Certificate
RPV	Roof PV

SAM	System Advisor Module
SNL	Sandia National Laboratory
TMY3	Typical Meteorological Year Revision 3
Ton	1 Ton of cooling = 12,000 BTU/hour
VBA	Visual Basic for Applications
DOE-2	A building modeling environment that preceded Energy Plus
Energy Plus	DOE sponsored open-source whole building energy modeling program that is the successor to DOE-2
eQUEST	A building modeling environment that uses DOE-2 as a modeling engine
Open Studio	DOE sponsored open-source front end to Energy Plus similar to eQUEST

1 INTRODUCTION

Reaching a state of sustainable consumption and production is a critical initiative that large institutions (national labs; city, state, and federal governments; school districts; military bases; industrial complexes; and others) must address as the global population increases and risks such as climate change are better understood [3, 4]. Reducing the resource consumption and emissions of large institutions which use transportation infrastructure, own hundreds of buildings, and invest in renewable energy is a critical economic and environmental challenge in the United States and around the world. If efforts to achieve this are guided with good strategies, they can simultaneously preserve the environment while sustaining economic growth and well-being [15]. The Institutional Transformation (IX) vision is to provide tools and processes that help planners to find such strategies through balancing limited resources across many sectors as seen in Figure 1. These tools will help minimize environmental impact and unneeded costs while promoting investments in technologies, which save the most energy without compromising productivity for a given site. To accomplish this, planners need models that have sufficient resolution and accuracy to identify the balance between saving resources and saving money for many competing conservation measures.

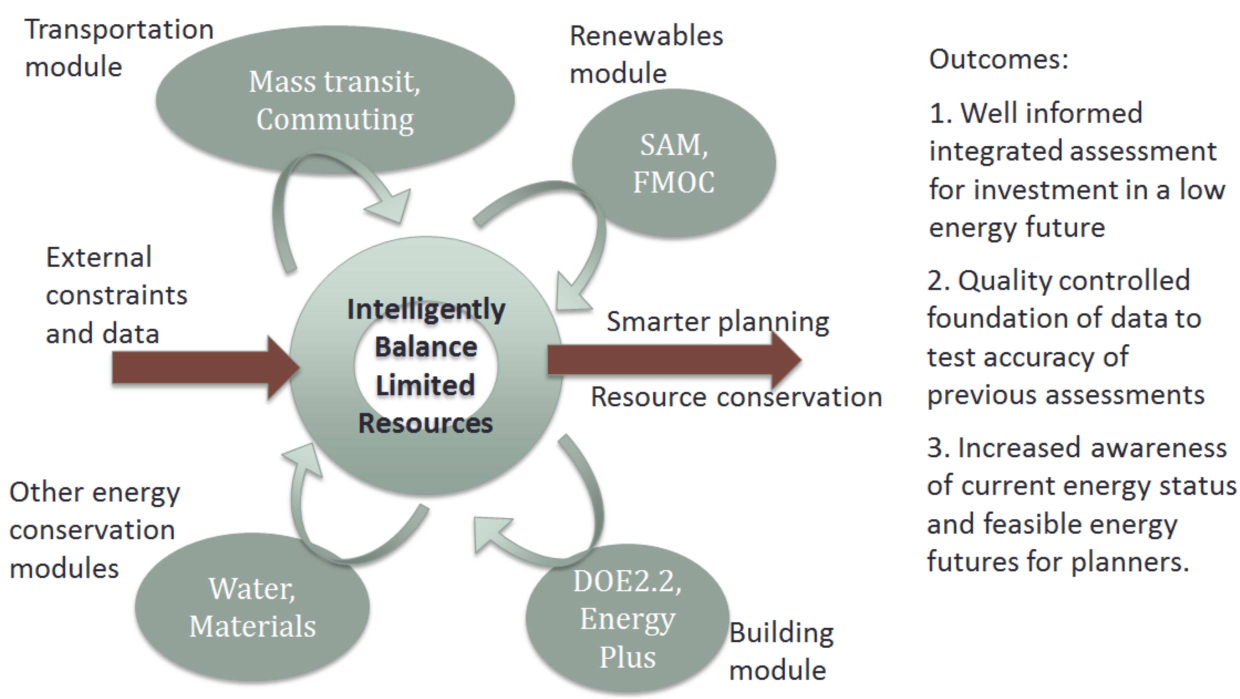

Figure 1. IX Vision

Using a bottom-up strategy to inform high level planning requires effective communication between multiple layers of complexity. Many tools already exist that have the level of detail needed to make well informed lower level choices. Even so, there are significant gaps between these detailed analyses and high level planners [5, 22]. To achieve the IX vision, these gaps must be overcome through coordinating detailed modeling so that results can be reliably used at a higher level. This requires connecting accurate data streams to modeling through new algorithms as seen in Figure 2. All of the required resources (data collection, computational power, and algorithms) to do this exist in the current technology and it is anticipated that sustained investment and applied research will overcome the gaps. Additional economic obstacles have to be considered as well. It is proposed that attaining connectivity between multiple applications beyond the IX vision (i.e. guidance for operations, energy analytics, model-based controls, energy assessments) with automation of tedious tasks can make en-masse detailed modeling economically efficient and can therefore be used for aggregate assessments. As a result, Sandia National Laboratories (SNL) is investing in many of these additional activities.

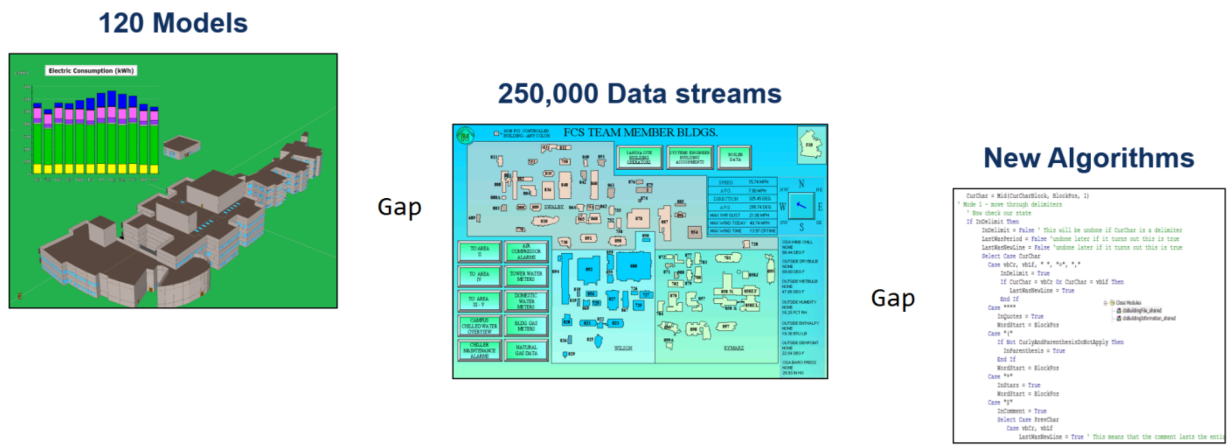

Figure 2. Gaps between modeling, data, and algorithms

According to the U.S. Energy Information Administration's Annual Energy Outlook report, the residential and commercial sectors, which account for most of the U.S. building sector's energy consumption, accounted for 40% of primary energy consumption in 2013 [2]. For SNL this percentage of consumption is mostly through buildings also. The building sector has therefore been the first area of focus.

For the building sector, using detailed modeling to inform higher level decisions concerning large sites is a new field of research [16]. The IX building module is a unique tool in this field requiring the maintenance of detailed models of individual buildings. Reinhart and Davila [16] argue that such an approach is too expensive, but their focus is on trying to model entire urban sites where thousands of structures have to be approximated by architypes to make the problem tractable because repetition is extensive and data sources are not well coordinated. IX's focus is on sites which have many unique, high energy consuming buildings. The response is often unique to the internal use-case of each building that is changing over time. IX therefore requires a much more detailed knowledge of each building that has additional potential benefits in model-based energy analytics and automated building controls. When detailed building modeling and data have been successfully coupled and algorithms have been created that stream to higher level planning, an unprecedented level of energy efficiency and capacity to effectively innovate will be realized. A coordinated effort to build and maintain large numbers of models will also lead to reduction of costs through mass production. Facilities organizations will have to transform to include a focus on modeling throughout the entire building lifecycle to reap these benefits.

The IX building module uses DOE-2® energy models, which have so far been created exclusively in eQUEST® [23][1]. Extension of IX to incorporate Energy Plus [24] models or any other whole building energy modeling platform is straightforward but beyond the scope of the current effort. Pacific Northwest National Laboratory's (PNNL) Facility Energy Decision System (FEDS) [18, 19] has some similarities and was considered as a possibility for use but suffers from the disadvantage that it encompasses building energy modeling within a closed framework that could not be extended to other areas of application mentioned above (energy analytics and controls). In addition, conservation measures are limited to those already pre-packaged in FEDS whereas IX has an open framework, which allows creating new measures similar to Energy Plus and Open Studio [25] measures. Another effort led by PNNL and funded by Department of Energy (DOE) is the Building Energy Asset Score tool. This tool combines energy modeling from Energy Plus and inferred values for undefined parameters and lifecycle cost analysis from FEDS. Similar to IX's architecture, a database of all buildings entered into this tool is being built for a national record of building energy benchmarks and models. Even so, accountability to output accuracy is not enforceable in such a broad context. At a city-wide scale Massachusetts Institute of Technology (MIT) Sustainable Design Lab has initiated the development of a model of Boston that expands to a higher level than envisioned by IX [16, 17]. Their approach uses individual building energy models (BEM) but relies on grouping buildings into architypes and therefore does not have the capacity to provide feedback to individual buildings. In Europe, the IEE-TABULA project has taken a similar approach, which once again focuses on the development of architypes to assess energy savings [20]. At an even larger scale, PNNL has developed the building energy demand (BEND) model for exploring regional issues experienced by the building sector [11]. Many of these efforts are congruent with the IX vision but lack formalized integration of quality control and configuration management which become critical for the continued maintenance of a fleet of BEMs. The IX building module has been designed to attempt to address these issues.

The IX building module is a partial realization of the IX vision with many lessons learned during its creation. It was developed with a unique collaboration between Sandia's facilities staff and research and development staff. The IX building module allows users to simulate the application of different combinations of energy conservation measures (ECMs) to different buildings over different time frames. For example, a user may wish to know how much heating and cooling energy could be saved by installing cool roofs on one set of buildings, replacing windows in another set of buildings, and replacing HVAC systems in a third set. The building module allows users to simulate the staging of all these efforts over time, because the renovations applied across many buildings could take many years. The building module tracks the energy savings for multiple long term facilities development scenarios, allowing the user to identify a preferred strategy. A schematic of the building module is shown in Figure 3.

In general, this approach helps:

1. Institutions identify and set energy savings goals and develop roadmaps for achieving them.
2. Reduce the uncertainty associated with long range facilities planning aimed at lower energy consumption.

---

[1] The underlying DOE-2 building design language (BDL) can take many forms beyond the format output by eQUEST. These forms have not been tested in the IX building module BDL parser.

3. Quantitatively illustrate strengths and weaknesses of competing plans.
4. Communicate the tradeoffs of competing strategies to other stakeholders.

The IX building module integrates DOE-2 within a Visual Basic for Applications (VBA) wrapper. eQUEST must be used in close conjunction with the building module to maintain and understand the models in IX and is used for individual building model applications. The building module is being used on SNL's California and New Mexico sites but is generalized to accept any set of DOE-2 BEMs that have had ECMs applied through DOE-2 expressions.

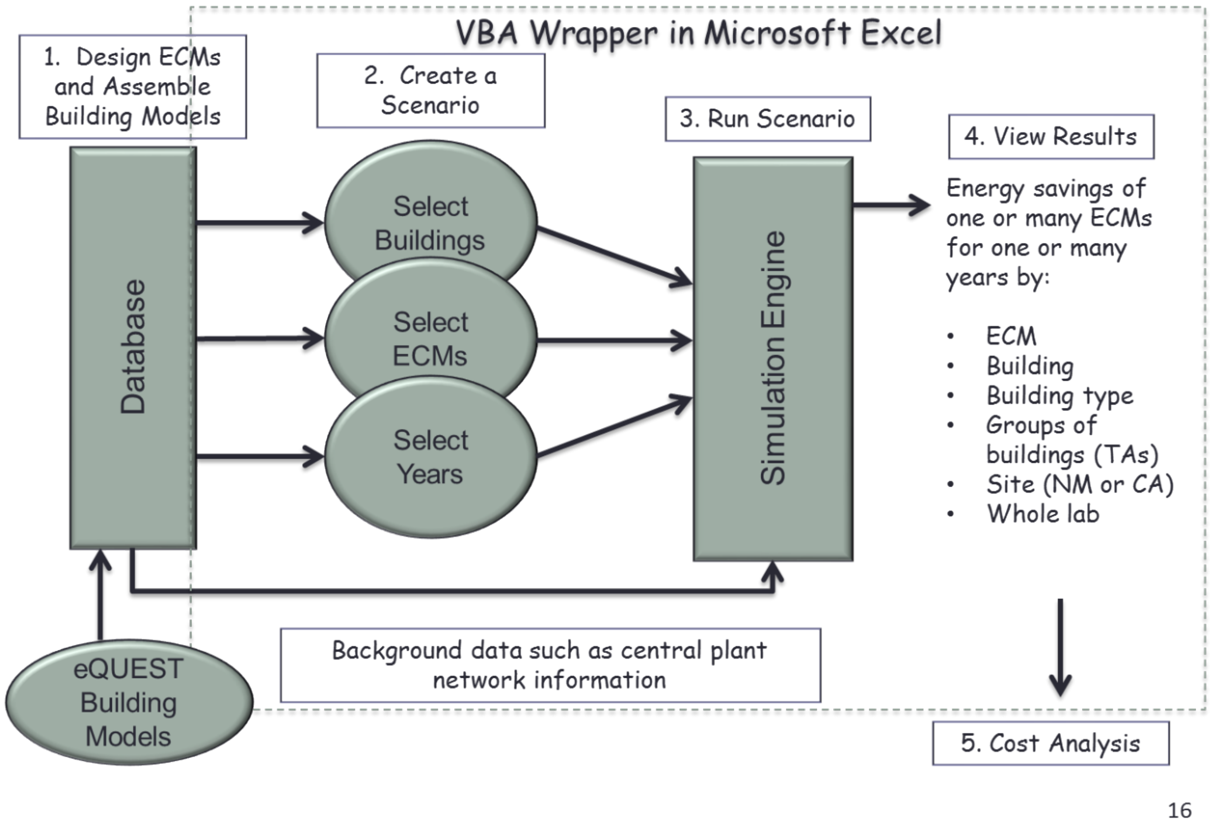

Figure 3. Schematic of IX model.

The current implementation includes all buildings at Sandia's New Mexico and California sites with areas greater than 10,000 ft^2. This includes 97 buildings in New Mexico and 23 in California. Combined, the models account for approximately 7.3 million ft^2 of building space and about 80% of SNL's energy consumption. Each of the buildings was modeled by Bridger and Paxton engineering firm and by Marlin Addison from Arizona State University. Thirty-nine ECMs have been implemented in the building models.

In addition to the IX building module, a solar module was also developed. The solar module is less generalized but could also be applied to other sites. It is designed to estimate the return on investment and electricity generation potential associated with three different solar technologies at 18 prospective sites at SNL/NM.

2 BUILDING MODULE

2.1 Overview

The IX building module allows a user to create scenarios of the effects of energy conservation measures (ECMs) applied to many buildings over many years. It organizes building models so that they can be changed simultaneously or individually, and can produce site-wide results. This captures the effects of detailed changes to individual buildings while still letting the user look at the global effects on an entire site. The building module is not only able to provide high-level generalizations about energy decisions at a site. It is also able to provide guidance to reduce energy for individual buildings. This stands in contrast to analysis that makes recommendations without considering individual building performance. In addition to this, the building module keeps track of the history of changes made to buildings by retaining a history of models so that the effectiveness of changes in the past can be illustrated alongside projections into the future. DOE-2 and eQUEST are both needed to use the building module as shown in Figure 4.

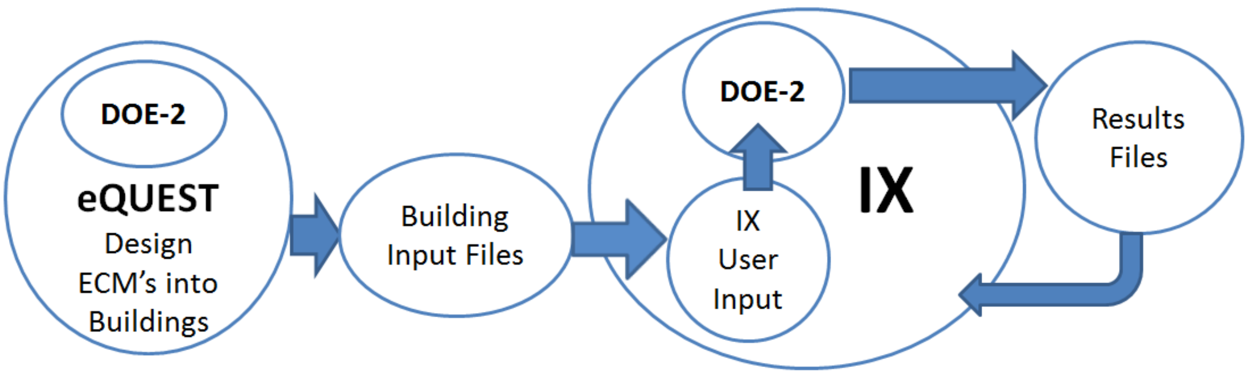

Figure 4. DOE-2, eQUEST, and IX relationships

2.1.1 User Interface and Database

The IX building module consists of a user interface and a database. The user interface serves to construct multiple scenarios for the same site as seen in Figure 5. The database has its own interface that allows the configuration of building models, ECMs, and weather. The user interface is created in Microsoft Excel® while the database is in Microsoft Access®. Most users access the IX building module through the Excel interface. The database application has had much less development and requires special knowledge to configure and use.

2.1.2 ECMs

In the building module, an ECM represents any change to a building that is intended to conserve energy. Replacing windows or applying weather stripping to entrances are examples of ECMs. ECMs require manual input through building design language (BDL) expressions in each building model. For example, the cool roof ECM requires input of a single parameter and an expression in each roof surface of a building model. The global parameter "Roof Absorbtance" has to be created at the beginning of the file:

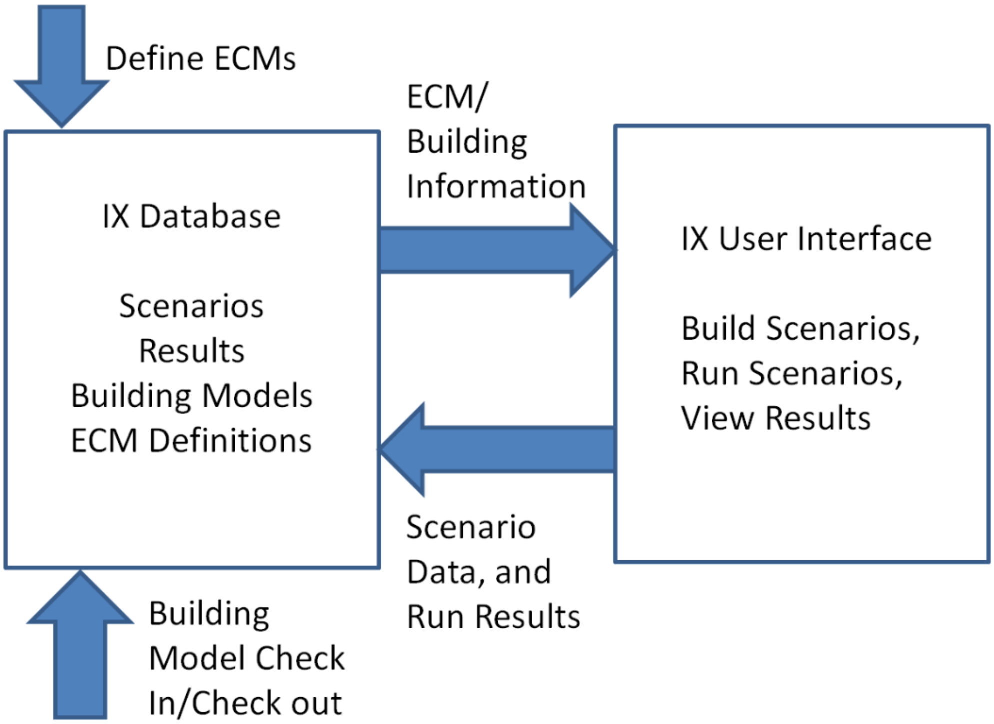

Figure 5. Relationship between the IX database and the IX interface.

```
PARAMETER
  "Roof Absorbtance"          = 0.5  ..
```

Every CONSTRUCTION BDL command assigned to a roof surface then has to be altered to include the following expression in red:

```
"Roof Construction" = CONSTRUCTION
  TYPE          = LAYERS
  ABSORPTANCE     = {#pa("Roof Absorbtance")}
  ROUGHNESS      = 1
  LAYERS        = "704EL3 Roof Cons Layers"
  ..
```

If an error is made such as only applying the "Roof Absorbtance" to one roof construction when two exist, then the ECM will not work as intended, which will lead to erroneous results in IX. The curly brackets ("{}") in BDL indicate an expression that allows input of a function with many features as described in the DOE-2 user documentation.

Each ECM is defined by two sets of parameters. The first set, called "eQUEST parameters," are the parameters that must be defined in each building model. This set of parameters must be manually inserted into BDL key word, key value pairs in commands within the building model through the use of expressions as illustrated above. These eQUEST parameters can also be used by more than one ECM.

Some changes, such as changing an HVAC system are very complex to represent by parameter expressions. Such changes cannot be represented easily as an ECM in IX. The user can still make such changes to a building model using eQUEST and checking in different building models so that energy savings between the two models can be quantified.

The second set of parameters is called the "user input parameters." Many times, user input needs to be different from the eQUEST parameters. This is desirable because it can simplify the complexity of parameter expressions in the building models and it enables user input to be presented in terms that may be more familiar to the user than building model parameters. The set of eQUEST parameters and the set of user input parameters are related through a function that can be as simple as an expression or as complex as a long VBA function.

$$\{eQUEST\ Parameters\} \equiv VBA\ Function(\{User\ Input\ Parameters\}) \tag{1}$$

Each ECM also requires the creation of an inverse function that relates the user input parameters as a function of the eQUEST parameters. This enables the calculation of default values for the user input parameters based on the value assigned to eQUEST parameters in each building model.

$$\{User\ Input\ Parameters\} \equiv Inverse\ VBA\ Function(\{eQUEST\ Parameters\}) \tag{2}$$

The 39 ECMs currently implemented in IX are listed in Table 1. These ECMs are described in detail in the IX user manual [21]. The descriptions include instructions on how to implement each ECM in building input files.

Table 1. IX building module ECMs

	ECM Name	Category
1	Air Management in IT Rooms & DCs	IT
2	Airside Economizer Control	Retrofit HVAC
3	Boiler Thermal Efficiency	Thermal Efficiency
4	Caulk & Weather strip Doors & Windows	Infiltration
5	Chilled Water Temperature Reset	Heat Recovery or Load Reduction
6	Cool Roof	Roof
7	CUB Chilled Water Temperature Reset	CUB
8	CUB Chiller Efficiency	CUB
9	CUB Cooling Tower Fan Control	CUB
10	CUB Flat Plate Economizer Use	CUB
11	CUB Pump Flow Control	CUB
12	Daylighting sensors for Top & Side lighting	Lighting
13	Duct Static Pressure Reset (repair & commission)	HVAC Distribution Systems (Duct & Pipe)
14	Exterior Insulated Finish System (EFIS)	Wall Treatments
15	High Efficiency Lighting Replacements	Lighting
16	Hot Water Pump Flow Control	Heat Recovery or Load Reduction

	ECM Name	Category
17	Hot Water Temperature Reset	Heat Recovery and Load Reduction
18	Improved Boiler Efficiency	CUB
19	Install Exterior Shading Overhangs	Windows
20	Install Interior Shading	Windows
21	Install Revolving Doors or Vestibules	Infiltration
22	Insulate Roof	Roof
23	Lab Exhaust	Exhaust
24	Limit Personal Space Heater Use	Plug Loads
25	New Window or Glass Properties	Windows
26	Night Cooling	Energy-Efficient Cooling Systems
27	Occupancy sensors	Lighting
28	Plug Load Power Switch	Plug Loads
29	Reduce Domestic Hot Water Recirculation Hours	Heat Recovery or Load Reduction
30	Reduce Fan Operation Hours	Building Automation system (BAS)
31	Reduce Illumination Levels	Lighting
32	Reduce Plug Loads	Plug Loads
33	Repair Duct and Pipe Leaks	HVAC Distribution Systems (Duct & Pipe)
34	Seal Vertical Shafts & Stairways	Envelope Sealing
35	Single Building Chiller Efficiency	Chiller Efficiency
36	Supply air temperature reset	Retrofit HVAC
37	Sweep Controls	Lighting
38	T-Stat management (Temperature setback & occupancy set-point)	Building Automation system (BAS)
39	VAV Box Occupancy Sensors	Retrofit HVAC

Once the set of eQUEST parameters have been placed in building input files, each ECM can be redesigned at the user input parameter level as needed. It is therefore desirable to parameterize models as much as possible even beyond current ECMs envisioned. For example, SNL's set of buildings have 72 eQUEST parameters built into every model that provides a plug load dissipation rate for each hour for weekdays, Fridays, and weekends. These parameters are used by both the "Reduce Plug Loads" ECM, which is a simple scale factor applied to plug loads and the more complicated "Plug Load Power Switch," which simulates a power switch that reduces plug loads according to a schedule. Once in place, the 72 parameters leave room for creation of many different ECMs that leverage hourly variations to plug loads.

It is necessary that ECMs be evaluated for accuracy with respect to their sensitivity in IX to expected energy savings for benchmark cases. This ECM validation process has not been carried out extensively for the current IX project even though expert knowledge has been applied. Several cases of clear misbehavior of ECMs have been resolved.

2.1.3 Buildings

Each building in IX has a begin year and an end year. If the begin and end years are different than the IX database begin and end years, then the building is assumed to be created in its first year and demolished in its last year. For every year that a building exists it can have a different building model represent it. This allows a building to evolve with time. For example, if the user wants to keep a record of calibrated buildings in the past, different years can be represented by different models. A second application of this can be to bring a building which is not part of a CUB and to integrate into the CUB model. A third application would involve representing an ECM which is too complex to model using parameters. An edited model in eQUEST can be checked into the database and energy savings tracked alongside other models.[2] All of these operations are handled by reconfiguring the building file history for each building in the IX database. Whenever a new building model is checked into the IX database, IX automatically searches for ECM parameters and assigns the building every ECM found in the model. Every building model can therefore have different sets of ECMs.

