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A Computational Framework for Low-Energy Community Analysis and Optimization

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ABSTRACT

The increasing world-wide emphasis on net zero (NZ) or low-energy communities (LECs) has brought with it a concomitant requirement for high quality technical analysis and optimization to support planners. The authors' experience in energy planning for military installations has identified best-practice processes as well as common analysis tasks performed by LEC planners. Requirements for data collection, modeling, optimization, and organization of inputs and results are significant, leading to higher cost, long study times, and limits on the number of alternative scenarios that can feasibly be considered. In addition, changes in data or scope can lead to considerable rework, leading to further delay and potential for the introduction of errors. This paper describes a computational framework and reference implementation for LEC analysis and optimization designed to automate many of the repetitive and time-consuming organizational, modeling, and optimization tasks involved in LEC planning. The framework incorporates whole building simulation, community-wide optimization of distribution and supply, geospatial data, and an overall approach to data organization that permits implementers to use their choice of modeling software. A reference implementation of the framework, the NZ planner was developed and tested at four Department of Defense installations. Results show decreased time to set up studies and to conduct simulations and optimization. This paper provides examples and discusses trade-offs between process steps that should be automated and those that are more appropriate for human judgment and experience.

INTRODUCTION

There are a number of important drivers for improving energy efficiency while reducing the use of fossil-fuel derived energy, including climate change mitigation, energy security, geopolitics, and economics. In our companion paper (Zhivov et al. 2014), we cite many of the applicable laws and policies, including the Energy Independence and Security Act of 2007 (EISA 2007) and the Energy Policy Act of 2005 (EPACT 2005). As organizations have adopted policies to meet or exceed these requirements, including a growing movement towards net-zero (NZ) or low-energy communities (LECs), there has been a growing need for comprehensive and integrated energy planning, as described in Zhivov (2012) and Zhivov et al. (2014). There are a number of definitions for NZ, including the definition used by the US Army, "A NZ Energy Installation is an installation that produces as much energy on site as it uses, over the course of a year" (US Army 2011). The Army Vision for NZ refers to a US Department of Energy publication for more information, implying that the intent is that on-site energy production should be performed using renewable sources (Booth et al. 2010). As defined, NZ is quite an ambitious goal that some communities might not be prepared to commit to, preferring instead to define their own low-energy community (LEC) goal, such as some significant reduction against a baseline. This paper uses the term installations to refer to communities and military installations with populations between 10,000 and 50,000, with the expectation that many of the principles applicable to installations may also apply to civilian communities.

Organizational experience with comprehensive energy planning processes in the US Army has shown that, although typically composed of fairly common steps, they are on the whole expensive and time consuming in terms of requirements

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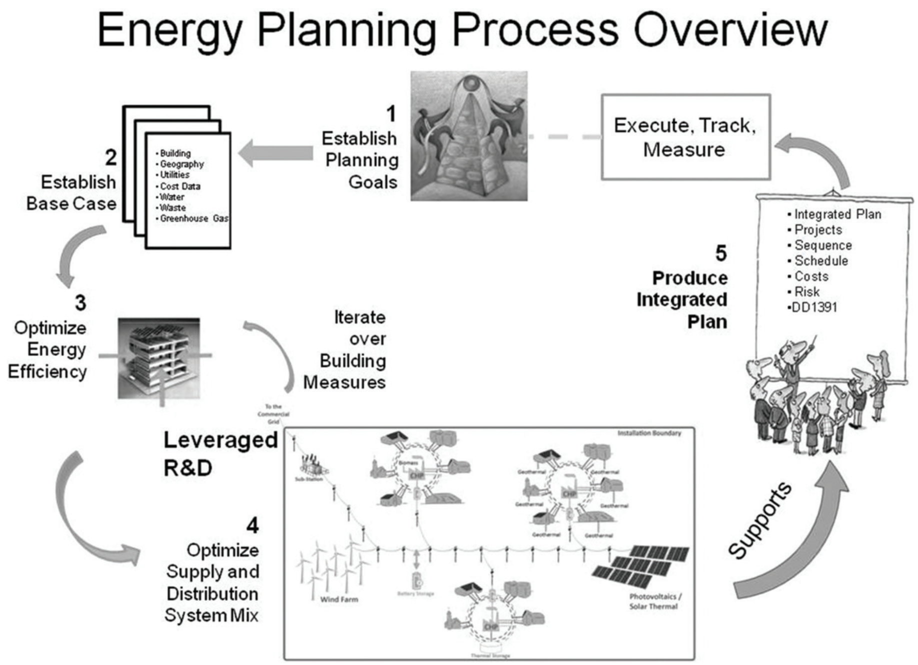