2.1.4 Weather

Each building has a weather history assigned to it. A weather history is a set of weather files that have begin and end years assigned to them. This enables the capacity to investigate climate change, maintain historical weather records, and inquire about the effects of changing location. For example, a weather history that alternated the location from Albuquerque to Phoenix to Minneapolis for two different weather file types is shown below. This weather history was used for development of a scenario which investigated the use of cool roofs and their effectiveness in different climates.

```
2013-2014: albuquerYWEC2.bin
2015-2016: phoenixYWEC2.bin
2017-2018: minneapoYWEC2.bin
2019-2020: NM_Albuquerque_Intl_ArptTMY3.bin
2021-2022: AZ_Phoenix_Sky_Harbor_IntTMY3.bin
2023-2024: MN_Minneapolis_St_Paul_InTMY3.bin
2025-2044: NM_Albuquerque_Intl_Arpt.bin
```

Figure 6. Cool roof scenario weather history leveraging different climates and two different sets of weather files for the same locations

2.1.5 Energy Savings

Energy savings have a special definition because IX includes variable weather. The energy savings are defined as the current building's energy use for the current weather minus the baseline building energy use for the current weather. Here "baseline" refers to the model, which represents a building for its first year of existence in a scenario. Energy savings are therefore equal to zero for the first year for all cases. If the weather history does not change, only one baseline run is needed. Otherwise, a baseline run is needed for every change in weather file.

Understanding energy savings in IX can be complicated if there are many changes to models and ECMs over many years. Isolating the effects of each ECM requires applying only a single ECM at a time.

[2] IX is not a replacement for eQUEST in any way. IX's strength lies in the capacity to perform parameter studies of many buildings. Whenever doing something custom beyond ECMs, the user should always run single cases in eQUEST and carefully verify that the correct intent has been implemented. Unlike eQUEST, IX is blind to the details in the models and inaccurate modeling will lead to inaccurate results.

2.2 Building Modeling

2.2.1 Planning

Because of the large number of buildings at SNL, the team determined that the IX project should focus on the largest users of energy across both the New Mexico and California sites. Therefore, only buildings larger than 10,000 ft^2 have been included. To streamline the modeling process, the buildings were divided into five different categories based on their primary usage. The selected categories were:

- Offices–Office/conference type spaces
- Light Laboratories–Primarily office with some laboratory type spaces
- Heavy Laboratories–Primarily laboratory type spaces
- Warehouses–Primarily storage with some office or laboratory type spaces
- One-Offs–Any buildings that do not fit into one of the above categories (i.e., data centers, auditoriums, cafeterias, etc.)

Categorizing buildings by type allowed the team to apply a template approach to defining/assigning ECMs. The resulting building count was 120 buildings (38 offices, 31 light laboratories, 29 heavy laboratories, 10 warehouses, and 12 "one-offs"). This database of models has been incrementally increased in size since 2013 with several rounds of calibration. A list of all of the building numbers is provided in Appendix A.

2.2.2 Modeling Process

All of the selected buildings were modeled using eQUEST. The models were built using architectural and mechanical drawings/schedules for the buildings. In addition, for some of the buildings, audit reports were available that gave information about the mechanical system types and run schedules. Figure 7 shows an example of the exterior view of the Building 899. Interior views showing rooms and zones are also produced.

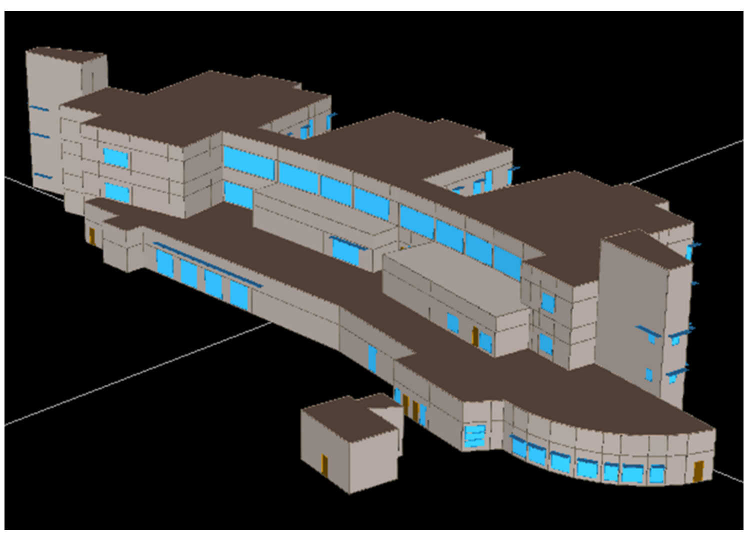

Figure 7. 3D view of Building 899 eQUEST model

2.2.2.1 Zoning

Within eQUEST, the buildings were split into zones based primarily on the anticipated space usage (i.e., conference, corridor, office, laboratory, etc.). Because eQUEST only allows one mechanical system to be assigned per zone, the zones were also broken up based on the mechanical system serving the space. In some cases, it was not possible or logical to break a space into multiple zones (primarily in cases where a single room was served by more than one mechanical system). In these instances, the mechanical systems serving the space were combined into a single system by adding the airflows, heating, and cooling capacities. The fan static pressures for the combined systems were calculated by using the weighted average of the static pressure of the systems to be combined.

2.2.2.2 Lighting/Equipment

To make reasonably accurate models, the team needed to make good assumptions about the building lighting and equipment loads. By using the lighting plans and fixture schedules from building records, the team was able to count the quantities of each fixture type within each individual model space. This information was documented in an Excel spreadsheet for each building to provide a "space-by-space" lighting density analysis that will allow future users to review lighting density changes by fixture type or by space type.

With the information in the "space-by-space" lighting density spreadsheets, it was possible to calculate a building average lighting power density (measured in W/ft^2). The calculated building average lighting density was applied to all spaces/zones within each model that were provided with lighting (i.e., not applied to plenums/crawl spaces).

The average miscellaneous equipment loads were more difficult to determine. Because very little information was available regarding existing plug loads, a default assumption of $1 W/ft^2$ was used initially for all buildings. This value was reviewed and refined during the calibration process.

2.2.2.3 Parameters/ECMs

As described above, to utilize the various ECMs within the IX building module, the eQUEST models were outfitted with parameters. All of the eQUEST parameters used in this project were numeric parameters. Through the building module, the user is able to toggle values of the parameters that are assigned to various fields within eQUEST. Changing the value of a parameter through the building module changes the value of the field(s) within eQUEST that the parameter is assigned to, which in turn can have an impact on the simulated building energy use.

We built a template model for each building type to ensure that a standard set of parameters were used in all buildings. The template models were coordinated with the IX building module to ensure that parameter adjustments had the expected results. On completion of a template model, the parameters and schedules from that model were imported into all of the buildings of the same type. After importing the template model, the team was able to assign the parameters/schedules and adjust their values as necessary.

2.2.3 Calibration

Because a number of assumptions had to be made while building the models (particularly regarding the equipment/plug loads), the team needed to calibrate the models against their actual energy usage.

2.2.3.1 Inputs

Many of the buildings being modeled have building-level energy meters (Square D®) that report hourly electrical (kW) usage. Reports were generated for each of these buildings that included a minimum of one year of hourly data. In addition, monthly gas usage data was available for most buildings. The electricity data appeared reliable for most of the models but, unfortunately, the gas data appears to be too far from expected gas usage and have therefore been deemed unreliable for calibration purposes. This mismatch between data types is illustrated for Building 1090 in Figure 8 and Figure 9.[3] This provides an example where calibrating models requires scrutiny of both the model and the calibration data. The root cause of the mismatch across many models and data sets is under investigation and is leading to changes to the gas data management practices at SNL.

Custom weather files were developed for use in the eQUEST models from historic weather data that aligned with the reported hourly kw/gas data. For buildings served by central utility buildings (CUBs), the modeled chiller, boiler, and/or pump energy was suspended from the hourly reports to avoid double counting the energy from items that are not located within the building.

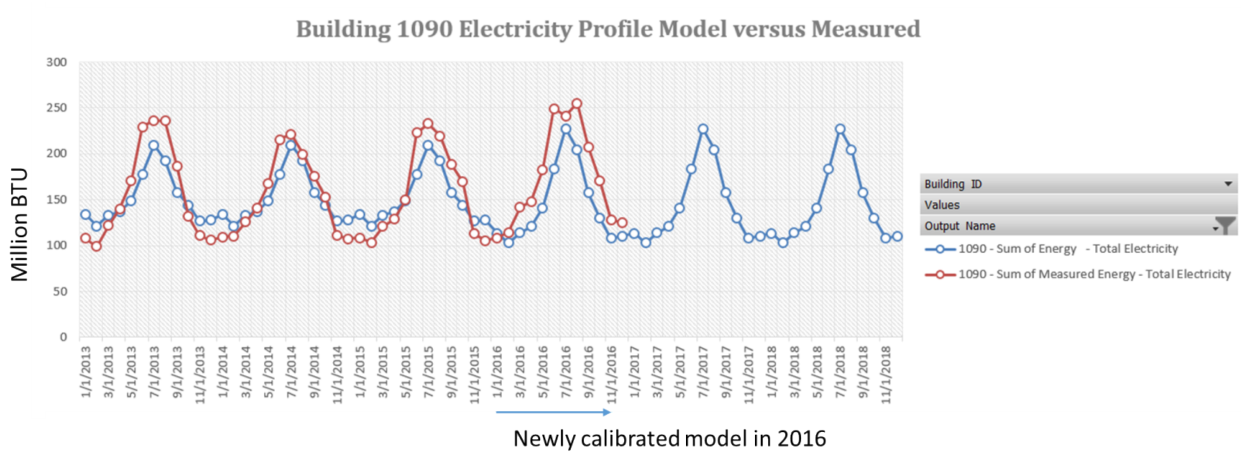

Figure 8. Building 1090 electricity comparison

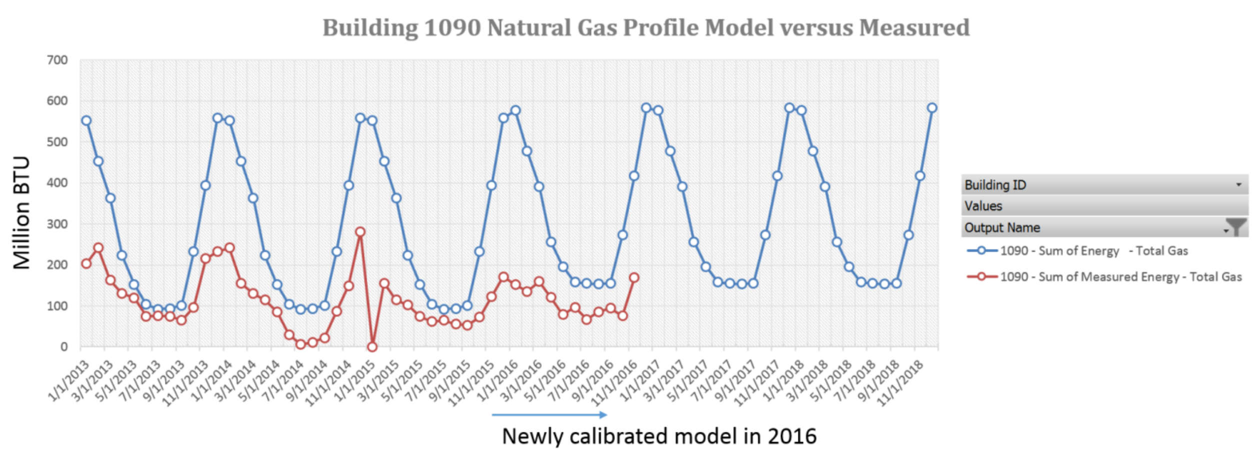

Figure 9. Building 1090 natural gas comparison

[3] The comparisons in these figures are not perfect because the model is used New Mexico average weather conditions whereas the data reflects response to actual weather variations. A complete record of actual historical weather still needs to be incorporated in the IX building module even though the calibration process included historical weather.

2.2.3.2 Calibration Process

To calibrate the building models, the hourly electric metered data were compared graphically to the modeled energy usage. Both the maximum hourly demand (kWh) and the total energy for the month (kWh/month) were used in tuning the model to the baseline data. Using a Microsoft Excel spreadsheet, graphs were generated for each month and each unique day type (Monday through Thursday, Friday, and weekends/holidays), as shown in Figure 10. The team used these graphs to identify what days and times the modeled energy differed from the meter data and provided adjustments for 76 buildings of the campus.

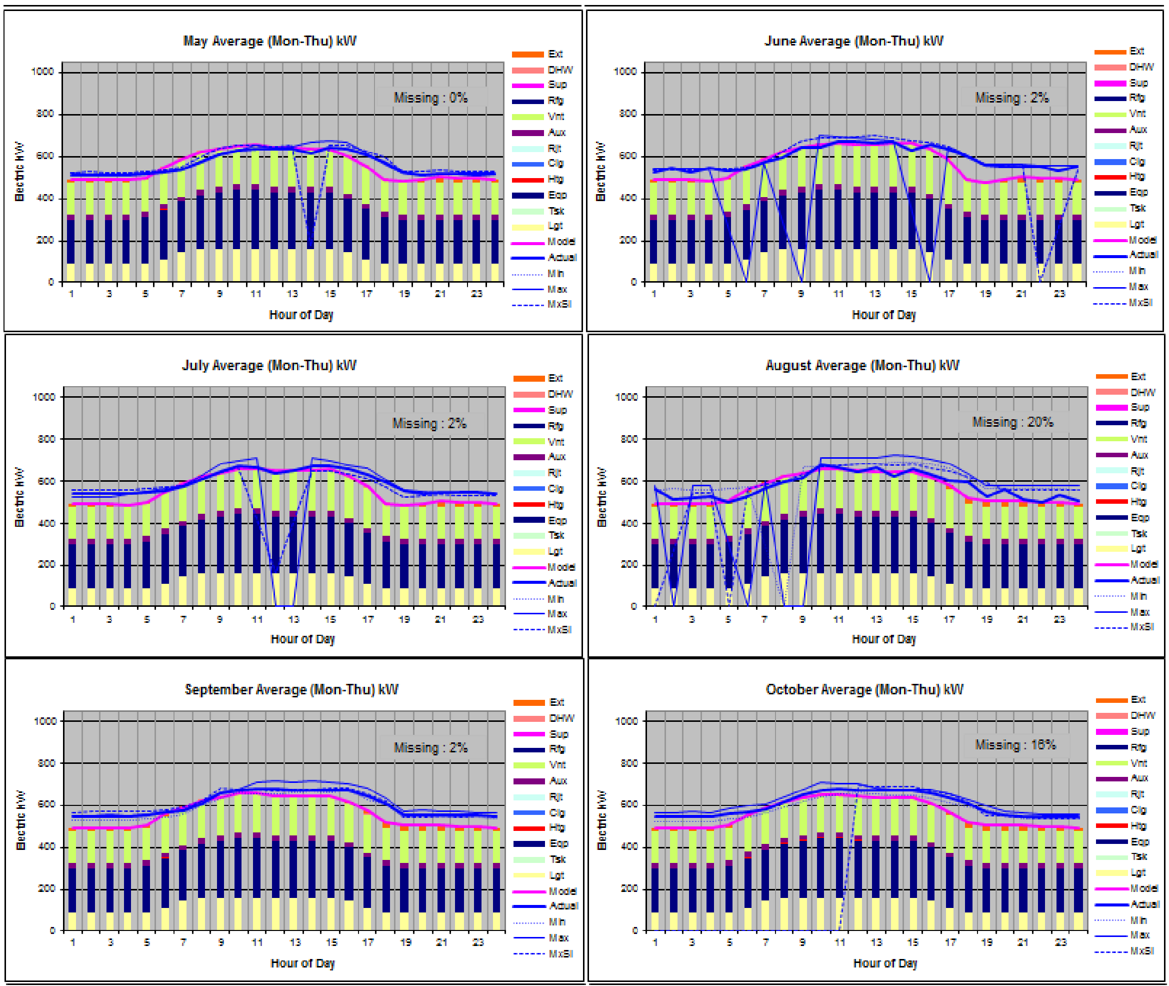

Figure 10. Typical calibration spreadsheet output. The vertical bars and the pink line show the modeled energy usage and the blue line shows the actual (metered) energy usage.

Adjustments were made to the models as necessary to align the modeled energy usage as closely as possible to the actual usage. The primary adjustments made to the models included:

1. **Operating Start/Stop Times**:
   Based on information from SNL, it was assumed that all of the modeled buildings operated from 6:00 a.m. to 6:00 p.m. with the exception of some buildings, which were run 24/7. For some buildings, it was apparent from the metered energy data that the building operated for times other than 6:00 a.m. to 6:00 p.m. In these cases, the fan

start/stop times were adjusted along with the schedules controlling plugs, occupants, and lighting. In addition, all units serving computer room type spaces, all mechanical systems serving laboratory spaces, and all laboratory exhaust fans were modeled to run 24/7.

2. **Plug Density**:
   The density of equipment (plug) loads was the single largest unknown when creating the models. These densities (and their associated operating schedules) were adjusted as necessary to calibrate the buildings. The densities were typically adjusted to as low as 0.75 W/ft^2 for office buildings up to approximately 3 W/ft^2 for heavy laboratory buildings.
3. **Supply/Exhaust Fan Static Pressure**:
   Many of the buildings were initially modeled with their scheduled fan static pressures for the supply and exhaust fans. The team found that this resulted in exceptionally high fan energy in some of the models. Using the SNL facility control system, it was possible to view a "snapshot" of how a given fan was actually operating. Based on this information, we inferred that many of the fans operate at approximately 70 to 90% of their scheduled (rated) static pressure.

2.2.3.3 Calibration Audit

In Fall 2016, an evaluation of every calibration based on standard metrics was requested. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides guidelines for measuring the calibration of building models [26]. ASHRAE 14 guidelines are established to assist industry and the public by offering a uniform method of testing for rating purposes, by suggesting safe practices in designing and installing equipment, and by providing other information that may serve to guide the industry. ASHRAE 14 discusses several parameters for measuring how well a mathematical model matches its real-world system, including the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)). They measure the difference between two data series y and $\hat{y}$, as shown in equations 3 and 4.

$$NMBE = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)}{(n-p) \times \bar{y}} \tag{3}$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{(n-p)}}}{\bar{y}} \tag{4}$$

Where, in this case, y is the observed total energy for the month (kWh/month); $\hat{y}$ is the DOE-2 model output; n is the number of measurement points (i.e. 12 months); $\bar{y}$ is the mean of n number of observations; and p is equal to one when calibrating to utility meter readings. We calculated these values for the 76 calibrated building models, using monthly data, and the results are shown in

Table 2. Due to a lack of data 7 buildings of the 76 produced errors during calculation. A list of the buildings which have not been calibrated at this time is shown in Table 3.

Table 2. Values for NMBE and CV(RMSE) for calibrated buildings

*Building models with 1 or more months of missing calibration data. Colorized table entries indicate values outside

Building	NMBE	CV(RMSE)		Building	NMBE	CV(RMSE)		Building	NMBE	CV(RMSE)
	%	%			%	%			%	%
518	-2.15	4.70		832	11.71	15.20		891	7.90	8.10
700	6.37	7.03		835	-2.04	10.06		894	2.81	10.46
701	3.79	4.64		855	11.12	10.96		895	0.70	3.08
702	-7.41	9.25		856	*	*		897	-4.32	7.08
703	-3.58	7.32		857	-7.35	11.04		898	-2.30	5.46
720	6.01	9.29		858	-2.92	5.41		899	2.23	7.61
725	6.20	6.60		858EL	0.42	2.84		954	2.47	20.52
727	-6.14	6.61		858N	2.00	3.20		956	-0.07	11.85
729	-9.60	13.04		859	4.46	11.73		957	-1.69	9.91
750	-2.94	5.90		861	-4.40	30.90		960	3.21	7.84
751	3.66	4.21		864	*	*		961	1.60	6.85
752	-6.09	6.62		865	29.76	35.86		969	0.57	9.36
755	-0.23	1.83		867	4.85	24.83		970	12.05	13.00
758	7.42	8.69		868	*	*		971	1.22	11.64
770	-10.40	12.01		869	10.66	12.50		980	-18.99	22.83
800	5.80	11.92		870	-10.40	10.70		981	-0.44	11.42
802	*	*		872	7.88	21.24		983	18.48	18.76
804	-174.	167.44		875	7.19	19.86		986	-1.00	4.10
808	5.64	10.93		878	-3.50	5.90		1090	6.50	9.54
809	-3.00	8.90		879	5.90	15.69		6539	*	*
810	*	*		880	-3.97	6.98		6584	3.49	6.14
811	6.50	9.46		880A	-7.90	10.10		6585	5.50	6.40
820	-3.53	6.89		886	7.12	17.63		6586	18.92	24.91
821	0.45	2.87		887	1.77	10.65		6587	*	*
827	12.54	14.19		890	2.81	10.46		6596	2.44%	6.00
831	-2.95	9.42								

Table 3. Forty-four Buildings that have not been calibrated at the time of publication

6526	850	C907	C941
6580	858EF	C910	C942
6588	860	C911	C943
6597	899A	C912	C960
704	905	C914	C963
705	962	C915	C9631
726	963	C916	C9633
730	9956	C926	C964
823	9981	C928	C968
825	C905	C929	C972
836	C906	C940	756

ASHRAE 14 suggests criteria, when modeling monthly data, for the values of NMBE and CV(RMSE), less than 5% and 15% respectively. For the 69 building models with adequate data, 38 have NMBE values less than or equal to 5% and 56 have CV(RMSE) less than or equal to 15%. Histograms in Figure 11 represent the distribution of the electrical calibration values. These results indicate that model calibration is a work in progress. Fifty-four percent of the building values fall within the suggested NMBE range while 79% fall within the CV(RMSE) suggested range. Some difficulties with calibration are due to a lack of observed data; the seven buildings mentioned earlier were missing an entire month of energy measurements. Several were missing multiple months of energy data during the calibration year. Recent modeling of a 6 building subset has found that calibrating with the “Week-Day-Average-Peak-Demand as kW” can provide a closer match and smaller values for the calibration measurement parameters.

The attempt to calibrate gas usage within the building models proved to be a diagnostic test. The values of NMBE and CV(RMSE) proved high enough to suggest errors in the readings of the gas utility data. Preliminary review of the data seems to find this is the case and further data gathering will be required. This has led to actions that are currently being taken towards assuring accurate gas data can be accessed.

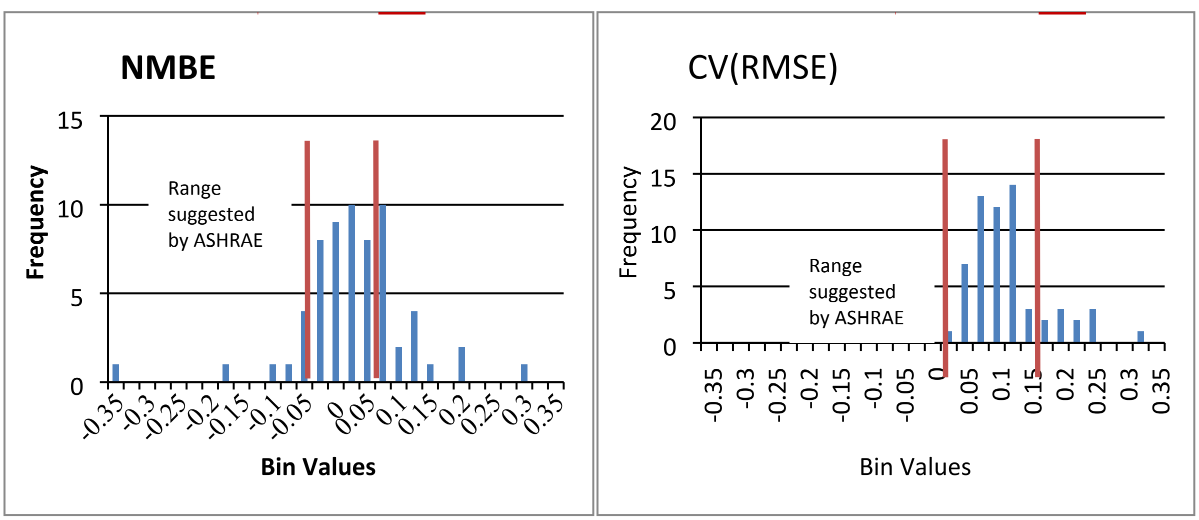

Figure 11. Distribution of NMBE and CV(RMSE) values for 69 buildings

2.3 Central Utility Building Modeling

2.3.1 Planning

A key objective in the design and implementation of IX has been the ability to assess the performance and potential improvements of the central utility building (CUB) plants on both the New Mexico and California campuses.

2.3.2 CUB Modeling Process

The IX eQUEST CUB models were developed in two phases. All of the selected buildings were modeled using eQUEST energy modeling software as described previously.

2.3.2.1 Phase One

In phase one, the team developed the individual models as though they were entirely served by dedicated building-level chilled water and hot water services. For CUB-served buildings, this meant the inclusion of "pseudo" chillers, cooling towers, boilers and pumps. Pseudo primary equipment in IX phase-one building models were dynamically sized (automatically sized by eQUEST at run time) according to simulation-determined peak load requirements. Primary equipment part-load performance was also eliminated by simulating the equipment as though each pseudo chiller or boiler always operated at an average efficiency estimated to be equal to the average efficiency for the CUB providing actual service.

2.3.2.2 Phase Two

In phase two, the team developed individual models for actual CUB buildings (i.e., from plans), including actual plant configurations, equipment capacities, equipment efficiencies and part-load performance (i.e., from manufacturer's data), pumping design pressure drops, etc. Each individual IX eQUEST building served by specific CUBs was then assembled into one CUB "meta-model," i.e., a single eQUEST model containing all elements of each CUB building and plant plus each of the buildings served by that CUB. Certain capabilities of eQUEST version 3.65 had to be expanded. For example, the number of allowable parameters, to accommodate the requirements of these larger CUB "meta-models." Table 4 and Table 5 illustrate which buildings are served by which CUB. Only chilled water loops have been connected in IX 2.5. The network between buildings becomes much more complicated if hot water loops are included.

Table 4. Sandia IX buildings served by chilled water CUBs

Bld I	Self	850/890/894	899A	858J	858N	726	823	962	C943	C907	802	836	860/864	983	981
	21	13	2	2	12	3	4	2	3	2	5	3			
C906										C906					
C905										C905					
C941									C941						
C942									C942						
C940									C940						
858N					858N										
898			898												
858EL				858EL											
802											802				
880		880													
962								962							
701					701										
890		890													
823							823								
891		891													
878		878													
894		894													
870	870				870										
858EF				858EF											
836												836			
963								963							
821							821								
895					895										
887		887													
858S					858S										
899			899												
860													860		
983														983	
880A		880A				880A									
981															981
857					857										
804											804				
6580															
800											800				
725						725									
702					702										
700					700										
859		859													
865													865		
727						727									
758		758													
755		755													
751													751		
752		752													
869							869								
825							825								
864													864		
980															980
703					703										
855		855													
886					886										
811											811				
879					879										
835												835			
877					877										

Table 5. Sandia IX buildings served by hot water CUBs

Bld I	Self	800	850/890/894	869	899A	858J	858N	726	823	981	962	C943	C907	804	6588	880	887
	59	1	0	2	2	4	1	0	3	2	0	3	2	4		3	3
C906													C906				
C905													C905				
C941												C941					
C942												C942					
C940												C940					
858N						858N											
898					898												
858EL						858EL											
802	802													802			
880																880	
962	962																
701	701																
890	890																
823									823								
891	891																
878	878																
894	894																
870	870																
858EF						858EF											
836														836			
963	963																
821									821								
895	895																
887																	887
858S						858S											
899					899												
860	860																
983																	
880A																880A	
981										981							
857	857																
804														804			
6580															6580		
800		800															
725	725						725										
702	702																
700	700																
859																859	
865	865																
727	727																
758	758																
755	755																
751	751																
752	752																
869				869													
825	825																
864	864																
980										980							
703	703																
855	855																
886																	886
811	811																
879	879																
835														835			
877																	

2.3.3 CUB Calibration

Adding to the individual building calibration task described previously, individual CUB hourly electric data (using Square D® meters) were obtained, along with hourly chilled water and hot water flow (gpm) and temperature (°F) data where available. More commonly, separate flow and temperature data were unavailable but CUB-level hourly BTU meter data were available. For natural gas consumption, only monthly consumption was generally available. For some CUBs, no hourly or monthly data were available.

2.3.3.1 Inputs

Hourly reports were defined separately for electric and gas equipment at each individual building level and at the CUB level (i.e., for CUB plant equipment).

2.3.3.2 Calibration Process

To calibrate the CUB meta-models, a combination of hourly electric metered data (e.g., for each chiller) plus additional thermal load data (flow rates and temperatures where available, otherwise BTU meters) were compared against the modeled energy usage or thermal data for the same time period. Custom weather files were developed for use in the eQUEST CUB meta-models from record weather data that aligned with the reported hourly electric and gas data. Through this comparison process, graphs were generated for each month and each unique day type (Monday through Thursday, Friday, and weekends/holidays. The team used these graphs to identify what days and times the modeled energy differed from the meter data.

Adjustments were made to the meta-models as necessary to align the modeled energy usage as close as possible to the actual usage. The primary adjustments made to the models included pressure drops and to a limited extent, primary equipment efficiencies or staging (load sequencing).

2.4 IX Building Module User Interface

The user interface is described extensively in the IX user manual [21] The IX user interface is the main tool used to create, run, and review results for scenarios. To use the interface, a license to Microsoft Excel® and Access® are required. The interface opens to a list that contains any scenarios stored in the IX database. A right click on these scenarios allows the user to choose one of six operations as seen in Figure 12.

1. New–create a new scenario
2. Edit–edit an existing scenario
3. Run–run an existing scenario
4. Results–view results for a scenario which has already been run
5. Delete–delete a scenario
6. Copy–create a new scenario which has all of the input and results of an existing scenario

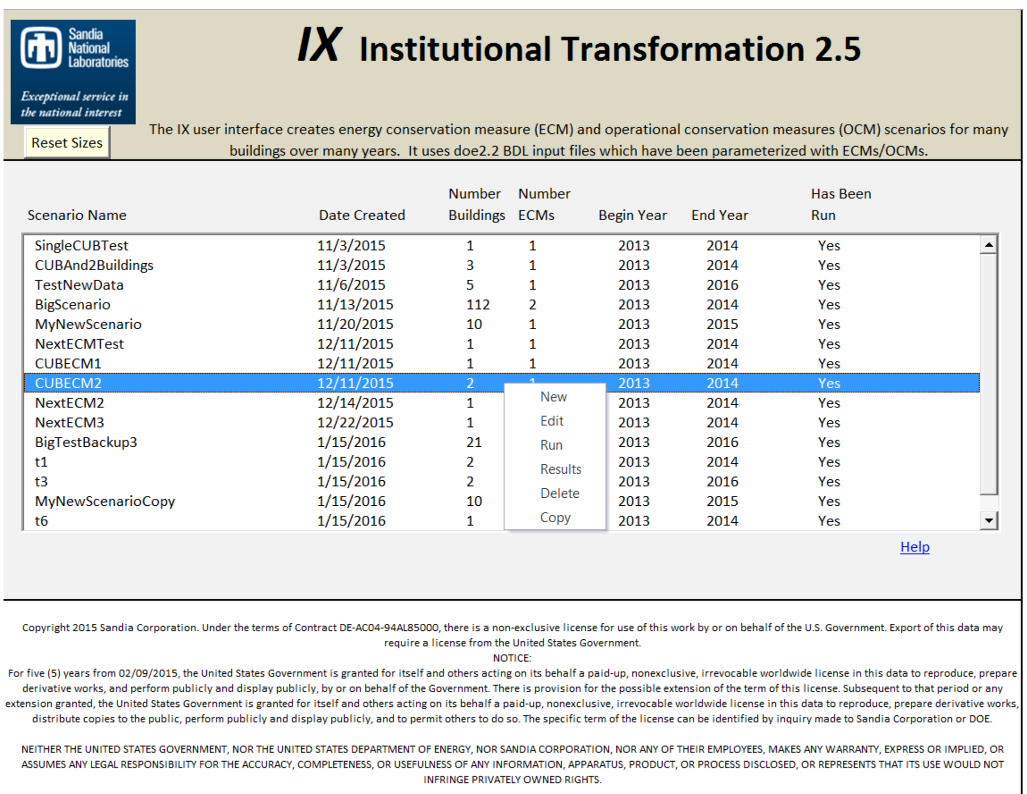

Figure 12. IX user interface scenario management screen

Once a new scenario has been created or an existing one has been selected, choosing the "edit" option takes the user to the input sheet. Please refer to Figure 13 for the following discussion on how to build up an IX scenario in the input sheet. The first step is to choose whether to add, edit, or delete an ECM. When edit or delete are selected, only ECMs that have already been added to the scenario are available. When add is selected, only ECMs that have not been added to the scenario are available. The user can then select an ECM and can move on to the years that the ECM will be simulated. Usually the begin year should be the present year but IX can be used to build up a historical record of building energy results and model results versus metered data can be compared for past years.[4] This can help the user be sure that the models being run are reasonably calibrated.[5] The end year can be set as far into the future as desired[6].

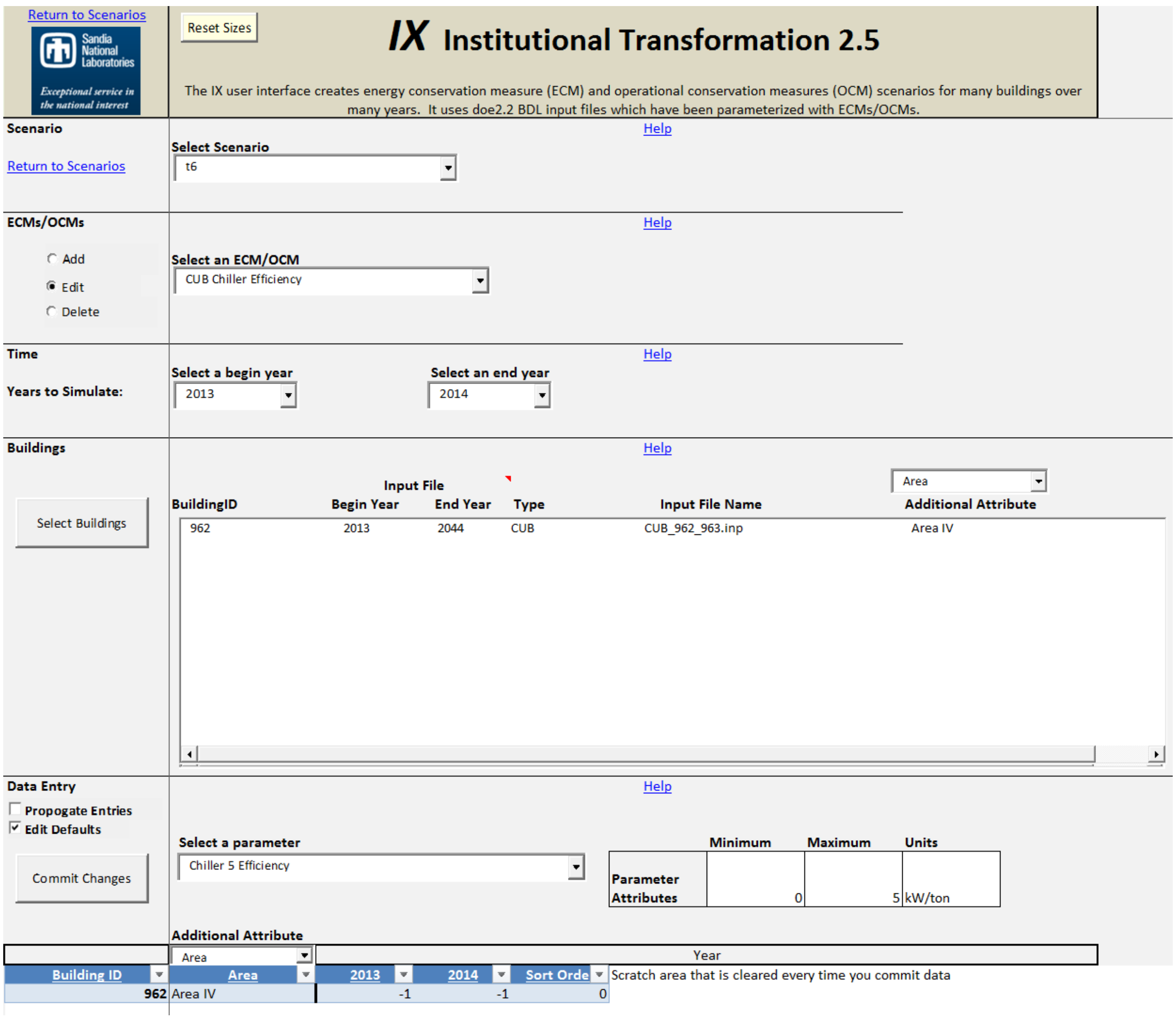

Figure 13. IX edit scenario form view 1

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[4] This requires that metered data be placed in the IX database.

[5] This comparison is not perfect unless a historical weather history has been compiled. It still is generally useful but one cannot expect a match since the historical weather and the average weather typically used are not the same.

[6] The current limit is 2044 but this is a simple adjustment in the database. There is no feedback in the IX model so time only exists to mark changes to buildings.

The next step is to select a set of buildings. This leads to a pop-up form that allows the user to select the desired set of buildings shown in Figure 14. Three list boxes are populated with all of the checked-in buildings in the database. The first, "eligible for selection," set contains any building that is selectable. The second, "selected," set consists of buildings that have already been selected. The third, "not available," set includes any building that either does not exist for any of the years selected or does not have the ECM being worked with for the years selected. This list is important because it helps users see if the building they want to select is present but not available. In addition to simple selection, the user can make the selected set into a preselected group by pressing "Add Group." This makes selection much easier if the same set of buildings is needed over and over again. The user can unselect a group from the current selection or add the group to the current selection. Any buildings that are not available are not added even if they are in a preselected group. The filters subtab is undeveloped. This feature was envisioned to enable selection by building square footage, location, building type, and other criteria.

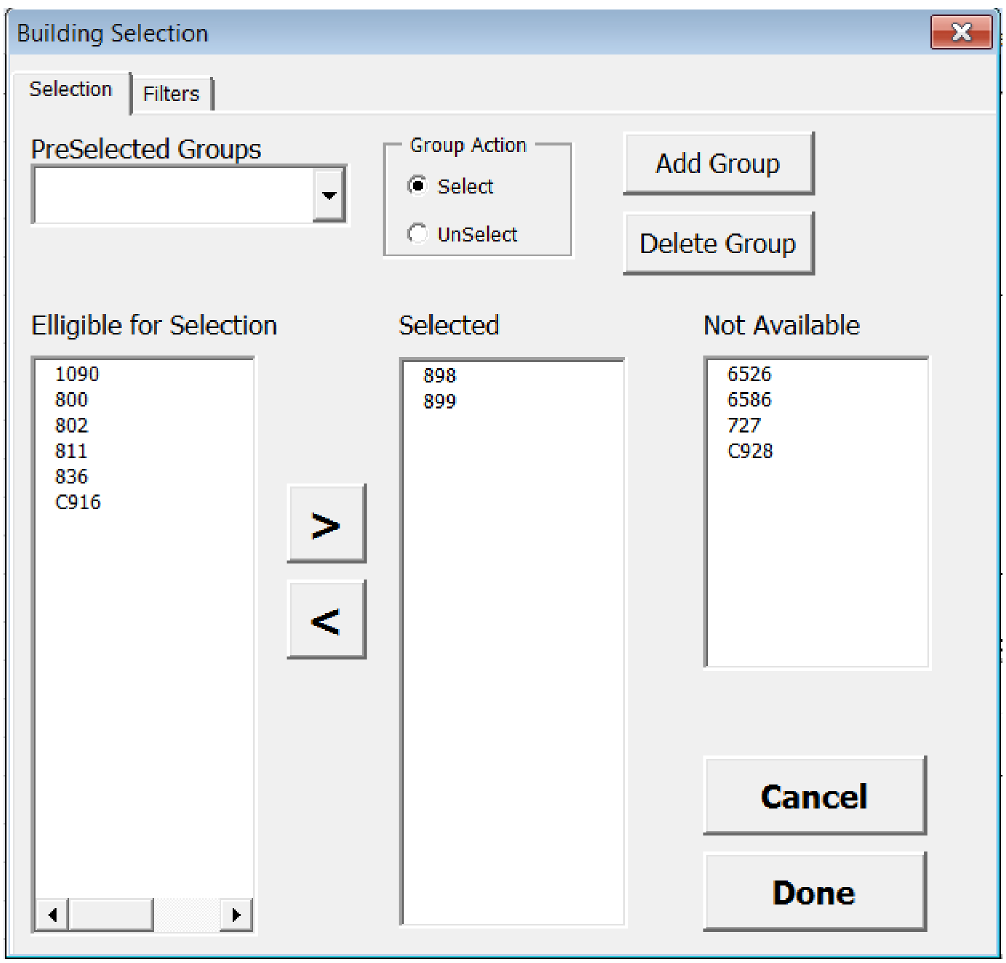


Figure 14. IX building selection form

Once the desired buildings are selected, the user can exit the dialogue by pressing "done." Any of the selections can be changed in a scenario but all data input that is unselected will be permanently lost. IX warns about this situation and prompts the user whether they want to accept the lost data. An example where Buildings 898 and 899 have been unselected is shown in Figure 15. The user may prefer to copy the scenario and then work forward from there.

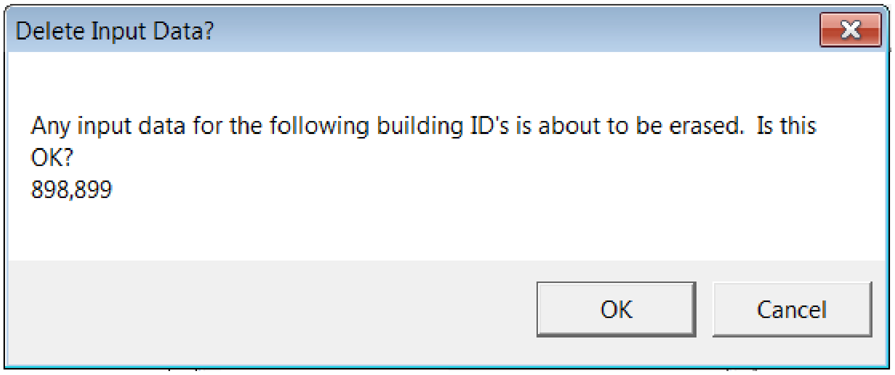


Figure 15. IX data loss warning message box

Scrolling down beyond building selection leads to the data input table as seen in Figure 16. This table only accepts values between the minimum and maximum indicated in "parameter attributes." It highlights in red any changes that have been made and allows the user to select a subset of the buildings without unselecting the buildings from the scenario. The "Additional Attribute" combo box enables displaying attributes such as the building square footage next to the data input.

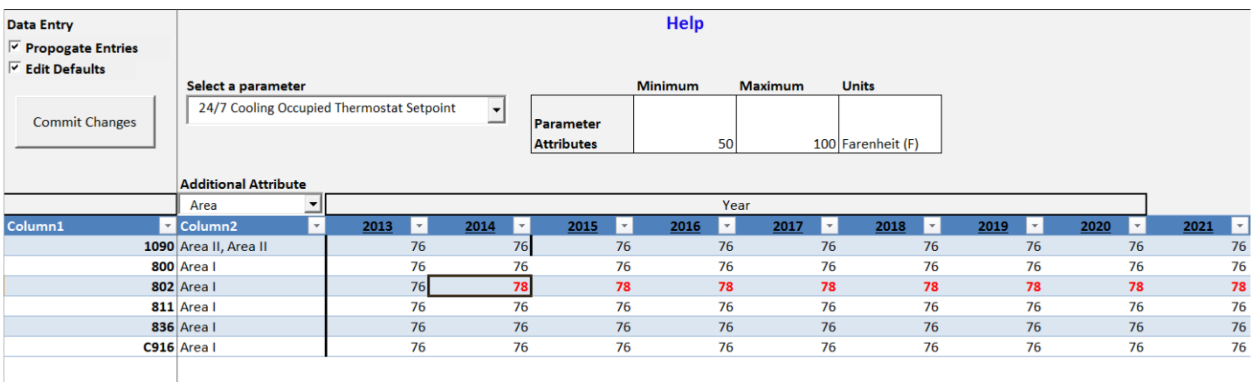


Figure 16. IX Data input table

The "select a parameter" combo box contains a list of all of the parameters used by the currently selected ECM. The user must understand the ECMs described in the IX user documentation [21]. The list of parameters contains a list of all of the user input parameters but also contains all of the eQUEST Parameters (see section 2.1.2) calculated from the user input parameters. eQUEST Parameters are at the end of the list and are followed by the text "(read only)" since they cannot be altered by the user. Viewing these parameters can be helpful to see if changing the user input parameters has led to the expected changes in eQUEST parameters. Once data entry for each user input parameter is complete, the user must press "commit changes" to send the data to the scenario's tables in the database. If a new selection is made without pressing "commit changes," IX will warn the user and allow the option of confirming or canceling the change.

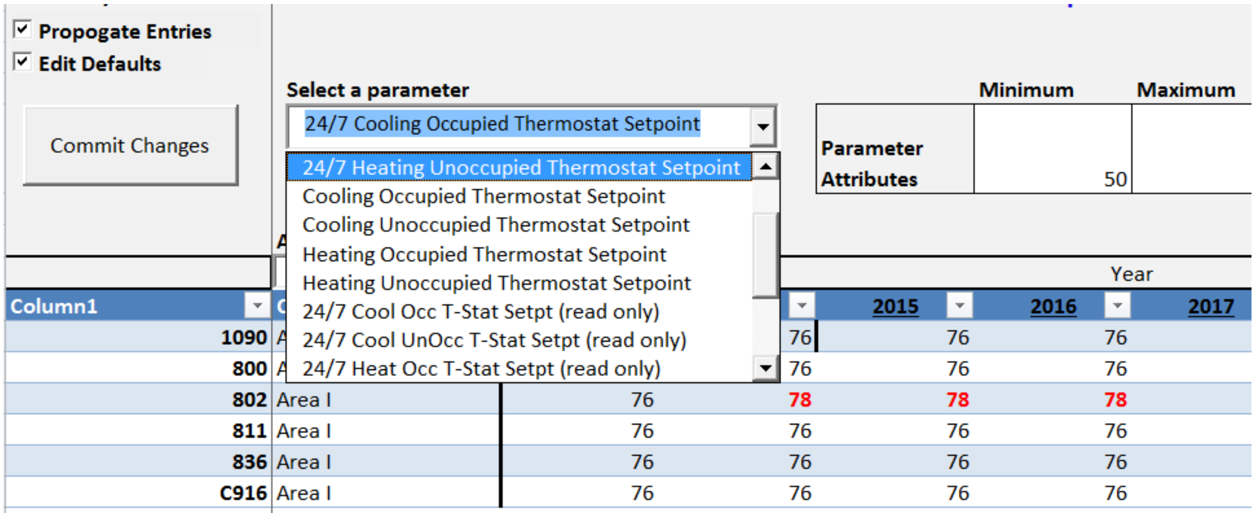


Figure 17. Parameter selection

When a user has finished making inputs to a scenario, they can proceed back to the scenario management form (Figure 12) and select "run." This leads to the form seen in Figure 18.

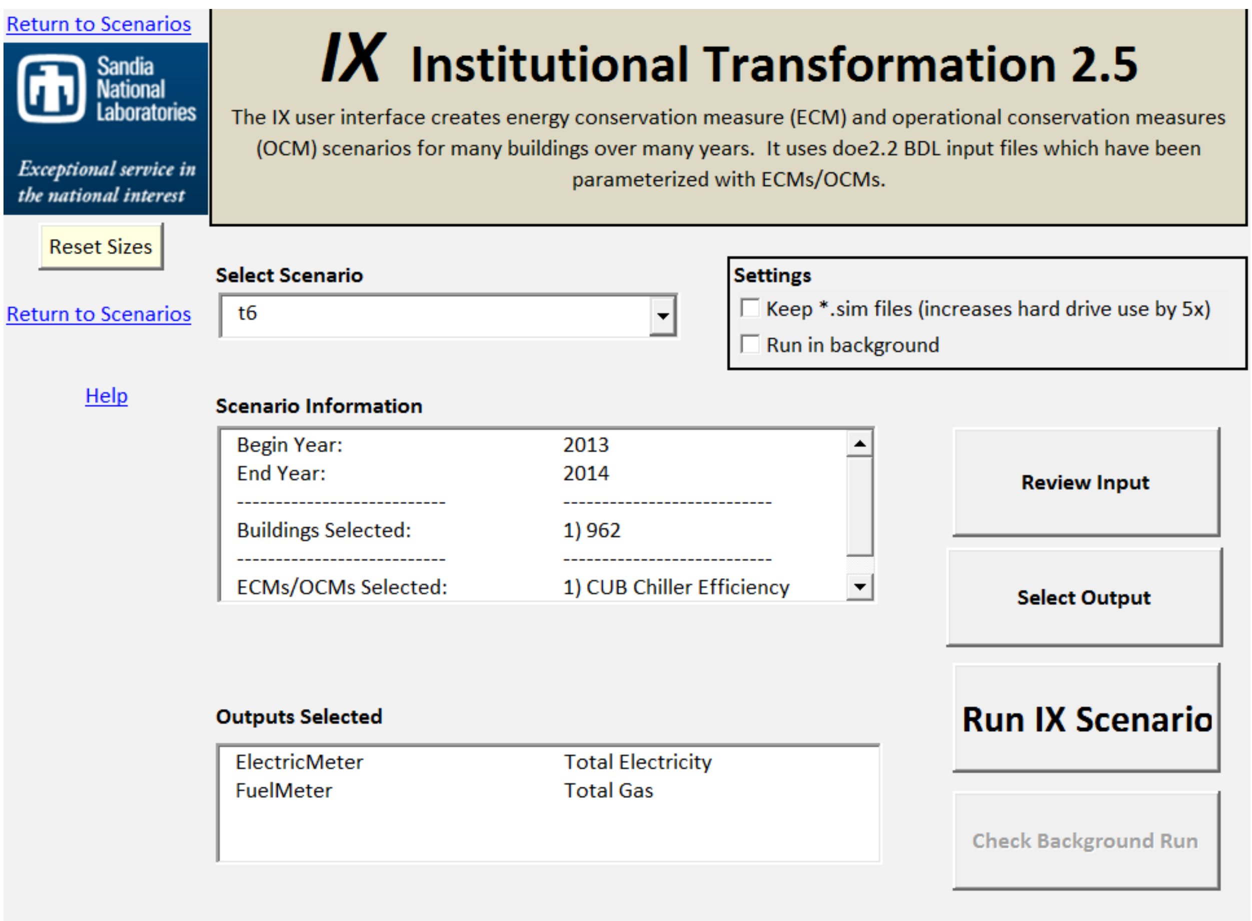


Figure 18. IX run scenario form

This form provides basic information about the scenario, allows selection of any scenario in the database, enables detailed review of input through a pivot table, lets the user select outputs, and initiates runs for the selected scenario. The user can press “review input” to navigate to a worksheet containing a pivot table with all of the changes made to the database from the default case as seen in Figure 19. Pivot tables can be used to drill down to specific information or to view large amounts of data in differing orders. This allows a much quicker review of complicated inputs than looking at the data in the input form.

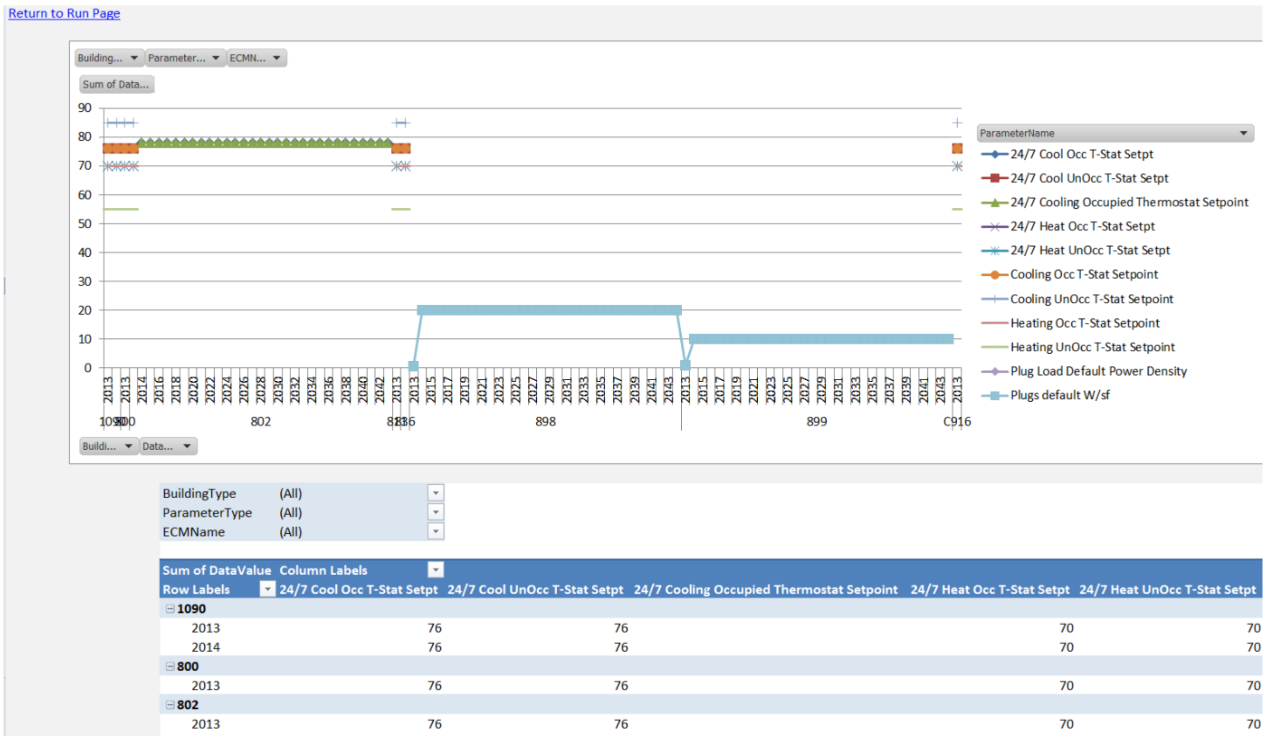


Figure 19. Review input worksheet

After reviewing input, the user can select outputs if desired. The default case is to only retain total electricity and gas but other end uses can be selected as seen in Figure 20.