Figure 1 *The integrated energy planning process used be the NZI framework and tool.*

for data collection, organization of data, modeling of systems, and analysis of results. Furthermore, the complexity and expense of modeling and analysis limits the number of energy measures that can be considered because of the available time, budget, and subject matter expertise of those conducting the analysis. The US Army began a project in 2010 called "Modeling NZ Energy Installations" with the goal of identifying best practices in the process of community-scale energy planning and creating a computational framework for modeling and simulation that would help to significantly automate parts of the process to reduce cost and time requirements. A reference implementation of the framework called the Net Zero Planner was developed to demonstrate use of the framework and was tested at four Department of Defense installations: the United States Military Academy at West Point, NY, the Portsmouth Naval Shipyard, ME, Fort Leonard Wood, MO, and the Waterways Experiment Station, MS. This paper is intended to initiate a conversation about the best role for automation tools in support of NZ and LEC integrated planning, and about how different types of tools could fit together in an automated framework.

The term computational framework is defined to mean a modular software architecture, set of communications protocols, data definitions, and processes designed to meet a particular goal. In this case, the goal is a computational framework that supports comprehensive energy planning for communities, including buildings, district energy systems, electrical power distribution, and other potential energy systems. At the present time, the scope includes buildings and industrial processes, but not transportation. Lighting, water, and waste processes that consume energy are included as loads, although efficiency measures for them are not yet included. A new research project is underway to add models of interactions between energy, water, solid waste, and to a limited extent, transportation systems. The framework presented here is a research framework, a work in progress, and is intended to identify the principal components and interactions required to do community energy planning. The web-based reference implementation, Net Zero Planner, was developed to test the framework in a real-world environment as well as to be a useful tool for the authors. The goal of this paper is to communicate progress to date in developing and implementing a computational framework for community energy planning, not to promote Net Zero Planner as a tool. Application of the framework, in the form of Net Zero Planner, to real-world installations as it is being developed has helped to validate required elements of the framework as well as to identify missing pieces. Ideally, any component of the framework could be replaced by a different, but compliant module, including the web-based user interface. In practice, such interchangeability would require a significant level of standards development. This paper represents an early step in such a process.

In conducting a large number of planning studies and working with practitioners from around the world, a picture of an integrated planning process has evolved (Figure 1). In terms of a computational framework, it is useful to divide the study process into five major steps:

1. **Goal Setting.** Establish scope, framing goals, and criteria that will be used to compare alternatives against the baseline and basecase. Examples are: (a) decrease energy usage by 40%, or (b) reduce fossil-based energy usage by 100% (i.e., NZ). The goals are used to compare the basecase and alternatives.