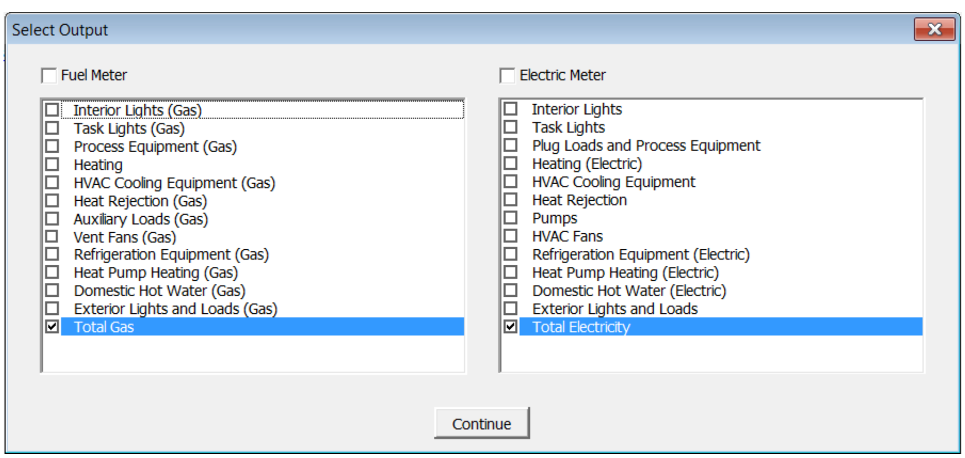


Figure 20. IX output selection form

Finally, the user can run the scenario. There are two check boxes that allow altering the run’s settings. The first enables the user to retain detailed DOE-2 files in the “./IXData/Results/”

directory. This is mostly for troubleshooting or for advanced applications such as custom scripts that process hourly data similar to IX. The second is to run DOE-2 in the background. This feature uses as many processors as are available to initiate multiple DOE-2 runs at a time. This leads to a considerably faster run time. The background run can be checked by clicking “check background run” as seen in Figure 18. When the run is finished, this button will also initiate the post processing needed on the DOE-2 run results. Once “run IX scenario” is pushed, a progress meter pops-up that informs the user what is happening and allows cancelation of the run as seen in Figure 21.

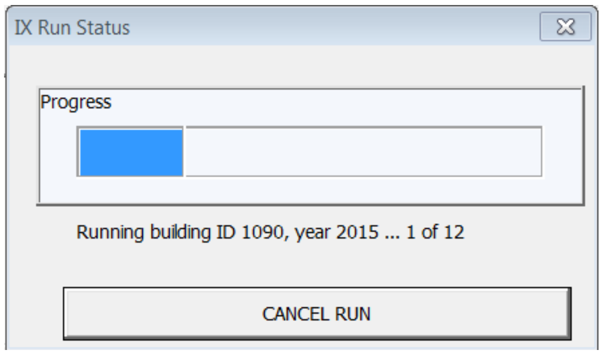
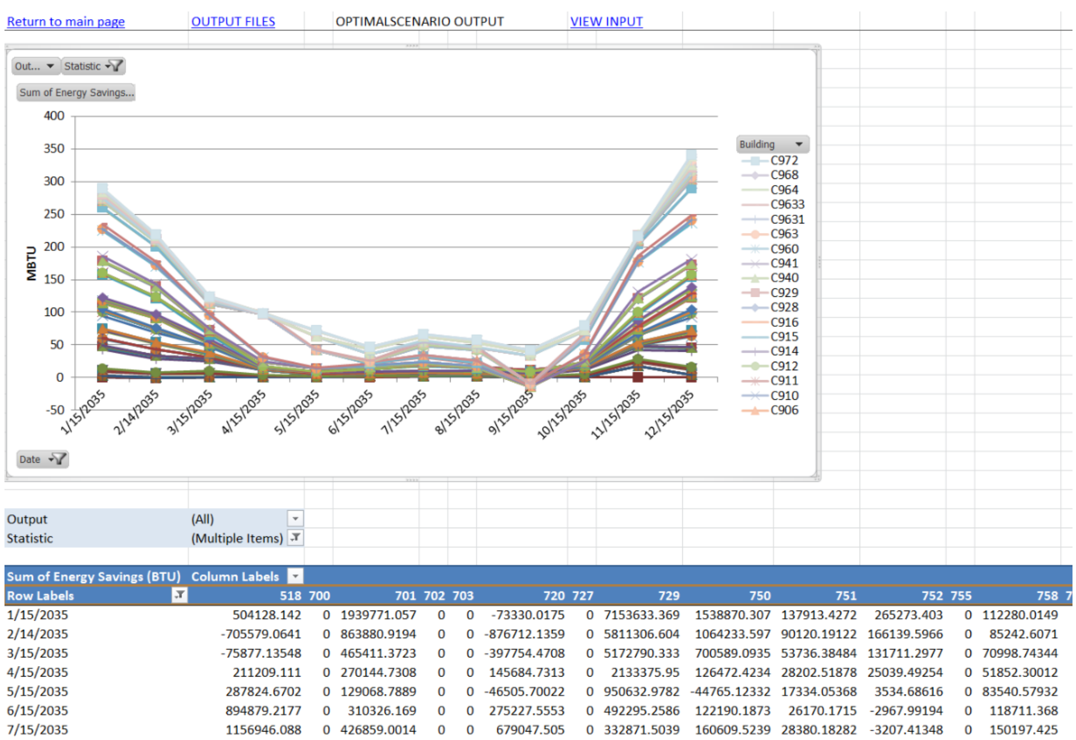


Figure 21. IX progress meter form

Upon completion of the run, the user can return to scenario management (Figure 12) and select “results.” This leads to a pivot table which contains all of the simulation results with a monthly time step as seen in Figure 22. The simulation was performed at an hourly rate but IX aggregates to monthly data to reduce the amount of data storage required while still capturing seasonal effects. The pivot table data can be copied to another workbook for further processing.



Output	(All)
Statistic	(Multiple Items)

Sum of Energy Savings (BTU)	Column Labels													
Row Labels	518	700	701	702	703	720	727	729	750	751	752	755	758	7
1/15/2035	504128.142	0	1939771.057	0	0	-73330.0175	0	7153633.369	1538870.307	137913.4272	265273.403	0	112280.0149	
2/14/2035	-705579.0641	0	863880.9194	0	0	-876712.1359	0	5811306.604	1064233.597	90120.19122	166139.5966	0	85242.6071	
3/15/2035	-75877.13548	0	465411.3723	0	0	-397754.4708	0	5172790.333	700589.0935	53736.38484	131711.2977	0	70998.74344	
4/15/2035	211209.111	0	270144.7308	0	0	145684.7313	0	2133375.95	126472.4234	28202.51878	25039.49254	0	51852.30012	
5/15/2035	287824.6702	0	129068.7889	0	0	-46505.70022	0	950632.9782	-44765.12332	17334.05368	3534.68616	0	83540.57932	
6/15/2035	894879.2177	0	310326.169	0	0	275227.5553	0	492295.2586	122190.1873	26170.1715	-2967.99194	0	118711.368	
7/15/2035	1156946.088	0	426859.0014	0	0	679047.505	0	332871.5039	160609.5239	28380.18282	-3207.41348	0	150197.425	

Figure 22. IX results worksheet

The IX user interface's features have been introduced in this section. It must be emphasized that IX is an engineering tool that requires expert knowledge of the data model involved. Once mastered, IX provides the capacity to effectively track site-wide data that is orders of magnitude larger than its complementary tool eQUEST. A more detailed description of how to use the IX user interface is present in the IX user manual [21].

2.5 IX Building Module Database

The IX database stores all of the information required to run the user interface. It has over seventy tables containing hundreds of attributes and relationships between tables. The database is a relational database and has one-to-one, one-to-many, and many-to-many relationships as seen in Figure 23. For example, there is a many-to-many relationship between building files (models) and buildings as seen in Figure 24. A building can be represented by many building files that allow the building to have different models over time. On the other hand, a single CUB building file can contain many buildings. Defining these relationships makes it much easier to manage the data by propagating actions across the database. For example, when a scenario is deleted from the scenario table, it automatically deletes data from many other tables which have a one-to-many relationship with the scenario table as seen in Figure 25.

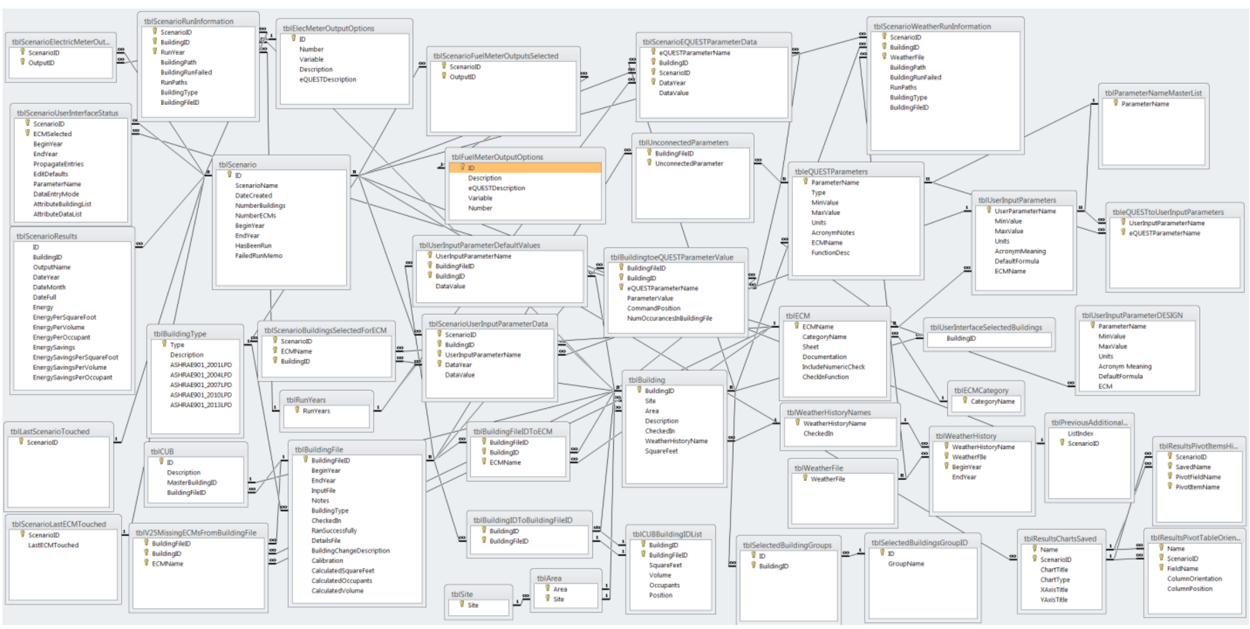


Figure 23. Relationships between tables in the IX building module database

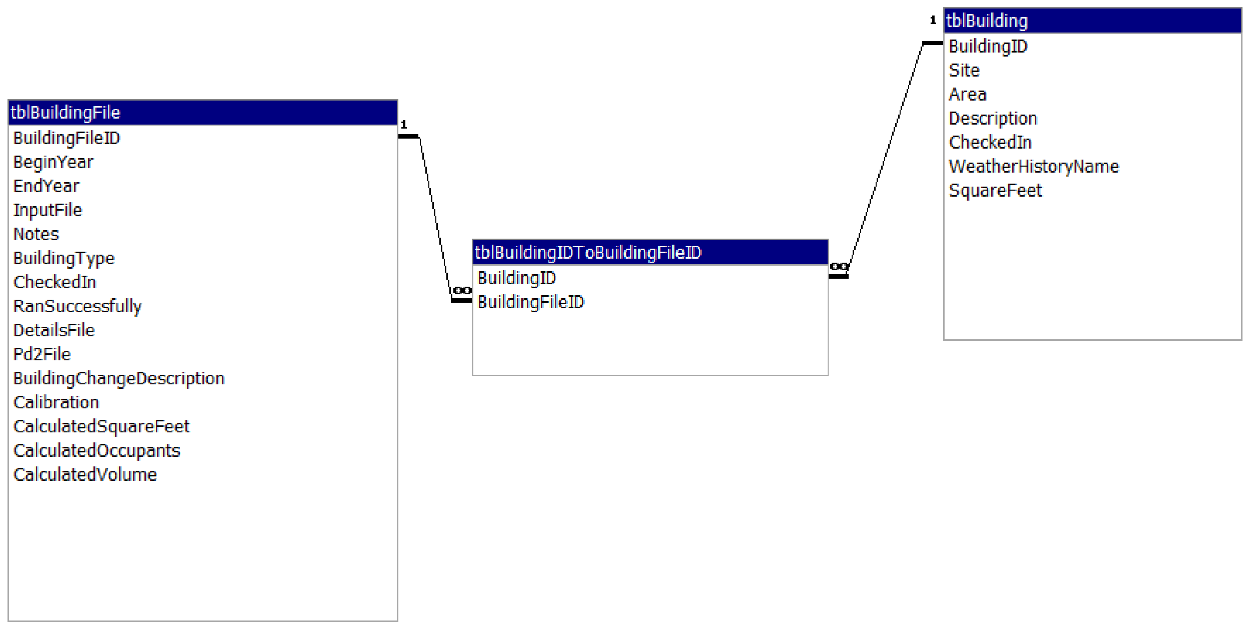


Figure 24. A many-to-many relationship between building files (models) and buildings

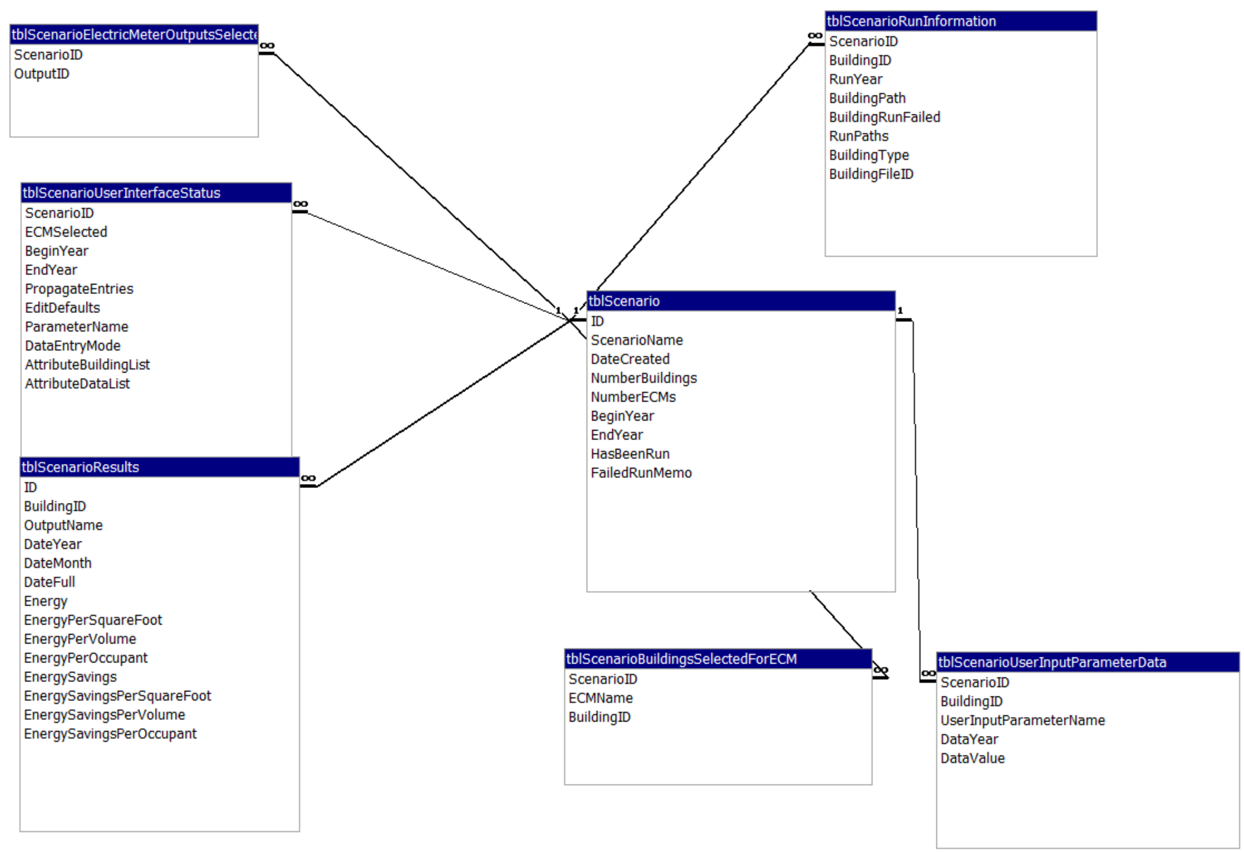


Figure 25. Deleting a scenario automatically propagates deletion to many other tables

2.5.1 *The IX Database Application*

The IX database application is a user interface which enables configuration of buildings, weather, and ECMs. A new instance of the database would require that the user populate the database with buildings, ECMs, ECM parameters, weather files, weather histories and time dependent building data. The choices are presented in the main menu as seen in Figure 26. The database user interface is also described more extensively in the IX user manual [21].

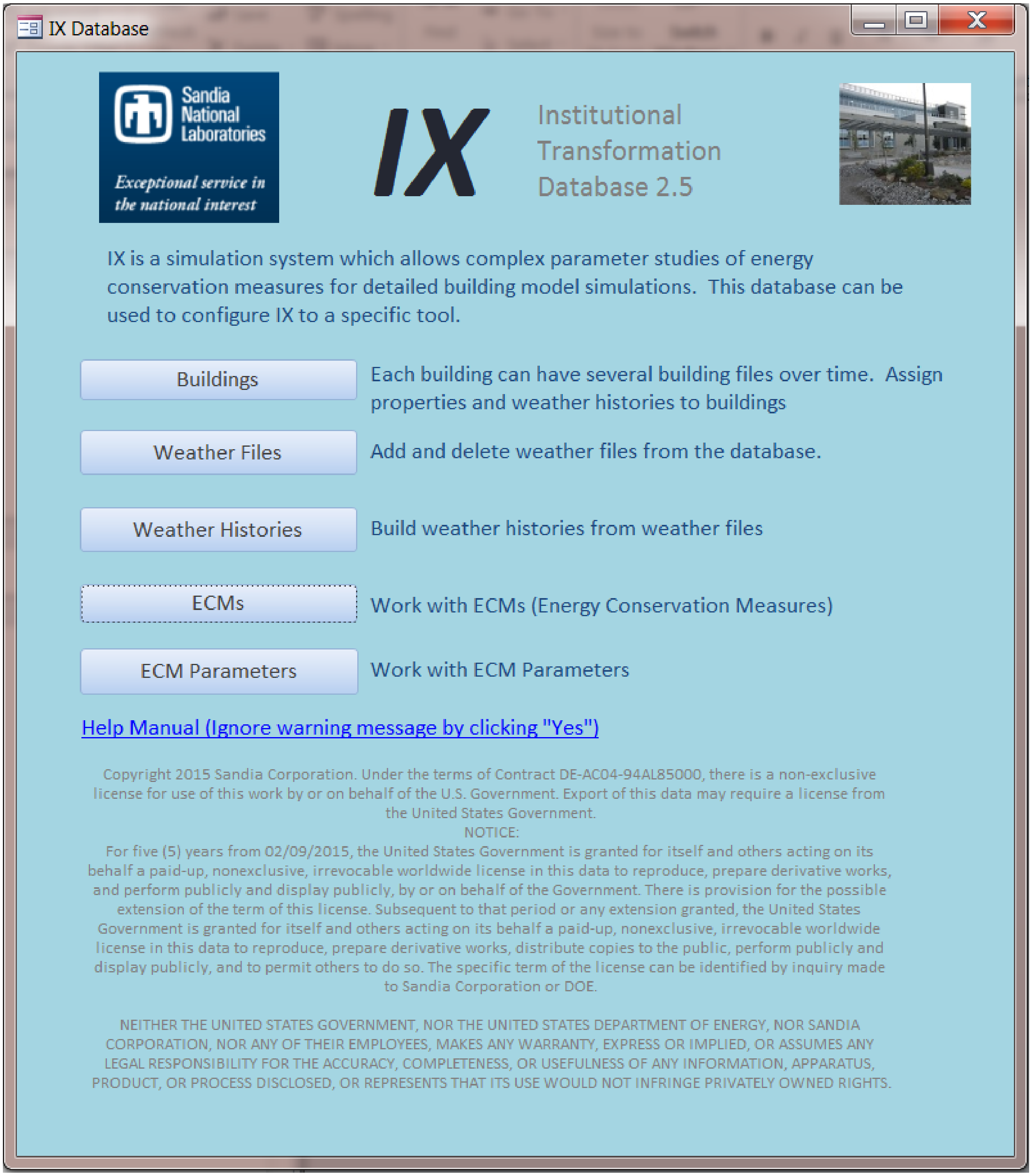


Figure 26. Database Main Menu.

Selecting “Buildings” opens up a form that allows the user to edit and create new buildings as seen in Figure 27. Each building is either checked in (indicated by large red letters to the upper right hand) or checked out. For a building to be checked in, all of the building files associated with it must also be checked in and the weather history associated with the building must cover all of the years covered by the building input files. Double clicking on the building file list box opens up the building file form as seen in Figure 28. Building files are also checked in and out. A building file can only be checked out if all of the buildings associated with it are also checked out. Figure 28 shows the input sheet for building file configuration management. A building file cannot be checked in until it is associated with a building, runs successfully in DOE-2 for all of the weather files used on the building file, has a consistent time history with no overlap to other building files assigned to the same building, and has at least one ECM contained by the database. If all of these criteria are met, the building is checked in and data is written to all of the tables that contain information pertaining to ECMs and parameters in the building file.

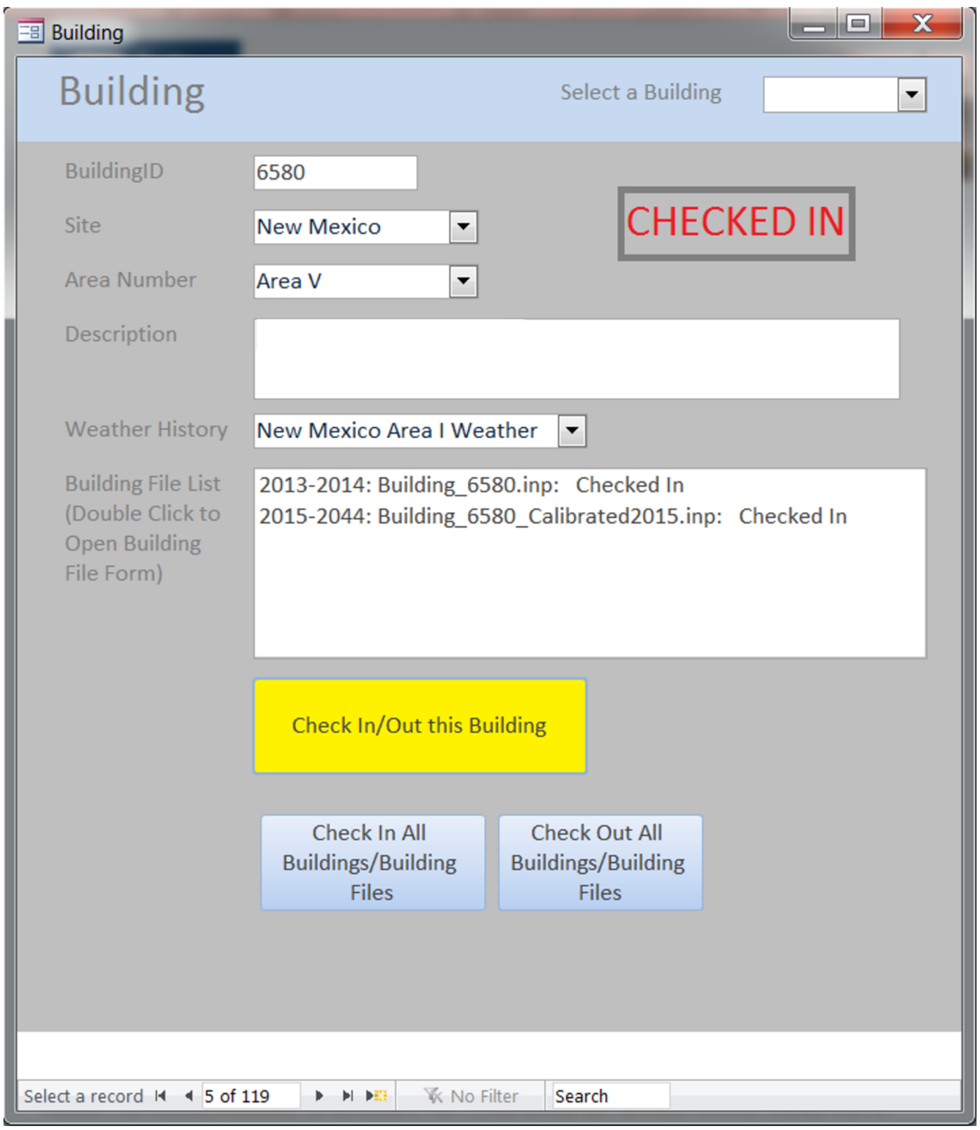


Figure 27. Maintaining building information.