2. **Baseline and Basecase Data Collection.** The importance of the most difficult part of doing an analysis—establishing the *baseline* energy usage—cannot be over emphasized. For the purpose of the study, the baseline is defined as the current energy consumption profile. It is essential that the baseline capture the quantity and type of energy used (transformed) by the community, such as grid electricity, natural gas, propane, and renewables. It is also important to understand how the energy is used, whether for heating, cooling, plug loads, or industrial processes. The baseline is a snapshot of a point in time and can be derived from a reference year or from consumption data averaged over a number of years to even out climatic variations. The *basecase* includes the baseline and factors in projected changes to the building inventory or process loads to calculate projected energy consumption over the entire study period. Alternatives considering portfolios of energy efficiency measures (EEMs), distribution, and supply measures may be compared against both the baseline and basecase.
3. **Building-Level Optimization.** Improving efficiency and reducing building loads is almost always less expensive than making changes to distribution or supply systems (The US Army generally uses the word facility instead of building. To avoid confusion, building is used in this paper, although the NZ planner uses facility.) Thus, we consider measures such as insulation, lighting, low flow fixtures, etc., before adding expensive renewable energy devices (e.g., photovoltaic solar panels) or other supply measures. At some point, additional EEMs may become more expensive than renewables, representing a logical stopping point for building efficiency improvement. Generically, we refer to any change done to a building (for the purpose of improving efficiency or reducing load) as an EEM. Building-level optimization refers to selecting the best set of EEMs for buildings in the community to meet the community's goals at the lowest cost. This statement does not presume a particular optimization method, which may range from generation of an exhaustive set of options to a more formal method.
4. **Supply and Distribution System Optimization.** Many communities began with centralized electrical and heating plants, usually using steam, and were then slowly converted to hot (and sometimes chilled) water distribution systems, or to completely decentralized systems using natural gas as a fuel and commercial power from the grid. Because of maintenance issues, steam distribution systems are almost never economically viable as new or recapitalized systems, compared to modern hot-water distribution systems, or even to completely decentralized systems. With a renewed emphasis on energy savings traced back to the source fuel, however, modern district systems may be the only way to meet policy goals economically. (Typical electrical generation, transmission, and distribution systems waste up to 70% of the source fuel [30% efficient] compared to cogeneration electrical/heat/cooling plants that can be up to 80% efficient [DOE 2013b].) Calculations and optimization are performed in this step to determine whether some form of centralized cogeneration or decentralization best meets the framing goals at the lowest cost. Industrial scale supply solutions such as solar photovoltaics, solar thermal, wind energy, biomass (wood chips, etc.), biogas, or synthetic gas need to be considered as part of the mix during distribution and supply optimization. They are almost always more expensive than making efficiency improvements or implementing cogeneration using natural gas as a fuel, but there may be other policy goals driving the use of these alternative technologies (e.g., NZ fossil fuel, support for a nascent industry, or energy security).
5. **Plan and Project Formulation.** The final integrated plan is produced by comparing the basecase and alternatives using the criteria defined as part of the framing goals. Multicriteria decision analysis (MCDA) methods may be used to support traceable decision processes and to integrate quantitative and qualitative factors selecting a preferred alternative. Sensitivity analysis should be conducted using the alternatives and risk factors such as price volatility (what happens if natural gas prices double), availability (is there a domestic supply?), and maintenance costs (e.g., relative risks of decentralized versus centralized equipment). The integrated plan contains a phased implementation strategy over the study period, showing investment costs (public or private), predicted energy, water, and waste reductions, and return on investment.

In light of the presented process steps and the goal of using automation to improve and speed up analysis, it is useful to examine automated approaches where they can be found in the literature. Although no integrated software approaches were found that covered all five task areas, there is significant automation support for building, supply, and distribution optimization. While some support was found for goal setting and decision support, very little was found for organizing collected data and establishing a baseline and basecase.

Building thermal performance calculations are designed for two primary reasons: to size and select mechanical equipment and to predict the annual energy consumption of a facility. While these two tasks are not mutually exclusive, and some programs can handle both tasks, they need to be evaluated separately. Most whole building annual energy simulation programs do both tasks; the initial steps of the simulation do the design calculations. These design results can be used by the program automatically to determine the inputs that can be used for the annual simulation.

Sizing or design programs are primarily designed to calculate peak hourly loads during the heating and cooling seasons. Therefore, extreme conditions and schedules are applied to get these peak results to ensure that the building can meet these conditions during actual operation. However, this is not the typical operation of the building, and design results cannot be extrapolated from peak calculations to obtain annual energy consumptions. Most sizing programs are based on procedures and algorithms established by ASHRAE, but many are proprietary products distributed or sold by equipment manufacturers.

Whole building energy programs are primarily designed to predict the annual energy performance and have become important as advanced technologies are evaluated and being specified. Many of today's advanced technologies can only be evaluated with longer simulation periods provided by these simulations.

The software examples listed below are not exhaustive; the programs listed and many more can be found at: http://apps1.eere.energy.gov/buildings/tools_directory/ (DOE 2013a).

Screening tools are primarily used during budgeting and programming of retrofits and retrofit strategies. Some examples include:

- The Federal Renewable Energy Screening Assistant (FRESA)
- The Facility Energy Decision System (FEDS)

Load calculation and HVAC sizing tools are used primarily during design development and construction documentation of new construction and major retrofits. Several of these programs can also be used to obtain annual hourly energy performance. Some examples include:

- Carrier's Hourly Analysis Program (HAP)
- Trane Corporation (TRACE)
- DOE-2
- Building Loads Analysis and System Thermodynamics (BLAST)
- VisualDOE
- EnergyPlus
- TRNSYS

Economic analysis tools are used throughout the design process to provide additional cost analysis, for example, the Building Life Cycle Cost (BLCC) program. Cost data, however, is usually provided by the user.

The net zero installation (NZI) tool uses a process that encompasses all of these steps: screening, energy, and economic analysis combined. At the heart of the energy assessment is the need for a rigorous energy analysis tool that can provide this assessment with the technical capability to discern, without bias, the sometimes subtle differences between technologies on at least an hourly resolution. The NZ planner uses EnergyPlus for this purpose (Crawley et al. 2001). In the spirit of a creating a framework, however, users should have the ability to choose a building simulation tool that they understand and that they trust.

Hourly whole building energy analysis programs are used to calculate energy performance and to analyze the energy efficiency of given designs or the efficiency of new technologies. Other uses include utility demand-side management and rebate programs, development and implementation of energy efficiency standards and compliance certification, and training new building professionals in architecture and engineering schools.

An integrated energy simulation means that all three of the major parts (building, system, and plant) must be solved simultaneously. In programs with sequential simulation, such as BLAST and DOE-2, the building zones, air-handling systems, and central plant equipment are simulated sequentially with no feedback. A zone heat balance is used to update the zone conditions and the heating and cooling loads are determined at each time step. This information is fed to the air-handling simulation to determine the system response, but that response does not affect zone conditions. This simulation technique works well when the system response is a well-defined function of the air temperature of the conditioned space. However, in most situations, the system capacity is dependent on outside conditions and/or other parameters of the conditioned space. The simple supply and demand situation becomes a more complex relationship, so the solution changes with the integrated feedback from the system and plant response in a real system. This real response does not happen in sequential simulation methods and the lack of feedback from the system to the building can lead to nonphysical results. To obtain a simulation that is physically realistic, the elements have to be linked in a simultaneous solution scheme. In EnergyPlus, all the elements are integrated and controlled by the integrated solution manager.

No program is able to handle every simulation situation. However, it is the intent of EnergyPlus to handle many building and HVAC design options and to calculate thermal loads and/or energy consumption for a design day or an extended period of time (up to, including, and beyond a year). Having this simulation as the heart of the energy analysis for the NZI tool allows for evaluation and the correct interactions when these technologies are trying to be evaluated and specified for cost-effectiveness.