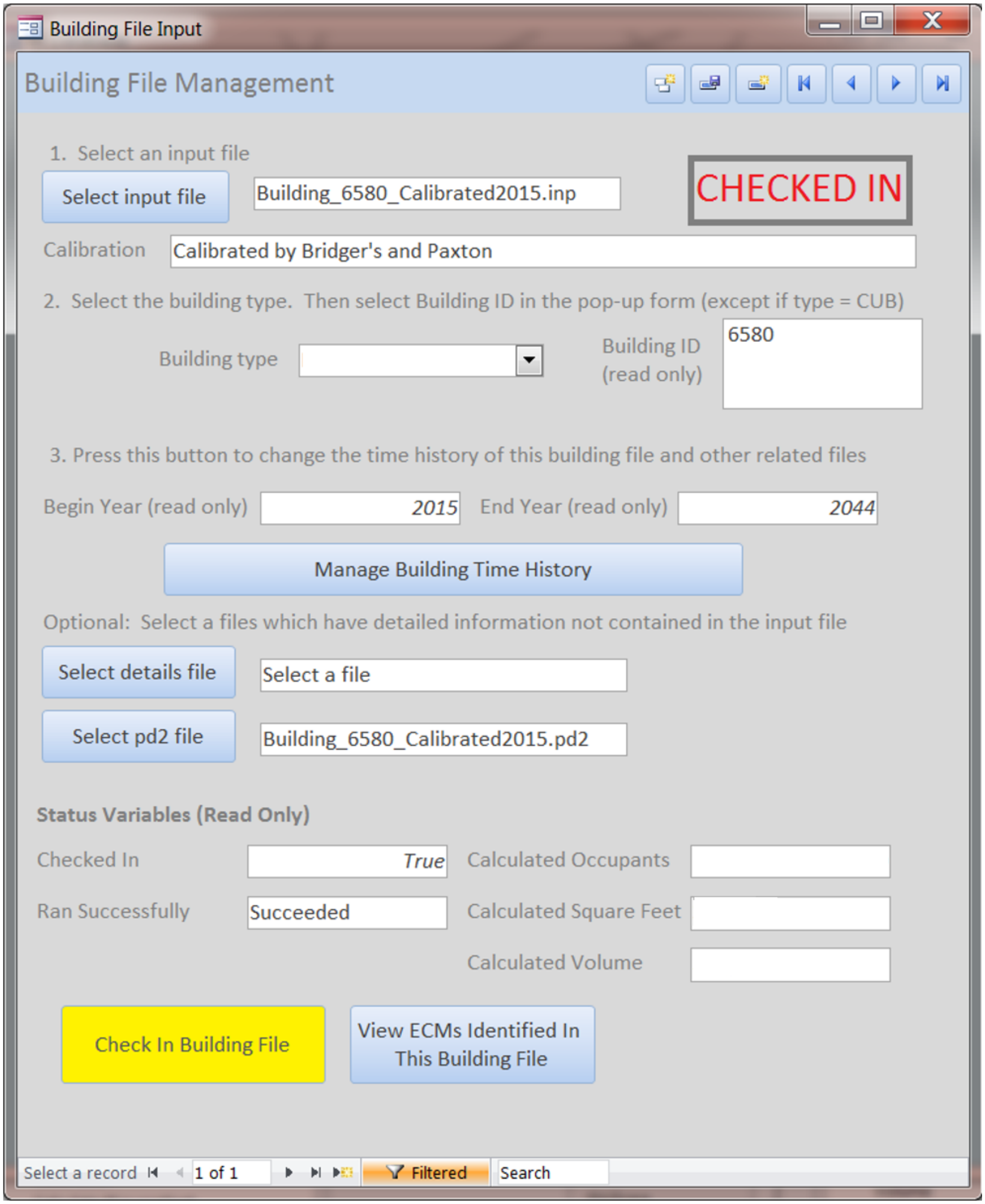


Figure 28. Building file form

Figure 29 shows the form used to create and edit ECMs that is opened by pressing "ECMs" as seen in Figure 26. This is a very simple dialogue that provides the ability to create an empty ECM. Figure 30 shows the association of ECM parameters to a specific ECM, which is opened by pressing "ECM Parameters" as seen in Figure 26. The set of eQUEST parameters is on the left hand side (grey and blue) while the user input parameters (yellow) are on the right hand side. The sets of parameters are described more fully in section 2.1.2.

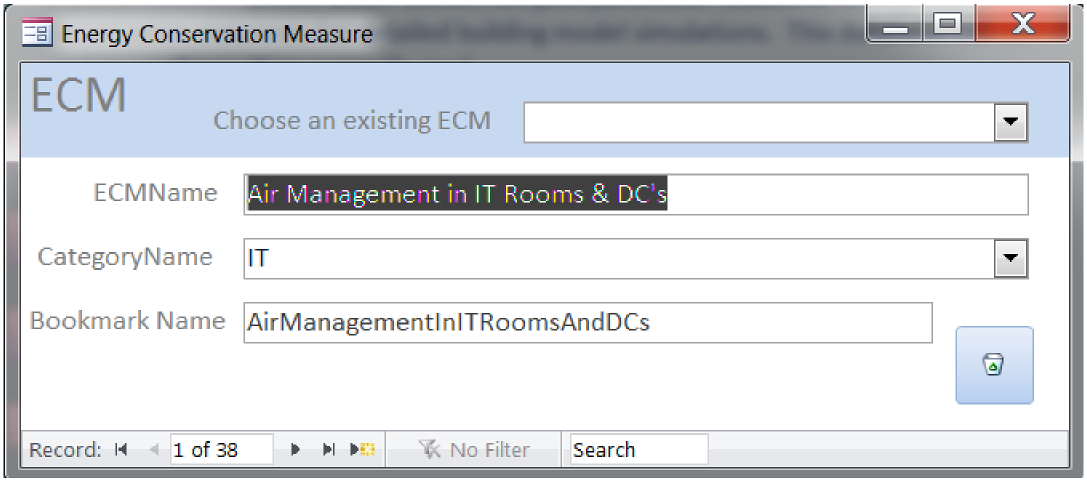


Figure 29. ECM Form

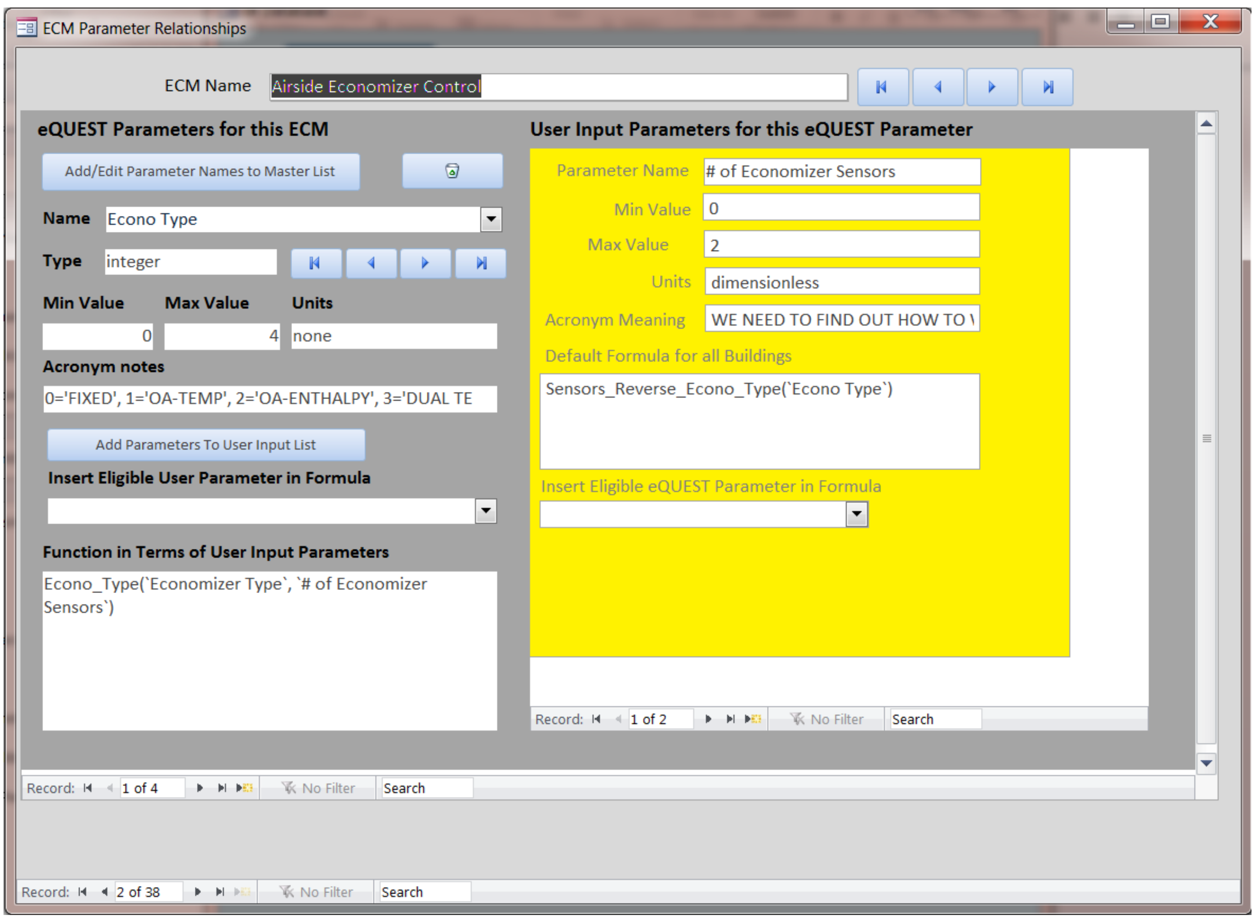


Figure 30. Managing the parameters that describe an ECM

Pressing the "Weather Files" button opens a form that allows weather files to be added to the database. Finally, pressing the "Weather Histories" button opens up a dialogue for creating weather histories from the weather files in the database as seen in Figure 31.

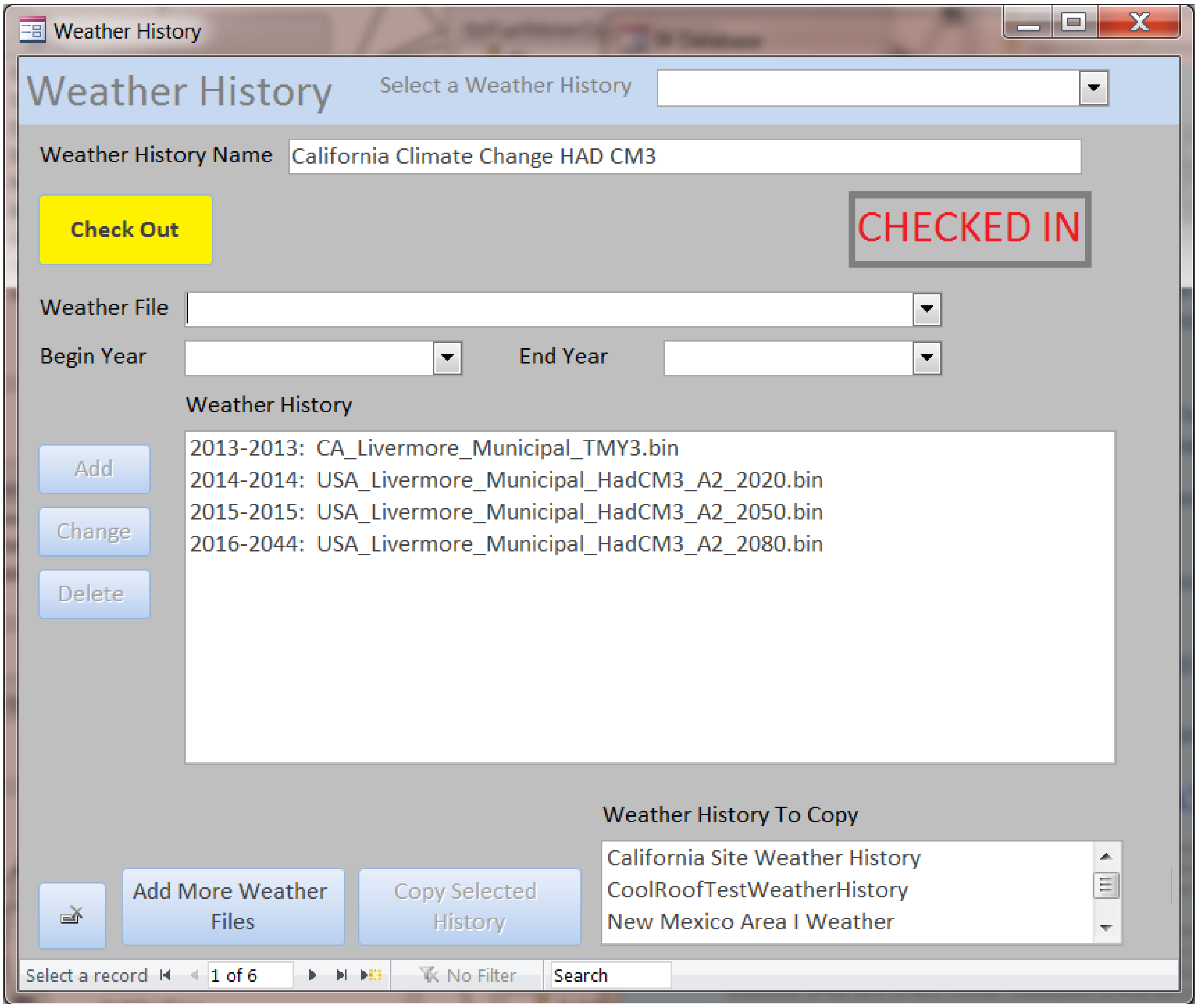


Figure 31. Weather histories form

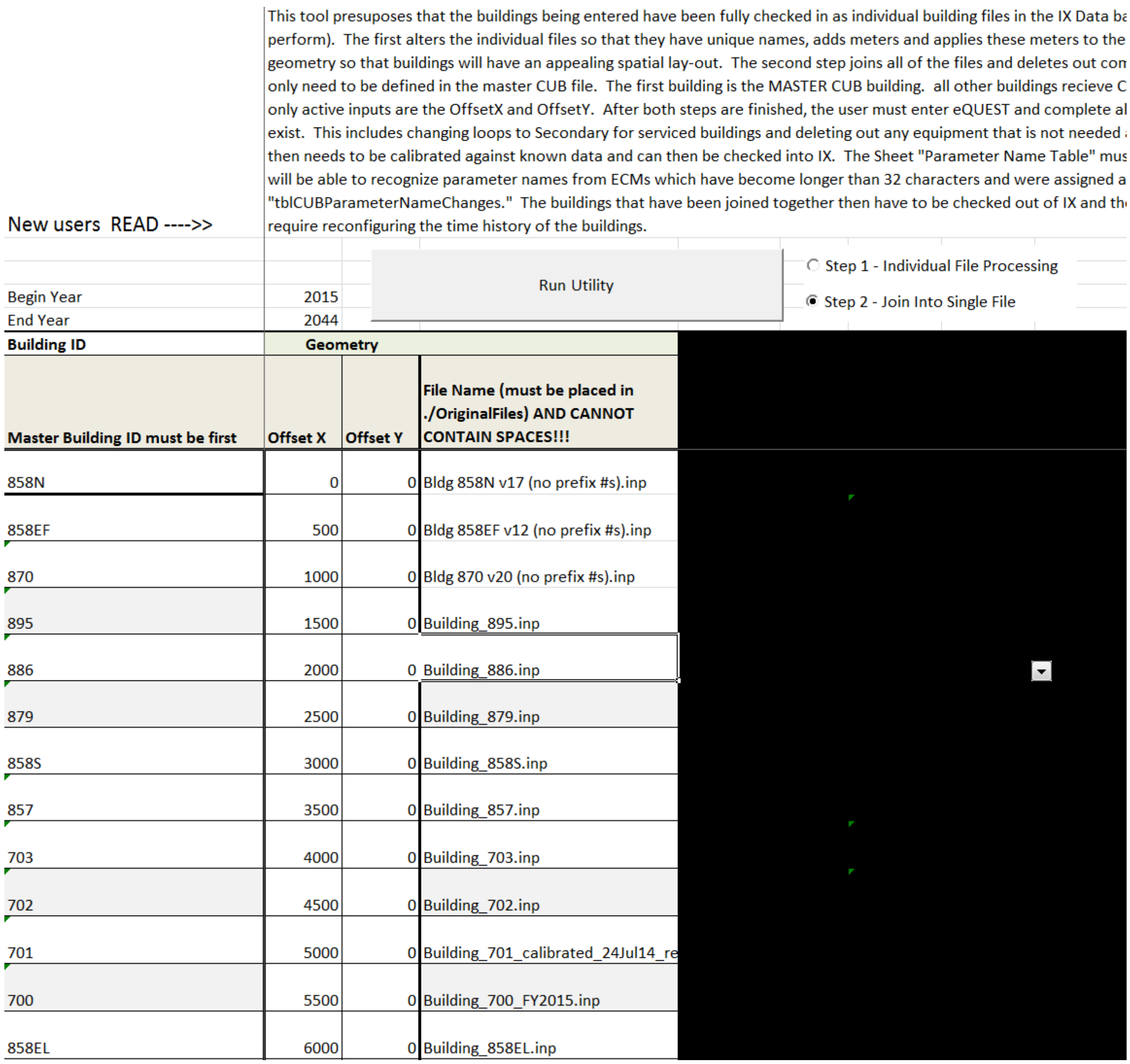
2.5.2 Operations Outside Interfaces

Measured energy use data and parameter names that exceed 32 characters in CUBs still require manually copying the data into the database to keep it current. For measured data, there is a utility in "./IXData/MonthlyElectricityAndGasUse" that can be used to arrange Sandia's format of monthly electricity and gas data. This utility requires a number of manual inputs and will not work on other data formats. The data has to be manually added to the "tblBuildingMonthlyEnergyMeasuredData" table in the database.

When CUB files are created using the CUB utility, every parameter is prefixed with the building ID and an underscore. If the new name exceeds 32 characters, it becomes illegal in DOE-2. A mapping using an integer naming convention has to be used to overcome this difficulty. IX reconstructs the names on the fly at runtime and then looks for the new name in "tblCUBNameChanges." Whenever a new CUB is being added, the IX user has to take the results output in the CUB utility (contained in the "Parameter Name Table" sheet) and place it in this table after deleting any old entries.

2.6 IX Building Module CUB Utility

A third interface located in "./IXData/CUB-BuildUtility/IXCUB-BuildUtility.xlsm" handles the joining of many building files into a single CUB file. This utility requires the user to place the set of building files to be joined in the file "./IXData/CUB-BuildUtility/OriginalFiles." The user then has to input the building ID, Offset X, Offset Y, and File Name as seen in Figure 32 where the first entry must be the building file that contains the CUB primary chilled water loops and chillers.



New users READ ---->>

This tool presuposes that the buildings being entered have been fully checked in as individual building files in the IX Data ba
perform). The first alters the individual files so that they have unique names, adds meters and applies these meters to the
geometry so that buildings will have an appealing spatial lay-out. The second step joins all of the files and deletes out con
only need to be defined in the master CUB file. The first building is the MASTER CUB building. all other buildings recieve C
only active inputs are the OffsetX and OffsetY. After both steps are finished, the user must enter eQUEST and complete al
exist. This includes changing loops to Secondary for serviced buildings and deleting out any equipment that is not needed
then needs to be calibrated against known data and can then be checked into IX. The Sheet "Parameter Name Table" mus
will be able to recognize parameter names from ECMs which have become longer than 32 characters and were assigned a
"tblCUBParameterNameChanges." The buildings that have been joined together then have to be checked out of IX and th
require reconfiguring the time history of the buildings.

Run Utility

Step 1 - Individual File Processing

Step 2 - Join Into Single File

Begin Year 2015

End Year 2044

Building ID	Geometry		
Master Building ID must be first	Offset X	Offset Y	File Name (must be placed in ./OriginalFiles) AND CANNOT CONTAIN SPACES!!!
858N	0	0	Bldg 858N v17 (no prefix #s).inp
858EF	500	0	Bldg 858EF v12 (no prefix #s).inp
870	1000	0	Bldg 870 v20 (no prefix #s).inp
895	1500	0	Building_895.inp
886	2000	0	Building_886.inp
879	2500	0	Building_879.inp
858S	3000	0	Building_858S.inp
857	3500	0	Building_857.inp
703	4000	0	Building_703.inp
702	4500	0	Building_702.inp
701	5000	0	Building_701_calibrated_24Jul14_re
700	5500	0	Building_700_FY2015.inp
858EL	6000	0	Building_858EL.inp

Figure 32. CUB build utility input sheet

The user also must enter the begin and end year located above the main list for the CUB being formed. Once everything has been entered, the user should select step 1 and press "Run Utility." A progress bar will indicate the steps being completed. Once this first process is finished, the user should select step 2 and press "Run Utility" again. The end product is a file named "CUB_<building ID1>_<building ID2>_..._NeedsEQUESTNext" where all of the building IDs are in the name. As the name indicates, there is a process that has to be followed manually in eQUEST to complete and clean up the CUB. This process is specified in the IX user manual [21].

2.7 Example Scenarios

Any number of scenarios can be developed in the IX building module but four scenarios are presented here to illustrate some specific cases. All three of these cases look at an entire site and were quick to develop because they applied simultaneous changes to all buildings. The user should remember that the same scenarios could be run with customized input for individual buildings. IX's use cases include the incremental improvement of scenarios as more data is acquired at the individual building level.

2.7.1 Climate Scenario

The IX building module was used to create a scenario that projects energy use for SNL as a function of climate change. This is an important capability providing specific results for SNL in contrast to generalized results for geographic regions [10,11]. Results were derived from the HADCM3 global circulation model [7,8,9], which used the intergovernmental panel on climate change (IPCC) A2 scenario. The A2 scenario is characterized by slow demographic, economic, and energy transitions [13].

Creation of the weather files was accomplished through a tool called "CCWorldWeatherGen" developed at University of Southampton [6,12]. Using this tool, HADCM3 results were combined with local Typical Meteorological Year Revision 3 (TMY3) weather files for the Livermore municipal airport and the New Mexico Sun Port Airport to create climate change files for 2020, 2050, and 2080. IX's weather history capability was then used to create a weather history for California and New Mexico. One hundred twelve buildings were included in the scenario.

TMY3 weather files have hourly data for wet bulb temperature, dry bulb temperature, pressure, snow flag, precipitation flag, cloud amount, wind direction, humidity ratio, density of air, specific enthalpy, total horizontal solar radiation, direct normal solar radiation, cloud type, and wind speed. The snow and precipitation flags were found to be zero for all of the files including the original TMY3 files. The cloud amount variable was found to be zero for the adjusted climate files but non-zero for the original file. The original cloud amounts were therefore applied to the climate files. The wind direction also did not change with climate.

The temperature rise is large for climate scenarios with a summer time dry bulb increase from 2015 to 2080 of 9.7 ^{o}F and 11.9 ^{o}F in Albuquerque and California as seen in Figure 33 and Figure 34. The wind speed and humidity ratio for Albuquerque and California are shown in Figure 35 and Figure 36.