In conducting a community-level planning and optimization study, there are two main uses for whole building energy analysis. The first use contributes to creating the energy baseline and basecase, while the second is to evaluate the performance of EEMs. Addressing the creation of an energy baseline first, it is important to deal with the case in which a large number of buildings must be considered in the baseline with limited metering data. In installations, it is common practice to group facilities into representative building types (e.g., office buildings, barracks/dormitories, commercial space, dining spaces, etc.) that can be modeled using a representative building model and then scaled by conditioned space to estimate the proportion of the total community energy that goes to each building. The total community energy can usually be obtained from meters at the boundary or from substations feeding the installation area. Some or (rarely) all of installation buildings may be metered as well (unlike most civilian communities). Typically, the authors use EnergyPlus to do this for each building type in the installation and then use a calibration process to match installation metered data against modeled data. This step of breaking down installation energy usage into its component parts is commonly called disaggregation and is a vital part of identifying the major uses of energy on the installation so that further analysis efforts can be directed to the most effective place. Ideally, the loads are broken down hourly over a typical year (8760 hours) to support further analysis of coincident and noncoincident peaks loads to support equipment sizing.

Calibration is a key step in establishing and disaggregating a baseline. Arguably, it requires a mixture of art and science, leavened by experience. In analyzing a large community with hundreds or thousands of buildings, resources are seldom available to conduct in-depth modeling or study of every building. Nor would the resources necessarily be well spent, given the granularity required of a planning-level study. The requirement is to get the models close enough to understand where most of the energy is used and, more importantly, to have some confidence that the models will reasonably predict the performance of EEMs applied to the buildings. Even if detailed meter data is available for all buildings for several years and is sufficient to create an energy baseline, the simulation models are still necessary for the purpose of predicting performance of EEMS.

Once a baseline has been determined, it remains to calculate the basecase described earlier. There are currently no automated tools that do this, with the exception of some proprietary spreadsheet models that the authors have been exposed to. The basecase is derived from the baseline by projecting energy use year after year for the life of the study, taking into account the demolition of facilities, construction of facilities to current required standards, scheduled capital improvements, and anything else likely to significantly affect the energy balance of the community.

The next major step is in building-level optimization of EEMs. In this iteration of the reference implementation, a manual optimization approach was used, in which building simulation was used to generate results from a standard set of EEM packages, developed for each standard reference manual. In the general approach, starting with a well-calibrated set of models covering the types of facilities in a community, the models can be adjusted to represent the modification of the facilities to include different technologies, control strategies, or management practices. Many of the same models that are useful for disaggregation are even more important in assessing the performance of EEMs. Crawley et al. prepared a survey paper that compares and contrasts 20 of the most commonly used building energy performance simulations (2008). The authors observe that, although many professionals use one particular simulation program for most of their work, the programs differ significantly in their capability; users might be better served by having a toolbox of programs that they use at different levels of resolution and for different technologies.

To assess the cost and feasibility of complying with the EISA (2007) and ASHRAE Standard 189.1 (ASHRAE 2009), the US Army Corps of Engineers (USACE) conducted a study using EnergyPlus and EEMs for the five most common building types built by the Army: (1) unaccompanied enlisted personnel housing (UEPH), (2) tactical equipment maintenance facilities (TEMF), (3) company operations facilities (COF), (4) brigade headquarters (BHQ), and (5) dining facilities (DFAC) (HQUSACE 2011). Further use of these building type models will be discussed later in the paper. EnergyPlus models were developed for standard USACE designs and for designs that met near passive house standards with advanced HVAC equipment (e.g., very high levels of insulation, low air infiltration, radiant heating and cooling, dedicated outside air systems). Results for three of the buildings studied are documented in Deru et al. (2012), Langner et al. (2012), and Liesen et al. (2012). In this case, the decision was made to use EnergyPlus because of the advanced technologies to be modeled. Many other building energy modeling programs are available; selection often depends on the experience, expertise, and judgment of the engineers performing an analysis. So long as the energy modeling simulation software is capable of predicting the performance of the EEMs being considered over the full 8760 hours in a year, selection of modeling software can be left up to the engineer.