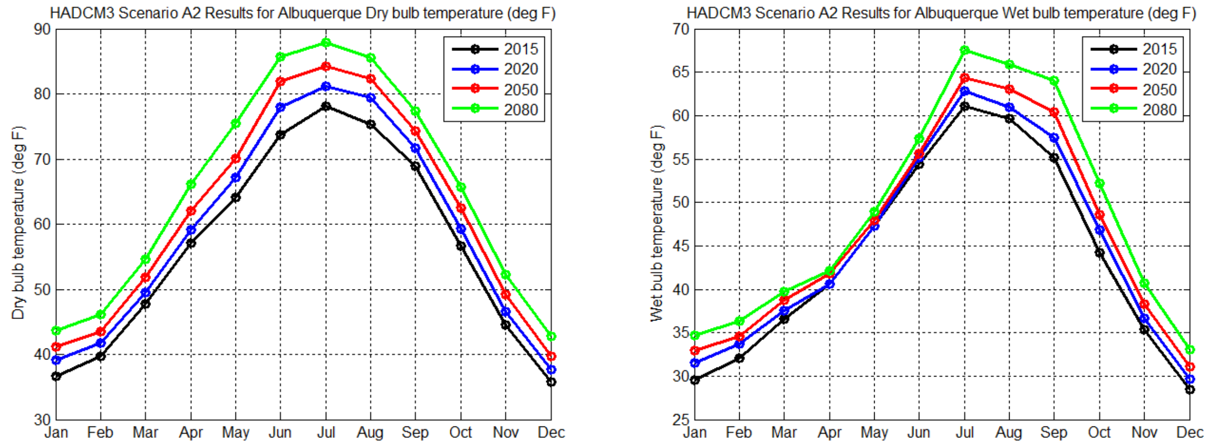


Figure 33. Climate scenario monthly average dry and wet bulb temperatures for Albuquerque

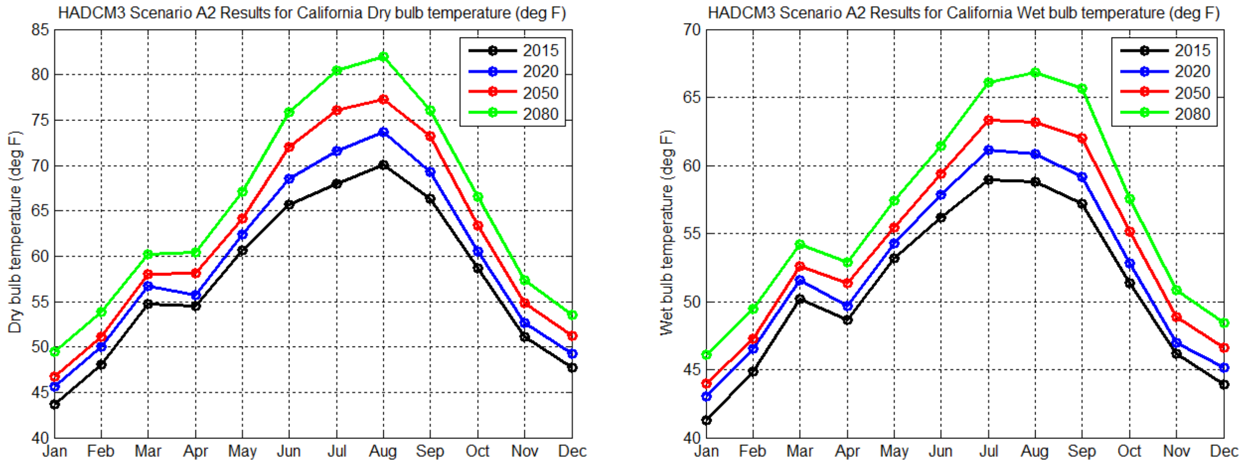


Figure 34. Climate scenario monthly average dry and wet bulb temperature for California

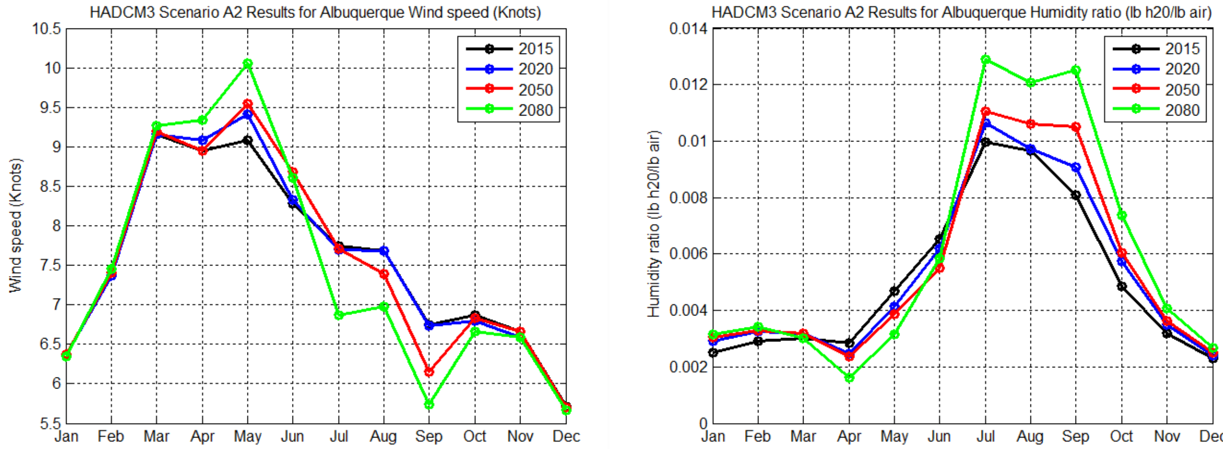


Figure 35. Climate scenario monthly average wind speed and humidity ratio for Albuquerque

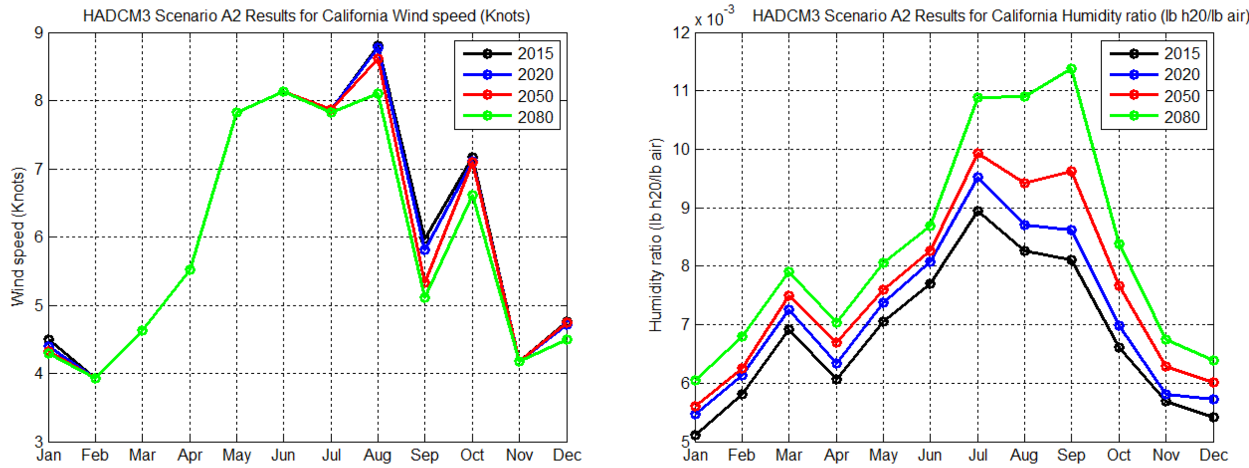


Figure 36. Climate scenario monthly average wind speed and humidity ratio for California

The results shown in Table 6, Figure 37, and Figure 38 indicate that by 2080 SNL is projected to have net energy savings with reduced natural gas use by nearly 19.7% but increased electricity use by 5.0%.[7] The site-wide reduction in energy use is projected to be 3.4% in 2080. It is obvious that the site will evolve in many ways that are unpredictable for projections so far into the future. These numbers therefore only serve as a guide to the direction climate change will give SNL's energy consumption in the coming years. The results provide individual projections for buildings that can be helpful as seen for building 700 in Figure 39.

Table 6. Energy change as a function of climate for SNL

	Energy (1e9xBTU)			Energy Savings (1e9xBTU)			% Savings		
Year	Total Electricity	Total Gas	Total	Total Electricity	Total Gas	Total	% Total Electricity	% Total Gas	% Total
2015	824.7	422.1	1246.7	0.0	0.0	0.0	0.0	0.0	0.0
2020	833.9	390.4	1224.3	-9.2	31.7	22.5	-1.1	7.5	1.8
2050	845.7	365.7	1211.4	-21.0	56.4	35.4	-2.6	13.4	2.8
2080	865.7	339.0	1204.7	-41.0	83.1	42.1	-5.0	19.7	3.4

[7] This result is contingent on the accuracy of modeling for natural gas, which has not been able to be calibrated because SNL's gas data is suspected to be unreliable.

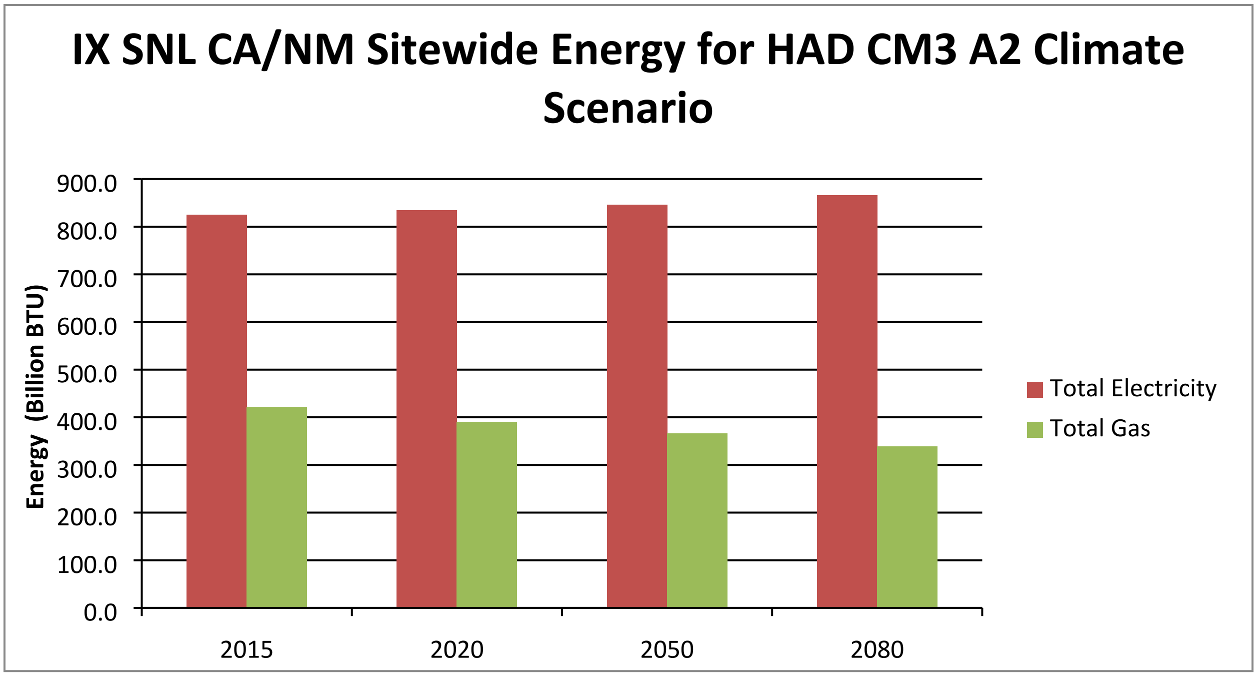


Figure 37. Site wide energy as a function of climate for SNL

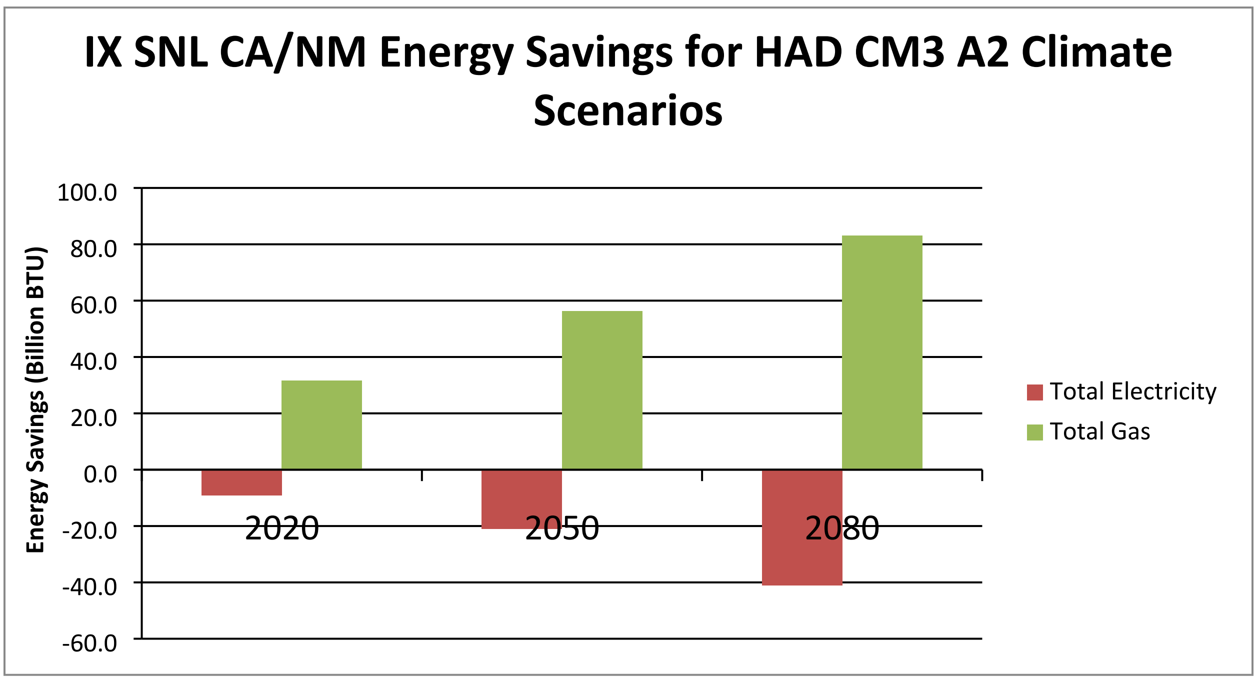


Figure 38. Energy savings as a function of climate for SNL

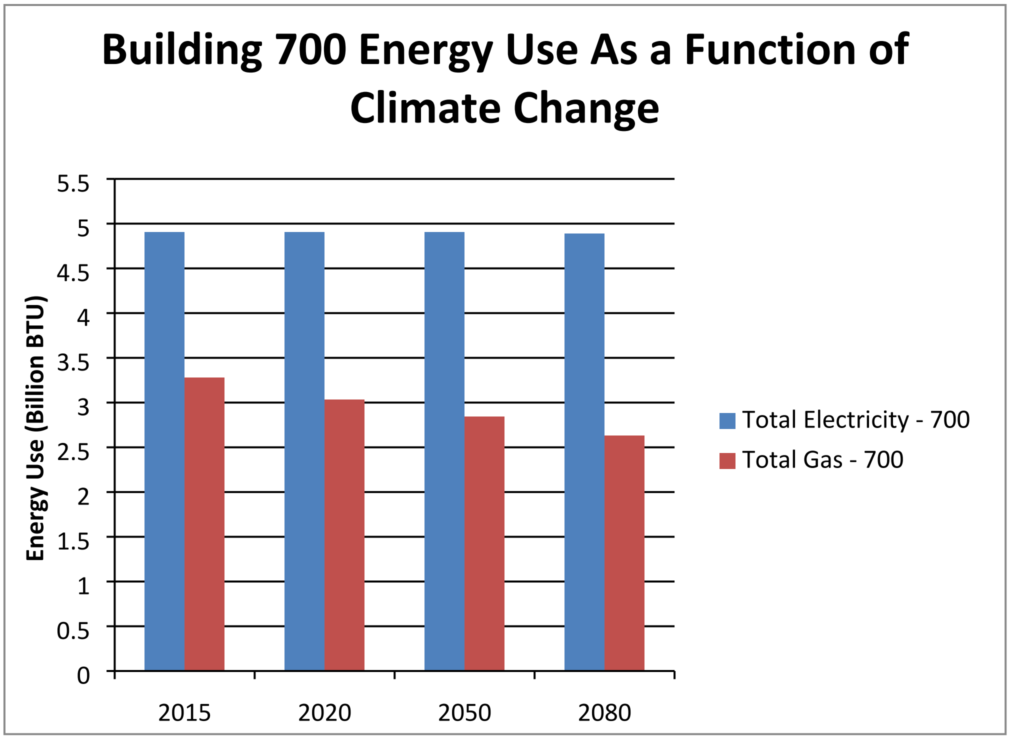


Figure 39. Building 700 energy use as a function of climate change

2.7.2 Chiller Efficiency Study

Chillers are one of the primary energy consumers in commercial buildings. Currently the IX building module has ten CUB chilled water loops for Albuquerque and two for California. In addition to this, there are 36 buildings that have stand-alone chillers. A scenario was developed that set the chiller efficiency at levels of 0.7, 0.6, 0.5, and 0.4 kW/ton. These numbers indicate the chiller performance at full load. If the existing chiller already had a smaller efficiency, then it was left unchanged as seen in Figure 40.

Commit Changes

Select a parameter: Chiller 1 Efficiency

Parameter Attributes — Minimum: 0

Additional Attribute: Area

Building ID	Area	Year 2015	2016	2017	2018	2019
720	Area I	1.412	0.7	0.6	0.5	0.4
726	Area I	0.5	0.5	0.5	0.5	0.4
802	Area I	0.579	0.579	0.579	0.5	0.4
823	Area I	0.534	0.534	0.534	0.5	0.4
836	Area I	0.55	0.55	0.55	0.5	0.4
858EF	Area I	0.6	0.6	0.6	0.5	0.4
858N	Area I	0.633	0.633	0.6	0.5	0.4
860	Area I	0.7	0.7	0.6	0.5	0.4
899A	Area I	0.627	0.627	0.6	0.5	0.4
962	Area IV	0.57	0.57	0.57	0.5	0.4
981	Area IV	1.412	0.7	0.6	0.5	0.4
C907	Area I	1.1	0.7	0.6	0.5	0.4
C943	Area I	0.7639	0.7	0.6	0.5	0.4

Figure 40. Chiller scenario input example

The results of this study indicate that the maximum site-wide potential for energy savings by increasing the full load efficiency of chillers is 1.4% based on a 1,340 billion BTU site-wide energy use per year as seen in Figure 41 and Table 7. This would require all chillers having a peak load efficiency of 0.4 kW/ton.

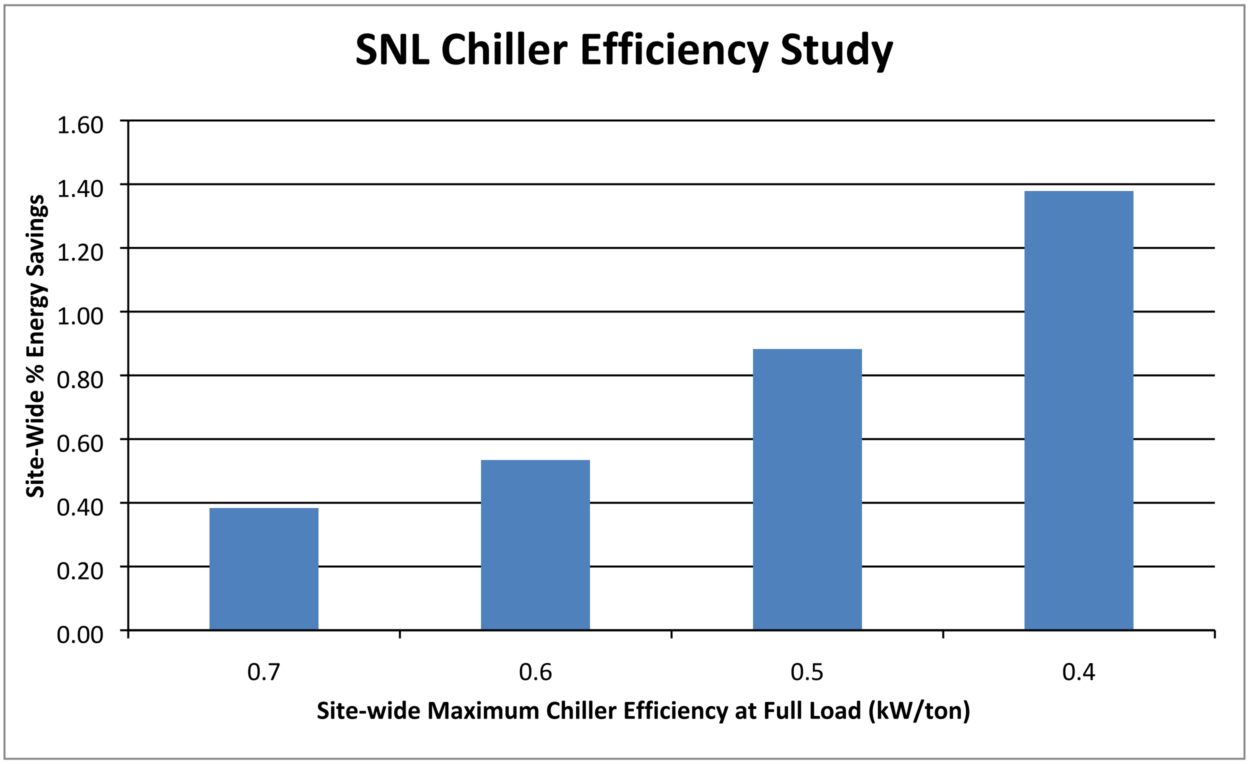


Figure 41. Chiller study results

It should be noted that most of the performance curves for chillers were not specified in the building files. Buildings C968, 730, 872, 983, C911, C914, C968, and C972 had a one-to-one performance curve between part load ratio and the chiller efficiency. Building 856 was the only building that had a specific call out of for a chiller performance curve. The performance curves for 856 and the other buildings specified above are shown in Figure 42. All other buildings were DOE-2 defaults.

Table 7. Chiller study data

Chiller Efficiency (kW/ton)	Energy Savings (Million BTU)	Total Energy (Million BTU)	% Savings
Current Site	0.000E+00	7.587E+05	0.00
0.7	5.141E+03	7.536E+05	0.38
0.6	7.165E+03	7.617E+05	0.53
0.5	1.184E+04	7.570E+05	0.88
0.4	1.849E+04	7.402E+05	1.38

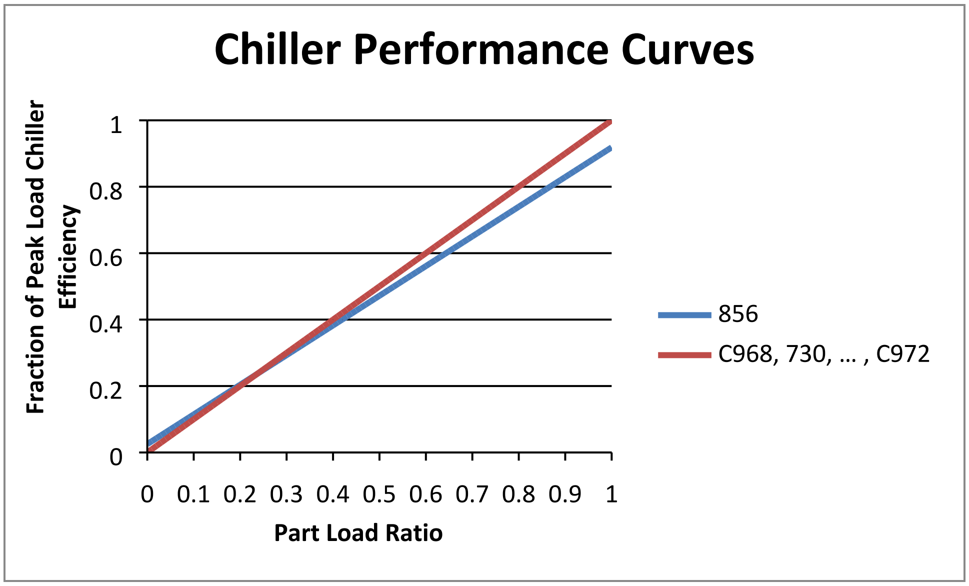


Figure 42. Chiller performance curves

2.7.3 Plug Load Power Switch Scenario

Reducing unnecessary plug loads at night could save significant amounts of energy. SNL is launching a pilot program to deploy power switches that automatically turn on during the day but off during the night. An ECM was developed in the IX building module to simulate this. The entire SNL CA and NM sites were simulated with plug load reductions between 7 p.m. and 5 a.m. as seen in Table 8. The energy savings potential accurately captures the penalty due to additional gas consumption as seen in Figure 43 and is therefore more accurate than a simple reduction of plug loads hand calculation. In Figure 43, the time axis is being used to represent change in a parameter rather than change in time. IX has provided an estimate of the potential of this measure across SNL's entire site. A follow up study is needed to estimate the percentage of plug loads that can be turned off at night. For example, datacenters and supercomputers are clearly cases of plug loads that cannot be turned off since scientific computing occurs 24-7.

Table 8. Plug load power strip results

IX site-wide study of reducing night-time (7p.m. - 5a.m) plug loads			
% plug loads shut off during the night	Electricity Savings	Gas Penalty	Total Savings
0%	0.00%	0.00%	0.00%
25%	1.66%	-0.10%	1.56%
50%	3.27%	-0.21%	3.06%
75%	4.91%	-0.31%	4.60%
100%	6.58%	-0.51%	6.08%

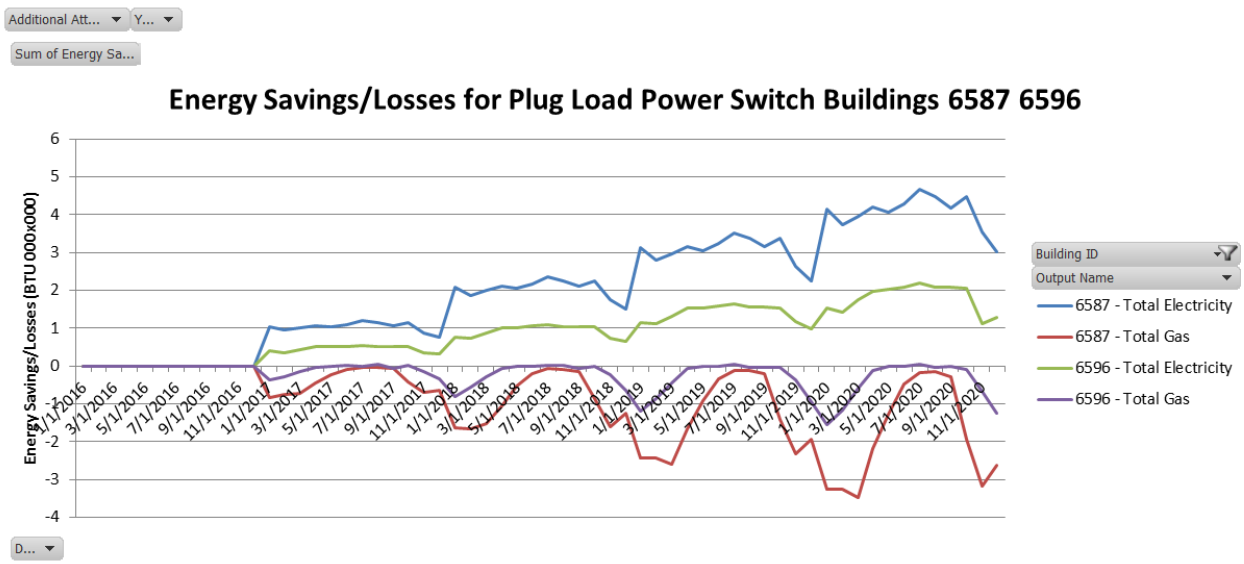


Figure 43. Plug load power switch ECM results for Buildings 6587 and 6596

2.7.4 *Energy Break-Down*

The IX building module provides a unique capability to classify electricity and gas consumption by end-use. The break-down accuracy is dependent on the accuracy of the calibration of individual models. The current estimate for the SNL New Mexico and California sites is provided below in Figure 44.

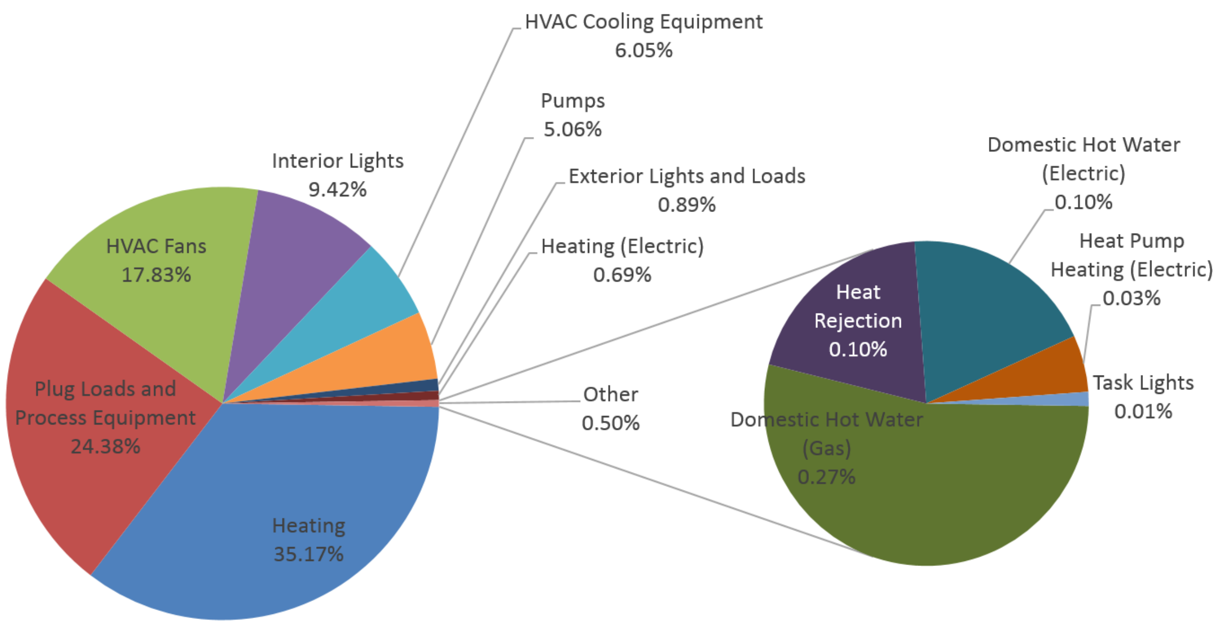


Figure 44 Sandia National Laboratories end-use breakdown estimated by IX (based on average weather for New Mexico and California from 2013-2017)

3 SOLAR MODULE

The IX solar module is designed to estimate the costs and electricity generation potential associated with three different solar technologies at 18 prospective sites at SNL/NM (see Figure 45) and SNL/CA through 2034. The module considers flat plate and membrane photovoltaic (PV) mounted on ground or roof, concentrating PV, and concentrating solar thermal (CST). For the purposes of IX, it was essential that the module have the capability of assessing the implications of installed solar technologies both on a site-specific and an aggregate basis. To accomplish this task, this module incorporates the single-site evaluative capabilities of the National Renewable Energy Laboratory's (NREL's) System Advisor Model™ (SAM™) and PowerSim Studio™ for aggregate cost and performance estimates over time.

Table 1. Site Investigation for Placing PV on the SNL/NM Site

	Sites / Description	Acreage	Technology	MW Capacity	Production MWh/yr
1	KAFB land east of PSEL Undeveloped land north of G Ave.	7.8	Ground-mounted PV	0.98	2187.4
2	South of G Ave. Undeveloped dirt strip of land	1.0	Ground-mounted PV	0.13	280.4
3	Building 887 existing parking lot North of H Ave.	9.0	PV on parking shade structure	1.13	2523.9
4	Building 832 parking lot Existing parking lot and buildings to be removed	4.5	PV on parking shade structure	0.56	1261.9
5	Building 878 roof South section of existing roof	0.9	Roof-mounted PV/PV membrane	0.11	252.4
6	Building 880 roof Center section of existing roof	1.1	Membrane or roof-mounted PV	0.14	308.5
7	South of Building 821 Existing parking lot	0.7	PV on parking shade structure	0.09	196.3
8	SW Corner Building 825 parking lot Existing parking lot	2.5	PV on parking shade structure	0.31	701.1
9	Building 956 running track Center of existing running track	1.7	Ground-mounted PV	0.21	467.7
10	East end of Area III Undeveloped land on top of escarpment	15.0	Ground-mounted PV	1.88	4206.4
11	South end of Area II Undeveloped land north of R Ave.	12.0	Ground-mounted PV	1.51	3365.2
12	North of Substation 42 Undeveloped land south of R Ave. and east of 9th St.	1.8	Ground-mounted PV	0.23	504.8
13	Area IV parking lot Existing parking lot south of S Ave. and east of 9th St.	6.5	PV on parking shade structure	0.81	1822.8
14	DETL site Paved land east of MO 290 and south of F Ave.	0.4	Ground-mounted PV	0.05	112.2
15	PSEL site Undeveloped land at north edge of PSEL site	0.5	Ground-mounted PV	0.06	140.2
16	Building 956 roof Center section of existing roof	0.4	Roof-mounted PV/PV membrane	0.05	112.2
17	Building 970 roof East section of existing roof	0.5	Roof-mounted PV/PV membrane	0.06	140.2
18	Building 897 roof South section of existing roof	0.2	Roof-mounted PV/PV membrane	0.03	56.1
	Totals	**66.9**		**8.34**	**18639.7**

FMOC — Site Investigation to Place PV at SNL/NM, May 2010 — Rev. 0, Page 4

Figure 45. SNL/NM Sites Considered in Solar Module

The solar module is a stand-alone tool. Two types of information are simulated by the solar module. Power generation is calculated for each site of interest and this is converted into revenue, thus allowing for a high-level analysis of the feasibility of construction at each site. The second aspect of the model is a financial analysis to see if it makes sense to invest in building a PV system and what the cost of produced electricity could be. For this we use the concept of net present value and levelized cost of electricity (LCOE). It considers two types of flat plate installations—ground-mount and roof-mounted systems. Cost and electrical generation curves are created using installed area specific parametric studies within SAM. Data from the curves is then accessed in PowerSim Studio® for the purpose of individual and aggregate comparisons of generation and cost over time.

3.1 Model Input

User-defined inputs to the model (Figure 46 and Figure 47) include both site- and simulation-specific parameters. Site-specific parameters and general model parameters are listed below. Default values are in parentheses.

- De-rating Percent–the amount of generation lost due to aging of the system (0.5 percent/year).
- Reduction in installation costs–savings in the construction process due to learning during previous installations (3 percent/year).
- Current SNL electricity cost–the cost SNL currently pays for electricity as an industrial customer ($0.06/year).
- Electricity annual increase–the rate the cost of electricity increases over time (1.5 percent/year).
- Federal rebate–Federal income tax rebate based on cost of system installation (30%).
- NM State incentive–A 10-year program paying for kWh produced. Average rate of $0.027/kWh.
- NM Capital Expense Tax Credit–Gross receipts tax credit for sale or installation of an eligible facility (10%).
- NM Advanced Energy Credit–A corporate tax credit for renewable energy (6%).
- Capital loan interest rate–Set at 6%.
- Loan repayment period–Set at 20 years.
- Inflation rate–Set at 3.0%
- Sandia cost multiplier–this represents the additional cost of doing business at SNL (default of 1.8).
- Public Service Company of New Mexico (PNM) Renewable Energy Credit (REC)–Revenue based on kWh generated. Rates vary over time and by system size ($0.035/$0.045/$0.020 per kWh).

Based on Pate [14], user input is constrained based on the feasibility of certain technologies installed at certain sites. For example, it would not be considered feasible to install CST on a small (1 acre) site or the roof of a building. Other parameters, such as the installation date, will influence the total cost and time to payback, as some incentives are only applicable until a specified date.

MODEL INPUTS

Enter percent installation and start date of solar technologies within installation types guidelines. Note that some installation types are not available at all sites. Types that are unavailable are represented by gray boxes below.

It is best if the Total % Install does not exceed 100%

	Site Name	Area (acres)	Installation Types Available	% Ground PV	Ground PV Start Date	% Roof PV	Roof PV Start Date	% CPV	CPV Start Date	% CST	CST Start Date	Total % Install
1	KAFB land East of PSEL north of G Ave.	7.80 acres	Ground PV, CPV, CST	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	100 %	1/1/2014	300 %
2	South of G Ave., undeveloped land	1.00 acre	Ground PV, CPV	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	200 %
3	Building 887 parking lot, north of H Ave.	9.00 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
4	Building 832 parking lot	4.50 acres	Roof PV, CPV	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	200 %
5	Building 878 roof, south section	0.90 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
6	Building 880 roof	1.10 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
7	South of Building 821, parking lot	0.70 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
8	SW corner of Building 825, parking lot	2.50 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
9	Building 956, center of running track	1.70 acres	Ground PV, CPV	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	200 %
10	East of Area II, undeveloped land	15.00 acres	Ground PV, CPV, CST	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	100 %	1/1/2014	300 %
11	South of Area II, undeveloped land	12.00 acres	Ground PV, CPV, CST	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	100 %	1/1/2014	300 %
12	North of Substation 42, undeveloped land	1.80 acres	Ground PV, CPV	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	200 %
13	Area IV, parking lot	6.50 acres	Roof PV, CPV	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
14	DETL site, paved land	0.40 acres	Ground PV, CPV	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	200 %
15	PSEL site, undeveloped land	0.50 acres	Ground PV, CPV	100 %	1/1/2014	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	200 %
16	Building 956 roof	0.40 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
17	Building 970 roof	0.50 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %
18	Building 897 roof	0.20 acres	Roof PV, CPV	0 %	1/1/2014	100 %	1/1/2014	0 %	1/1/2014	0 %	1/1/2014	100 %

Figure 46. Controls for User-defined Technology and Area

User Defined Variables

All input variables will retain values determined by the user between model runs.

Derating percent	0.5 %/yr
Reduction in installation costs	3.00 %/yr
Current SNL Electricity Cost	$0.06 per kWh
Electricity annual increase	1.50 %
Federal rebate	30 %
NM State incentive	0.03 USD/(kWh/yr)
NM Capital expense tax credit	10 %
NM Advanced Energy Credit	6 %
Capital Loan Interest Rate	6.00 %
Loan Repayment Period (years)	20 yr
Inflation rate	3.0 %
Sandia Cost Multiplier	1.80

PNM Renewable Energy Credit (REC)

Systems 0 - 10 kW	$0.035 per kWh
Systems 10 - 100 kW	$0.045 per kWh
Systems 100 - 1000 kW	$0.020 per kWh

Electricity Cost Scenarios

Select one of the electricity cost scenarios listed below. Annual price increase is compounded annually after 2016 when the current electricity contract ends. Manual selection option requires user to drag pricing graph to predicted cost levels. Graphed prices are displayed in the table below.

ELECTRICITY COST SCENARIO
- (•) Annual increase in price
- ( ) Block price manual selection

SNL Electricity Use Scenarios

Select SNL/NM energy use projections below. Option one refers to 25% energy reduction through 2017 and zero reduction afterwards. Option two is a variation of option one but with a 1% annual decrease in energy use in following years.

SNL ENERGY USE SWITCH
- ( ) Conservative Reduction in Energy Us
- (•) Aggressive Reduction in Energy Use

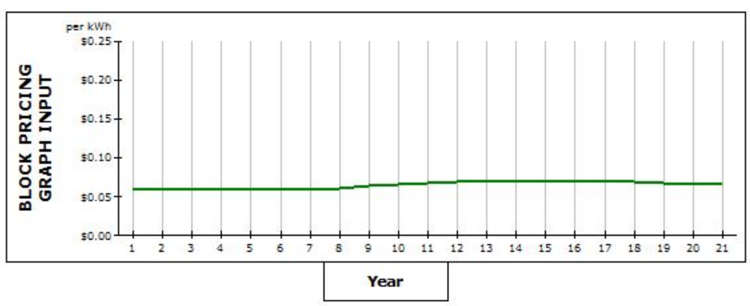


Figure 47. User-defined costs and incentives (sample)

Customized start dates at each of the sites and the ability to mix and match generation technologies on the sites is possible in the interface. For example, if more than one technology is viable at a particular site you can adjust the area percentages of each technology. The model can be varied between only installing a single technology on a fraction of the site area to installing all available technologies on 100% of the site. Though the latter scenario is physically unrealistic, it does allow the direct comparison of each technology on a specific site.

Cost of electricity can be varied in two scenarios. The first, or cheap electricity scenario, takes the “Current SNL Electricity Cost” variable and increases it by the specified percentage. The $0.06 per kWh that SNL currently pays is the negotiated cost of a large industrial campus, which is lower than a residential customer of PNM. Applying this rate as the value of electricity generated produces a small amount of revenue. A second scenario, or block pricing selection, allows for a variable price set by the user. This is done by drawing a line on a dynamic graph with a maximum price of $0.25 per kWh. It allows for increasing electricity prices which generate greater revenue on each site.

Electricity usage at SNL can be modified in the interface. Usage is projected to decline in the future and the model has the option of choosing a conservative decline or an aggressive reduction. In the conservative scenario electricity usage is reduced by 25%over 5 years, starting at the 2012 level. Then there is no further reduction after 2017. The aggressive reduction scenario starts with the same 25% reduction in usage but then continues with a 1%decline annually.

3.2 Rebates and Incentives

Rebates or incentives offered to encourage renewable energy generation vary widely over time and from state to state. For this project we assumed values of rebates based on what was available in April 2014. In actuality many of the rebates and incentives are applied for during the pre-construction permitting process and the rate will be set when construction finishes. During this time frame rebate values, and Renewable Energy Certificates (REC) especially, can change drastically. As an example, the rate PNM reimburses generators is decreasing year by year and is reduced further by increasing the number of systems that come on-line each year. A summary of each of the incentives in the model is provided.

<u>Federal Tax Credit or the Solar Investment Tax Credit (ITC)</u>. This is a 30%.tax credit for residential and commercial solar systems but it begins to decline in 2019 and expires in 2022. It is a deduction on income taxes to the federal government equal to 30% of the basis of eligible property used in solar generation. State rebates, buy downs, grants or other incentives do not decrease the amount eligible for the ITC.

<u>New Mexico State Incentive or the Renewable Energy Production Tax Credit (Corporate)</u>. Enacted in 2002, the New Mexico Renewable Energy Production Tax Credit provides a credit against the corporate income tax of an average of 2.7¢ per kilowatt-hour, for companies that generate electricity from solar energy. The average value is used in the model, but for informational purposes the actual 10-year values are listed below:

- Year 1: 1.5¢/kWh
- Year 2: 2¢/kWh
- Year 3: 2.5¢/kWh
- Year 4: 3¢/kWh
- Year 5: 3.5¢/kWh
- Year 6: 4¢/kWh
- Year 7: 3.5¢/kWh
- Year 8: 3¢/kWh
- Year 9: 2.5¢/kWh
- Year 10: 2¢/kWh

A limit of 2,000,000 MWh generation exists for the state and a maximum of 400,000 MWh per year is chargeable for each generator.

3.3 How the Solar Module Works

The following provides a detailed description of how the Solar Module, written in PowerSim Studio, works. The code has four branches that correspond to the four technologies on the Sandia campus: Ground PV (GPV), Roof PV (RPV), Concentrating PV (CPV), and Concentrating Solar Thermal (CST). All descriptions in this section pertain to the Ground PV section of the code but you can extrapolate to other sections by modifying the auxiliary names from GPV to RPV, CPV, and CST.

The System Advisor Model (SAM) from NREL is the basis for all costs and production data in this code. When you run the photovoltaic section of SAM you can choose which collectors and inverters you will use in your system. For this analysis "BEoptCA Default Module" was chosen as the collectors and "Advanced Energy Solaron 333" was chosen as the inverter. The characteristics of this technology were then applied to various sized systems such as 100, 500, 1000, 2000 and 3000 kW. By entering these numbers into SAM, output is generated in terms of system annual output (kWh/yr), area for installation (acre), and cost ($). As mentioned elsewhere in this report, the outputs of SAM are quite linear with respect to the system area variable. This applies to PV, concentrating PV, and solar thermal technologies within the ranges we studied. So plotting the SAM outputs relative to area of construction we created a function to approximate system annual output, system capacity, and cost. An example is shown below as Figure 48, with area on the x axis and kWh/yr on the y axis. The function, $y = 286568x–25.077$, was then used in the PowerSim Studio Solar Module to estimate GPV generation.

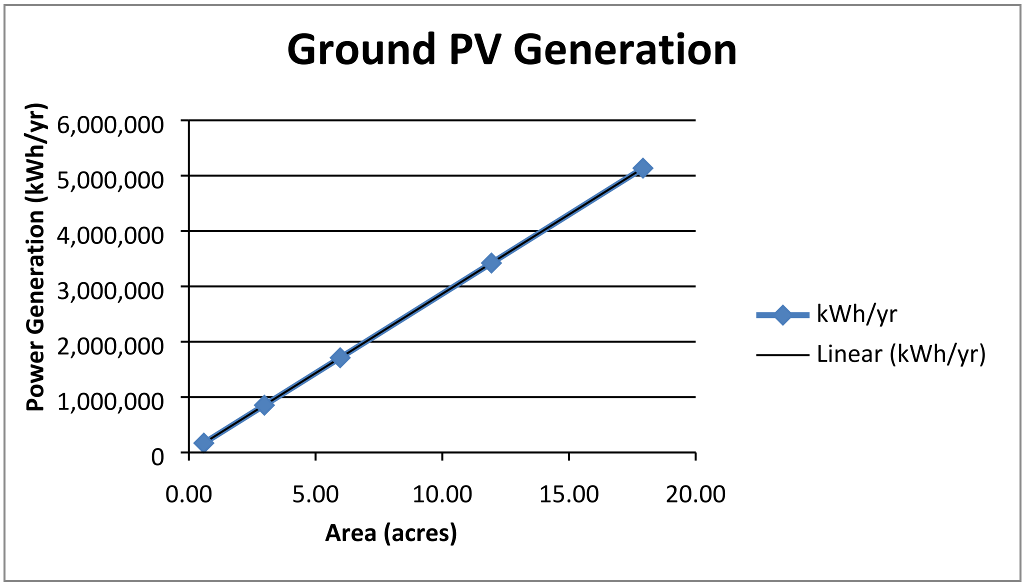


Figure 48. Function generated using NREL's SAM code for solar electrical generation

With this function, the solar module then takes a construction area from a specific site (SNL/NM or SNL/CA) and plugs that area into the Studio code, producing values for GPV annual generation (kWh/yr), GPV MW capacity (kW), and GPV calculated capital, or construction costs. A section of the code is shown in Figure 49. Looking more closely at annual generation, there is a test for whether the site is suitable for the technology (ground suitability), as well as a de-rating multiplier (0.5 percent per year). De-rated generation calculation is done in a flow into a stock. This stock (Cumulative GPV Generation) adds up the values of kWh/yr for all the electricity generated in the GPV systems, up to the lifespan of the systems. Once the system reaches an age of 25 years it is considered obsolete and generation goes to zero. This value of cumulative generation is used in the calculation of LCOE.

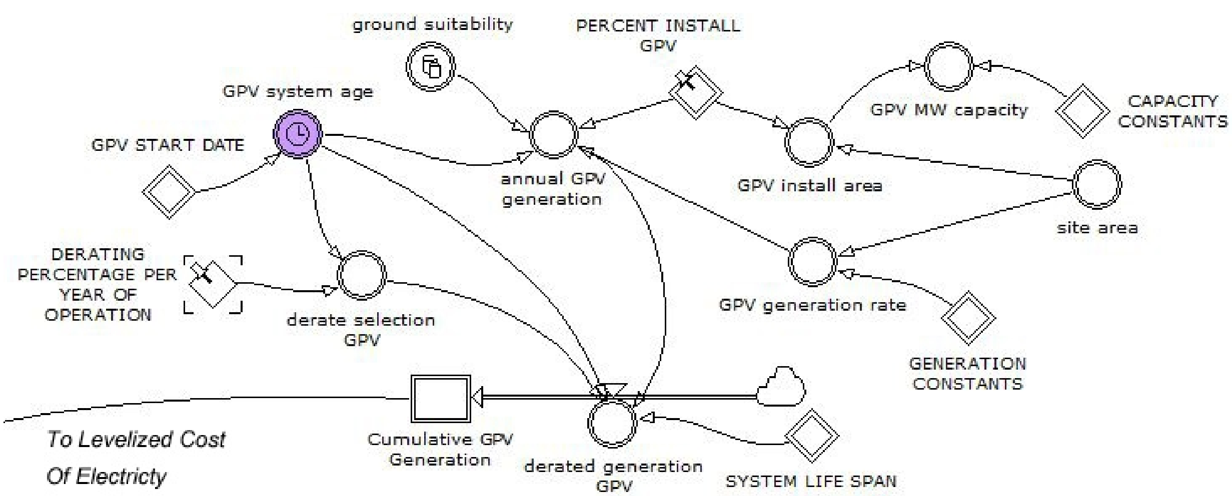


Figure 49. PowerSim Studio code for ground photovoltaic electrical generation

A similar function is used to calculate the capacity of the constructed system. The concept is simple. Enter the area of the system and this function will yield the name plate capacity of the system in kW. The “CAPACITY CONSTANTS” are multiplied by the install area and the final auxiliary is GPV MW capacity.

Similar to generation and capacity, cost of construction is estimated based on a curve-fitted functional form. The “COST CONSTANTS,” shown in Figure 50 feed into the calculation found in the auxiliary “GPV calculated capital.” This calculation is decreased by the “Learning Rate,” a measure of cost savings based on increased knowledge and efficiency of construction as time increases. The learning rate is currently 1 percent/year. The “Sandia Cost Multiplier” is also applied to the calculated capital in this auxiliary, raising the costs of construction by a factor between one and two. Calculated Capital is stored in stock once the project start date is exceeded. This Calculated Capital is then used to calculate installation credits and the final construction loan amount. Starting project capital is also used to calculate the system parameter “USD per Watt Installed GPV.”

There were two types of rebates given by grid owners and operators during the writing of the solar module. One is based on size of the system such that the rebate is a percentage of the installation cost. These rebates normally apply to residential or small corporate installations. The other is an REC, which is based on generation. The REC generally pays back at a rate that could be in the range of 2 to 4 cents per kWh. This varies from place to place, by size, and by year. This model has three different REC rates based on system size. Any time this model is run, the REC rates should be re-evaluated based on the prices local utilities and governmental entities may or may not be offering.

The rebates represented in this simulation also require values for system capacity and install area during calculation. Some rebates only apply to systems of an area 1 acre or larger or of a capacity greater than 1 MW. When the system start date is exceeded by the simulation, the value of the rebate is stored in a stock, “GPV Sum of Rebates.” This value is then used to calculate the construction loan amount.

The construction loan amount is the difference between the “Starting Project Capital” and the “Sum of Rebates.” This loan amount is the reason that capital and rebates must be saved in stocks. If they are not saved in stocks the value of the loan will vary year to year because rebates change year to year, leading to errors in calculation of loan repayment. This loan amount then feeds into an auxiliary flow that calculates the annual loan payment using the PowerSim Studio PMT function. This annual payment is next stored in a stock to collect the total amount paid on the loan over the years. The value in the stock is used to calculate the LCOE while the annual loan payment amount is an input to the auxiliary “current net benefits GPV.”

Revenue for the electrical generation systems is based on the de-rated generation, the REC rate, and the “cost of electricity selected.” Cost of electricity is set in the user interface. The calculation of the REC value is based on the size of the generation system and thus the auxiliary “GPV MW Capacity’ is included. “Annual revenue GPV” is an input to the auxiliary “current net benefits GPV.”

“Current net benefits GPV” is the sum of revenue minus expenses, shown in Figure 51. It becomes the data source for the net present value (NPV) calculations as well as the internal rate of return (IRR) calculations. Income in the solar module comes from the “annual revenue GPV” while expenses are the “GPV annual capital payment” and “O&M annual expense GPV.” Operations and maintenance values are based on work done by Pate [14] and, in the case of concentrating solar technology, personal communication with technicians at Sun Power. Annual

O&M expenses flow into a stock to calculate the total O&M expenses over the lifetime of the system. This total O&M value is used in the calculation of the LCOE.

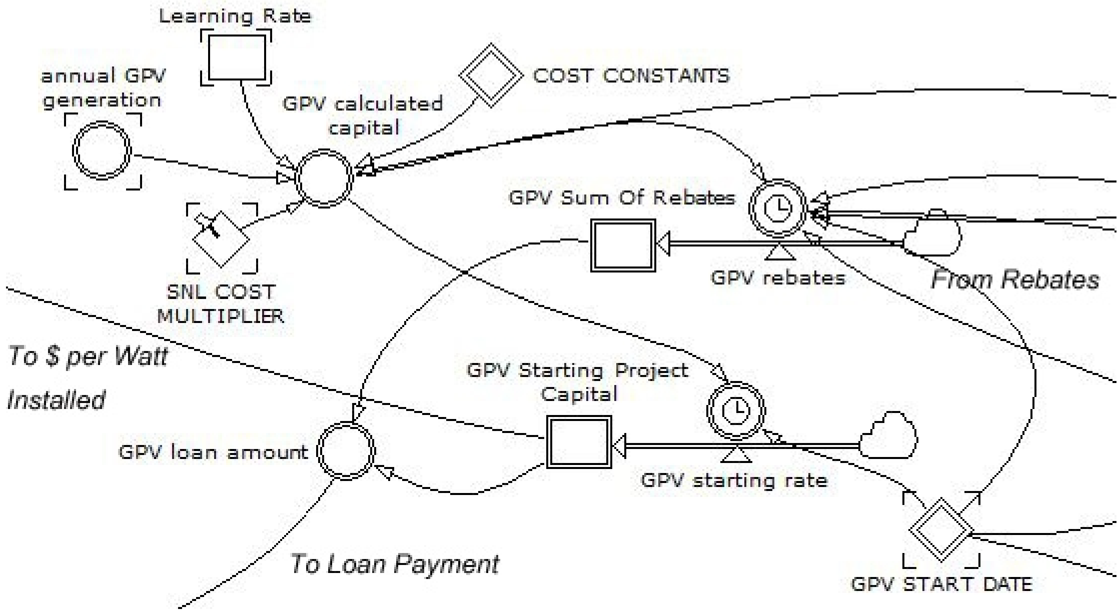


Figure 50. Calculating project capital, rebates, and the loan amount

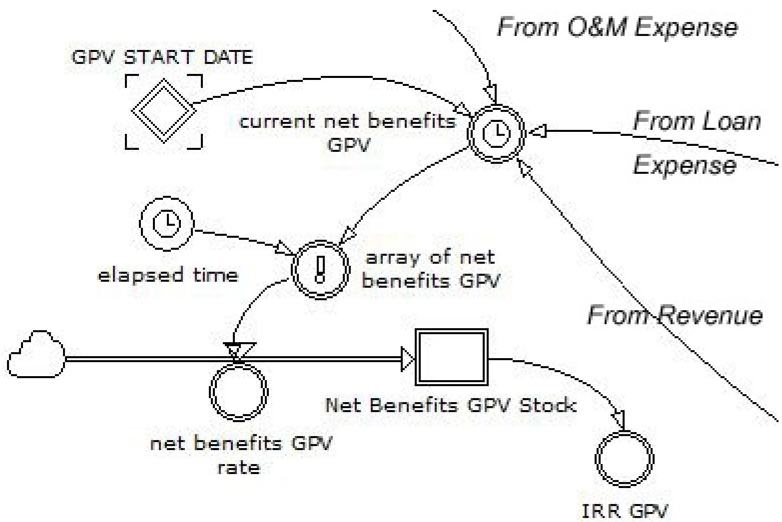


Figure 51. PowerSim Studio code to calculate the Internal Rate of Return.

3.4 Model Output

The module is designed to produce multiple outputs that can be compared on an individual or aggregate basis. These outputs include: system size in MW; total electricity generation based on percent of site developed, technology used and year installed; total capital costs, net present value of individual projects and for all technologies; cost per kWh per installed watt; percent of labs-wide usage met by simulated renewable energy installations. Output data is displayed graphically so that the user can compare total generation by site, by technology, by year, etc. Additional comparisons include the total percent of existing energy use that is met by solar generation, net present value, and investment recovery time. The results generated in the IX solar module allow planners to assess the various costs and benefits (financial, energy, conservation requirements, etc.) and compare different scenarios over time.

"Total Generating Capacity by Site and Technology," as shown in Figure 52, is compared in a bar chart, allowing the user to see at a glance which generation technology will perform best at a specific site. Not all technologies are available at all sites and no comparison of costs is considered in this figure.

"Annual Generating Capacity by Technology" is presented as a line graph in Figure 53. It compares the total energy produced over time, by each of the four technologies on the Sandia campus. Area dedicated to each generation technology is set by the user in model inputs. Note that the slope of the lines indicates the de-rating percentage.

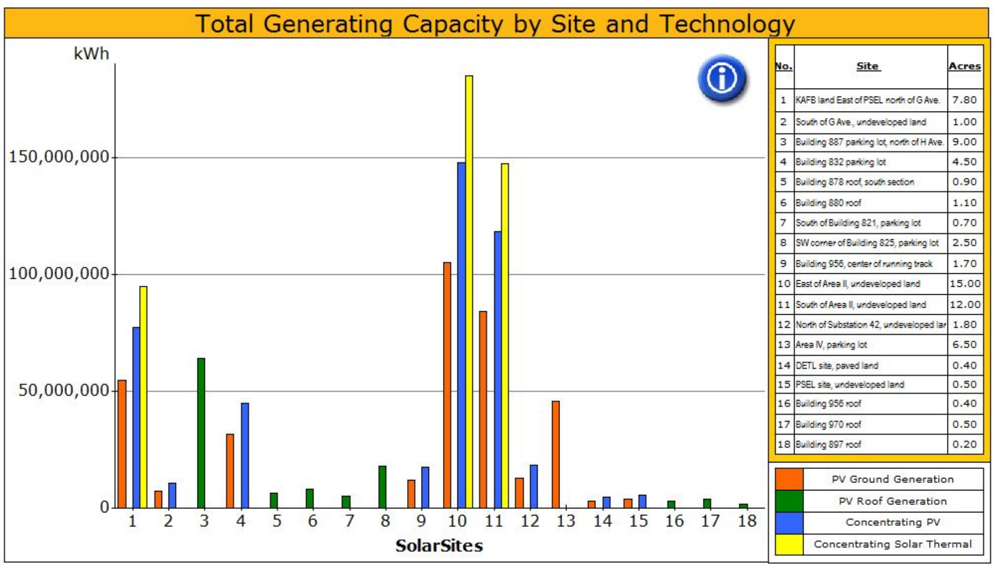


Figure 52. Sample IX Solar module output showing total generating capacity by site and technology

The second aspect of the model is a financial analysis to see if it makes financial sense to invest in building a system and what the cost of produced electricity could be. For this we use the concept of net present value (NPV) and levelized cost of electricity (LCOE).

3.5 Net Present Value

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows. The formula for calculating NPV is:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{5}$$

Where C_t is the net cash inflow during the period, C_0 is the initial investment, r is the discount/interest rate, and T is the number of time periods. Using this formula accounts for the time value of money, or the discounted value of the investment. The solar module uses the PowerSim Studio built in NPV function for the calculation, which uses the "current net benefits" and the loan rate. The summation, shown in the above formula, is done in two stocks labeled as "Accumulated NPV GPV." One of the stocks is the sum of all GPV generation across the site while the other is broken down by site.

When considering NPV you must consider the overall value of accumulated NPV (positive or negative) as well as the slope of the plotted line. If the accumulated value is positive, then the investment has broken even and has paid off the loan. If the value is negative, then the debt has not been paid off yet. If the slope of the line is negative, then the project is losing money. If the slope is positive, then the project is making money. In "cheap electricity" scenarios it is common to see the projects in debt and losing money. Over time most projects do generally turn around and make money, showing a negative accumulated NPV but with a positive slope. This occurs most quickly if the cost of electricity is high, thus generating more revenue. Figure 54 is a combination of a Sandia multiplier of 1.8 percent coupled with relatively expensive block priced electricity.

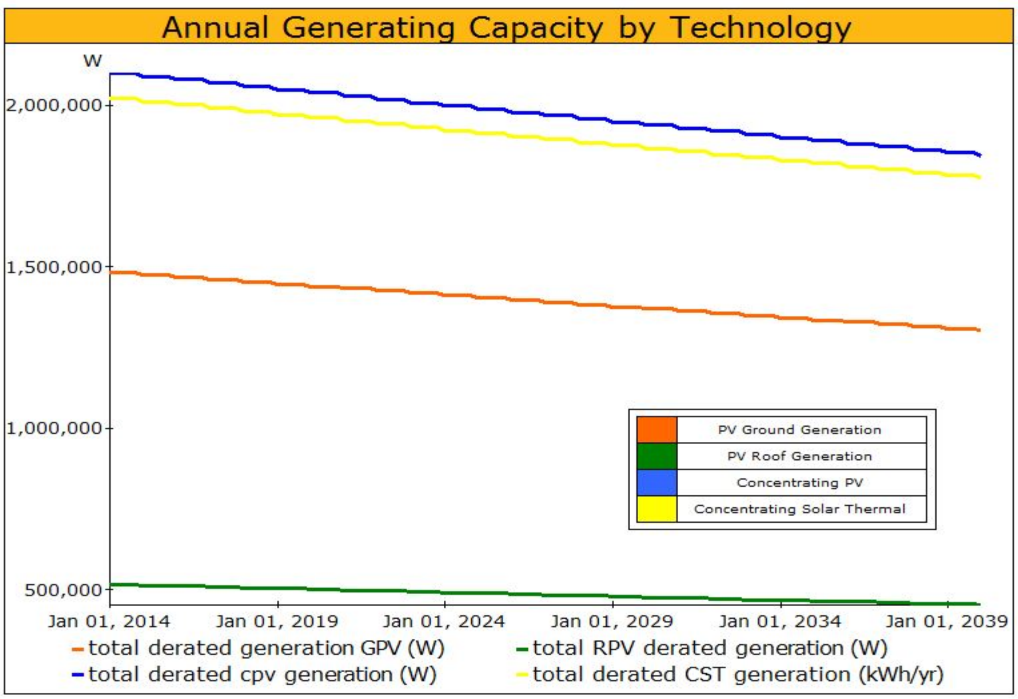


Figure 53. Comparison of Annual Generating Capacity by solar technology across the site, over time

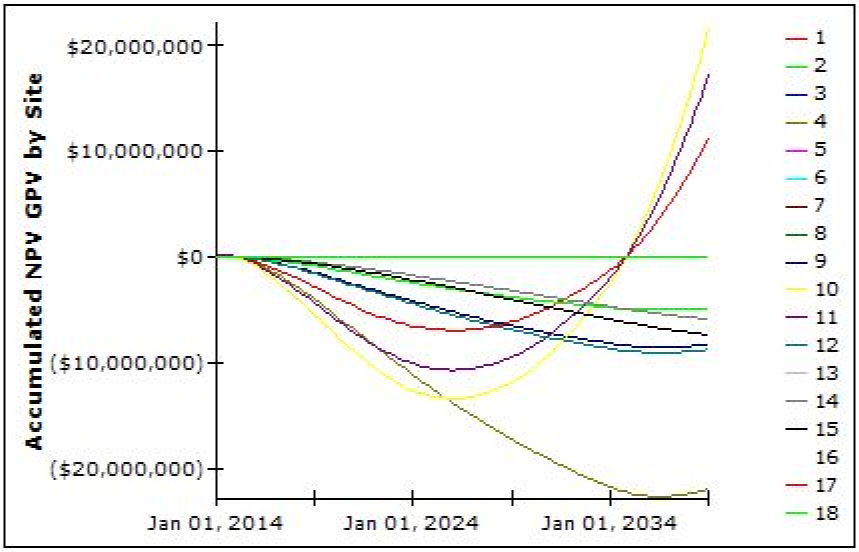


Figure 54. Accumulated NPV suggesting good and poor investments

The NPV values shown in Figure 55 represent a similar scenario but only show the results of a single year, rather than the time series.

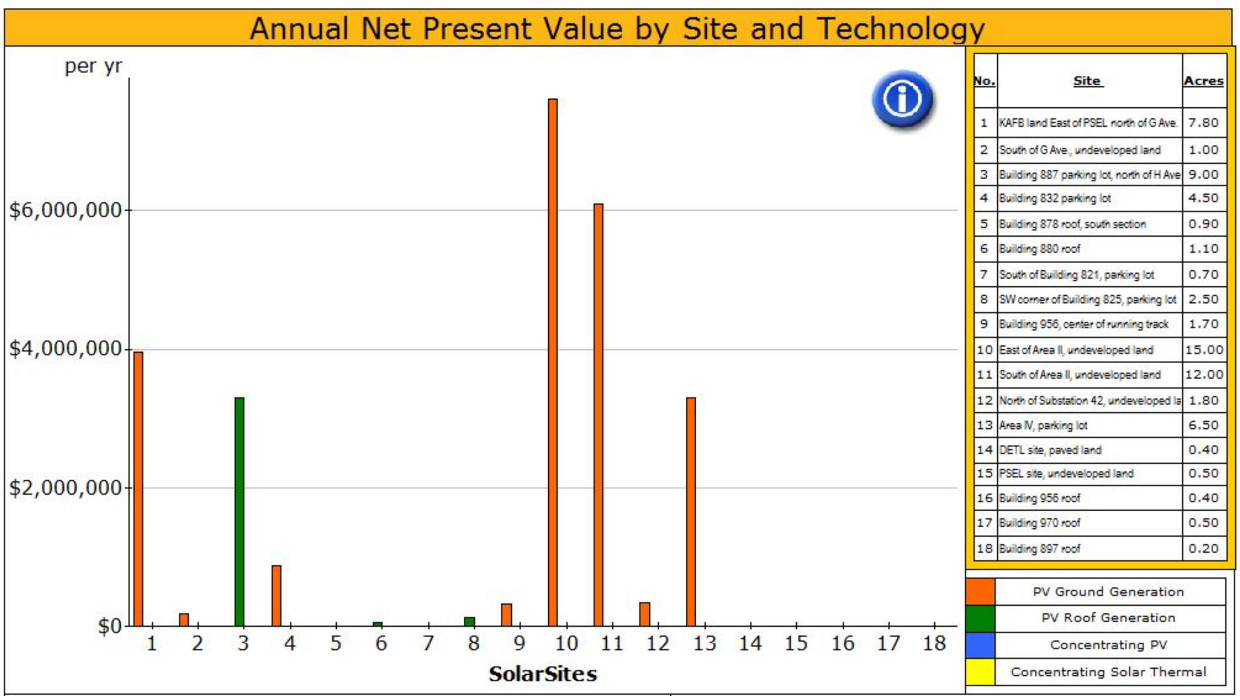


Figure 55. Sample IX Solar module NPV expressed as millions of US dollars. This graph shows the NPV for a scenario with relatively expensive electricity.

3.6 Levelized Cost of Electricity

LCOE is a concept used to calculate how much the produced electricity will cost in the long term, after considering all expenses during the system lifespan and the total amount of electricity generated. For the definition of LCOE we used the following formula.

$$LCOE = \frac{C_L + C_{OM}}{E_G} \tag{6}$$

Where C_L is the total payments made on the construction loan, C_{OM} is the lifetime operations and maintenance costs, and E_G is the cumulative electrical generation. The LCOE has units of dollars per kWh. Definitions of LCOE can differ from one project to another so care must be taken when comparing values. The projected LCOE for Sandia National Laboratories is shown in Figure 56 Generally, desirable costs for production fall in the range of $0.07 per kWh, which is met at several sites, using ground and roof mounted photovoltaic generation, in this model scenario.

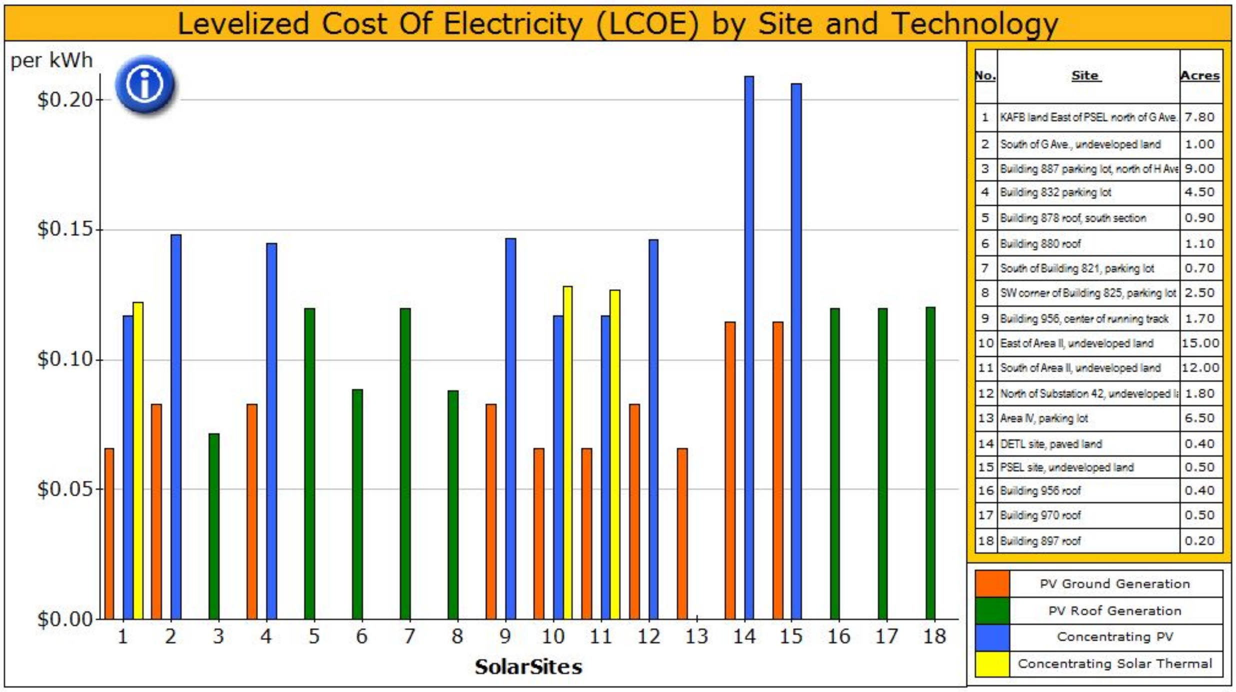


Figure 56. IX Solar Module calculated LCOE for each of the sites and technologies.

3.7 Internal Rate of Return

The internal rate of return (IRR) on an investment is the annualized compounded rate of return that makes the net present value from the investment equal to zero. It is the rate at which an investment breaks even. The calculation requires a time series of data from the "current net benefits" auxiliary so those values are stored in a matrix (with dimensions (number of sites) x (years of simulation)). A VB Function in the auxiliary "array of net benefits GPV" does the processing that feeds the numbers to the "Net Benefits GPV" stock, creating the time series. From this data stored in the stock, the module uses the PowerSim Studio IRR function to calculate the final percentages. It is worthy to note that the IRR calculation is well behaved for monotonic data series. In this analysis the profitability of most of the sites goes up, down, and then up again mainly due to the ending of rebates/RECs followed by increasing electricity prices. Thus most of the IRR analyses do not provide believable numbers.

4 NEXT STEPS

4.1 Distribution of IX 2.5

IX version 2.5 has a completed copyright assertion and is ready for distribution to interested parties that SNL approves. The set of 120 building models and ECMs developed by SNL may not be included depending on SNL's approval. Because IX uses DOE-2, any distribution outside the department of energy (DOE) must be without DOE-2 included in order to not violate DOE-2's independent licensing agreement. DOE-2 is freeware requiring initiation of a signed contract with Jeff Hirsch and Associates as explained on the DOE-2 website (www.doe2.com). Once a potential user has acquired an independent DOE-2 license agreement, Sandia can distribute IX 2.5 and the "./IXData/doe22" directory inserted by the potential user.

IX version 2.6 is currently under development but does not have a copyright assertion. The changes are minimal. The main difference is that IX 2.6 runs in Microsoft Office 2016. Further development will only be in IX 2.6

4.2 Future Development of IX 3.0

There is considerable potential for enhancement of IX 2.5. The original goal was to step from IX 2.0 to IX 3.0 but the proposed enhancements to reach IX 3.0 were beyond the time and resources available. Table 9 provides a summary of the major features that were proposed to be changed for IX versions 2.0, 2.5, and 3.0. The most important aspects of IX 3.0 that had to be excluded were automating ECMs and CUBs. Both of these tasks intertwined in ways that required the IX database to become much more complex than anticipated.

Automation of ECMs in IX was seen to be increasingly important as issues had to be worked out for the IX version 2.0 dataset. During actual IX use, errors in ECMs were incrementally discovered whenever results clearly did not align with intuition. The result was a continuous need to update hundreds of files. To make matters worse, as files were passed between different users, the state of ECMs in each file was forgotten. This lead to most files behaving reasonably with anomalous behavior in others that turned out to be errors that had already been fixed in other files This inefficient process, coupled with the capacity for ECM errors to remain hidden in individual files, underscored the need to automate the ECM implementation process so that an update to an ECM would automatically be applied to all building files in IX and the logic behind the ECM would be audited directly in the database with no need to view input files. Automating ECMs has the additional benefit that code can include less common cases such as two ECMs interfering with each other. For example, a user may currently overwrite part of an ECM manually in a BDL file in order to implement a new ECM or when simply making changes to the file. The result can be a partially corrupted old ECM that may still have all of its parameters but will frustrate an unknowing user when it doesn't work. An even worse case would be that the ECM still seems to be working but is actually producing erroneous results. Automated code would enable saving each BDL address that an ECM accesses for each building and flag an error if another ECM tries to write to that location.

Table 9. Major feature comparison for IX versions 2.0, 2.5, and 3.0

Feature	2.0	2.5	3.0	Comments
CUBs	No CUBs	Single buildings or	Single Buildings that	As much of the

Feature	2.0	2.5	3.0	Comments
		single CUB files that have been created outside of IX and checked in as type "CUB" only one chilled water loop per CUB (no hot water loops)	can be built into CUBs directly in IX with simultaneous application of ECMs (this is hard)	process for building CUBs as is possible will be included in a CUB utility for version 2.5 of IX.
Multiple Files	Single BDL input file per building	Multiple input files per building (required to allow CUB configuration changes over time)	Multiple instances of a building per year.	Enables archiving historical calibrated files and drastic changes to buildings. (e.g., adding a building to a CUB)
	Single weather file per building	Multiple weather files per building	Direct selection and creation of weather histories in the user interface.	Enables climate change studies
ECMs	ECMs accomplished through BDL parameters	ECMs accomplished through BDL parameters	ECMs applied through code and indexed in IX database to allow consistent application of each ECM to each building. Application of ECMs at precise day, month, year.	IX 3.0 is needed to ensure IX's data quality model is defensible. Automation will only be tested to work with eQUEST BDL input files
Input	Input data in Excel tables	Input data accomplished through dialogue that writes and deletes data to the IX database through queries	Input data accomplished through dialogue that writes and deletes data to the IX database through queries	
Modules	Building Module only	Same as 2.0	Multiple modules with ability to combine energy results across modules to form scenarios	
Development Language	VBA	VBA	TBD (Java, Python, C#, Ruby, Open Studio Measures, etc.)	
Energy Model Types	DOE-2	DOE-2	DOE-2 and Energy Plus	This requires ECMs to be implemented in

Feature	2.0	2.5	3.0	Comments
				IX instead of in the energy models

The IX 2.5 building module was built to meet the current needs of planners in the SNL Facilities Management and Operations Center. Modifications and additions for future versions were identified. The most immediate changes will advance the model to V. 3.0, which will include the following steps:

- Internalization of ECMs. Currently ECMs are included in eQUEST building models, so the addition of a new ECM would require manually adding that ECM to all the building models. Internalizing ECMs means that developers could add a new ECM to the IX architecture, and then that ECM would be available to any buildings in the IX model.
- Construction of algorithms for generalizing CUBs. Currently CUBs must be constructed by a developer. Algorithms for generalizing CUBs will allow users to reconfigure existing CUBs and configure new CUBs through the IX interface.
- Extend capabilities to post-process IX results. This will allow the generation of richer and more useful and informative results.
- Migrate IX from VBA software to an open-source platform. This will allow developers to streamline and speed up model processes and will make IX an application which does not require Microsoft Access and Excel.
- Improve the user interface.

An important objective for future versions of IX is to make the software appropriate for commercial distribution. This means producing a software package that has undergone rigorous testing to ensure that the software is robust. It will also allow fixes and updates to be added in more streamlined ways.

Various other modules that would increase the overall analytical and planning capabilities of the IX platform are also under consideration. These modules will address the following:

- Renewable energy sources including wind, geothermal, and solar hot water
- Energy storage including batteries, flywheels, and capacitors
- Water use and conservation
- Transportation, including on campus transportation, commuting, and business travel
- Materials
- Costs
- Coupling IX with real time building energy modeling systems

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5 CONCLUSION

The IX vision is to provide methodologies and tools that use aggregated results from detailed models so planners can make well-informed decisions concerning energy efficiency and sustainability across entire institutions. IX is envisioned to include comprehensive resource management including management of water, electricity, gas, materials, renewable energy, and infrastructures such as buildings and transportation. This broad vision is expected to be realized through many different tools. Currently, two modules have been created that address the building sector and the renewable energy sector.

This report has introduced the IX building module created collaboratively by Sandia National Laboratories, Bridgers and Paxton Engineering Firm, and Arizona State University. There are tremendous challenges that need to be addressed to make bottom up tools like the IX building module useful for large institutions. In order for building energy modeling to be economical, the models need to be used for multiple purposes in processes beyond IX. Applications should include initial energy assessments of building designs, individual use of models in eQUEST, site-wide use of models in the IX building module, building controls, and whole building model energy analytics.   Building energy models also need to be continuously maintained and vetted for accuracy. This effort has shown that even years after their creation, many of the models out of a fleet of 120 buildings still need calibration or require recalibration. The entire gas measurement system on a building level has been shown to have inadequate accuracy for the calibration of the building energy models. Actions to correct this are underway.

Overcoming these challenges requires significant investment to connect data streams, modeling, and users of the models in a new way. All of the technology exists to accomplish this but the tasks of integration of data streams, application of advanced algorithms, and making intensive use of modeling a common part of energy management will take many years to accomplish. As tools like the IX building module become increasingly common, the processes needed to create accurate models will become more efficient which will feedback into an accelerating capacity to make wise energy choices with less investment. Smart technologies tied to information technology will cause energy efficiency to reach unprecedented levels as a result which will in turn enable institutions to reach sustainable operations.

The IX building module 2.5 has been introduced in this report including the theory and an introduction to the software. The building module has been designed to be able to accept any group of DOE-2 building energy models and to coordinate these models in multiple ECM scenarios over many years. Scenarios for climate change, chiller efficiency, plug load power switches, and energy use break-down were presented to demonstrate the building module's diverse capabilities. Though the IX building module is ready to be applied across other sites, many tasks remain to increase its usefulness. The most important task is to remove ECMs from being hard-wired in building models. This will significantly reduce quality control problems when implementing ECMs. Another important task is to enable the module to receive Energy Plus models.

The IX renewables module has also been presented. It has undergone less development but provided important feedback concerning the return on investment for renewables at Sandia. Several scenarios were run that indicate that renewables did not have returns that were favorable in 2013-2014. Unlike the building module, the renewables module needs further generalization to be applicable to any site.

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APPENDIX A

No.	BuildingID	Site	Area
1	1090	New Mexico	Area II
2	518	New Mexico	Area IX
3	6526	New Mexico	Area III
4	6539	New Mexico	Area III
5	6580	New Mexico	Area V
6	6584	New Mexico	Area III
7	6585	New Mexico	Area V
8	6586	New Mexico	Area V
9	6587	New Mexico	Area III
10	6588	New Mexico	Area V
11	6596	New Mexico	Area V
12	6597	New Mexico	Area V
13	700	New Mexico	Area I
14	701	New Mexico	Area I
15	702	New Mexico	Area I
16	703	New Mexico	Area I
17	704	New Mexico	Area I
18	705	New Mexico	Area I
19	720	New Mexico	Area I
20	725	New Mexico	Area I
21	726	New Mexico	Area I
22	727	New Mexico	Area I
23	729	New Mexico	Area I
24	730	New Mexico	Area I
25	750	New Mexico	Area I
26	751	New Mexico	Area I
27	752	New Mexico	Area I
28	755	New Mexico	Area I
29	756	New Mexico	Area I
30	758	New Mexico	Area I
31	770	New Mexico	Area I
32	800	New Mexico	Area I
33	802	New Mexico	Area I
34	804	New Mexico	Area I
35	808	New Mexico	Area I
36	809	New Mexico	Area I
37	810	New Mexico	Area I
38	811	New Mexico	Area I
39	820	New Mexico	Area I

No.	BuildingID	Site	Area
40	821	New Mexico	Area I
41	823	New Mexico	Area I
42	825	New Mexico	Area I
43	827	New Mexico	Area I
44	831	New Mexico	Area I
45	832	New Mexico	Area I
46	835	New Mexico	Area I
47	836	New Mexico	Area I
48	850	New Mexico	Area I
49	855	New Mexico	Area I
50	856	New Mexico	Area I
51	857	New Mexico	Area I
52	858EF	New Mexico	Area I
53	858EL	New Mexico	Area I
54	858N	New Mexico	Area I
55	858S	New Mexico	Area I
56	859	New Mexico	Area I
57	860	New Mexico	Area I
58	861	New Mexico	Area I
59	864	New Mexico	Area I
60	865	New Mexico	Area I
61	867	New Mexico	Area I
62	868	New Mexico	Area I
63	869	New Mexico	Area I
64	870	New Mexico	Area I
65	872	New Mexico	Area I
66	875	New Mexico	Area I
67	878	New Mexico	Area I
68	879	New Mexico	Area I
69	880	New Mexico	Area I
70	880A	New Mexico	Area I
71	886	New Mexico	Area I
72	887	New Mexico	Area I
73	890	New Mexico	Area I
74	891	New Mexico	Area I
75	894	New Mexico	Area I
76	895	New Mexico	Area I
77	897	New Mexico	Area I
78	898	New Mexico	Area I
79	899	New Mexico	Area I
80	899A	New Mexico	Area I
81	905	New Mexico	Area II

No.	BuildingID	Site	Area
82	954	New Mexico	Area I
83	956	New Mexico	Area II
84	957	New Mexico	Area II
85	960	New Mexico	Area IV
86	961	New Mexico	Area IV
87	962	New Mexico	Area IV
88	963	New Mexico	Area IV
89	969	New Mexico	Area IV
90	970	New Mexico	Area IV
91	971	New Mexico	Area I
92	980	New Mexico	Area IV
93	981	New Mexico	Area IV
94	983	New Mexico	Area IV
95	986	New Mexico	Area IV
96	9956	New Mexico	Area VII
97	9981	New Mexico	Area VII
98	C905	California	Area I
99	C906	California	Area I
100	C907	California	Area I
101	C910	California	Area I
102	C911	California	Area I
103	C912	California	Area I
104	C914	California	Area I
105	C915	California	Area I
106	C916	California	Area I
107	C926	California	Area I
108	C928	California	Area I
109	C929	California	Area I
110	C940	California	Area I
111	C941	California	Area I
112	C942	California	Area I
113	C943	California	Area I
114	C960	California	Area I
115	C963	California	Area I
116	C9631	California	Area I
117	C9633	California	Area I
118	C964	California	Area I
119	C968	California	Area I
120	C972	California	Area I

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