Screening tools are frequently used to identify EEMs. The Department of Defense Renewables and Energy Efficiency Planning (REEP) program (Nemeth et al. 1995) and the FEDS (PNNL 2008) are screening tools that may also be used to identify EEMs as well. REEP uses a rule of thumb approach to estimate potential EEM savings while FEDS uses an internal building energy model that can be taken through a calibration step. REEP is no longer supported, but FEDS often serves as a valuable source of information in installation-level planning studies, especially as way to cross-check calibration of models and to ensure that potential EEMs are not overlooked. A goal for the framework, however, is to go beyond screening and to be able to model at the level of detail that time, situation, and resources allow. Thus, the users should be able to choose how detailed a building simulation they want to employ based on resources and the types of buildings that they encounter.

Once the basecase and alternatives have been calculated, including building loads and industrial processes, economic analysis can be conducted for reduction of building level loads. This step requires planning-level cost engineering and it can be quite difficult to get accurate costs. Aside from general purpose cost engineering databases such as RS Means (2013), there are few resources available to provide first, operations, and maintenance costs.

An important product of many of the available building analysis tools is a set of load profiles (heating, cooling, domestic hot water, and electricity) for all of the buildings included in the study. Many study teams stop at this point and identify projects. Integrated energy analysis studies, however, go beyond this point to consider district or cluster solutions, where cluster is defined as a system or systems serving a number of buildings ranging from a few to an entire district. This paper uses the term cluster and stipulates whether the focus is on one large cluster or many small clusters.

There are relatively few tools that have been developed for analysis of heating, cooling, and cogeneration clusters. The general problem is to determine whether it is economically feasible to use a common heating and cooling network to service a set of buildings when compared with a completely decentralized solution in which each building has its own heating and cooling equipment. Furthermore, we want to determine what size and type of energy conversion devices should be used, including, but not limited to, boilers, electric chillers, absorption chillers, cogeneration reciprocating engines or turbines, solar thermal panels, solar photovoltaic panels, wind turbines, and thermal or electrical storage. In general, two categories of models can be identified at the cluster level, simulation and optimization. Simulation approaches model the performance of a set of components and parameters (such as size or efficiency) defined by the user over a period of time at some time step (e.g., 8760 hours over the course of a year). In most simulations, the user can change components or parameters and run the simulation again in a new alternative to compare the performance of different design decisions. Optimization, on the other hand, uses some algorithm (e.g., linear programming, genetic algorithm, etc.) to explore the design space of components and parameters subject to a set of constraints. Because of the computational complexity of exploring a large design space, optimization models tend to be simpler linear models, while simulations may be more detailed and nonlinear.

Unlike the case of building energy simulation programs, there are relatively few examples of simulations set up to perform energy simulation at a city scale. CitySim (Robinson et al. 2009) is one such example of a simulation model with a graphical user interface that can be set up to model energy use in a community (Robinson et al. 2009). One benefit of such a model is that it allows users to explore the design space, placing buildings, energy conversion, and storage devices in a community setting and to analyze their performance. Users can play what-if scenarios and assess the consequences of their decisions. The drawback of this method is that it may take an inordinate amount of time to find a good solution, with no assurance that the design will be optimal.

There also exists a number of optimization models set up to use some form of optimization algorithm at an installation level. Notably, NZI-Opt (Swanson et al. 2014), MODEST (Henning 1997), and POLIS (Zhivov et al. 2010) all use linear programming or mixed-integer linear programming to size and dispatch energy conversion and storage devices for clusters of buildings at an installation scale. NZI-Opt sets up a superstructure of many possible devices. This, along with information about existing distribution and storage networks and mixed-integer linear programming, is used to select the optimal set of devices and control schedule to include in the system to meet a given set of loads. The common elements of most of these optimization approaches are that they require a specified electrical and thermal load (typically hourly data for a year), fuel and electricity rates, a set of devices to consider, and information about distribution and storage networks.

COMPUTATIONAL FRAMEWORK APPROACH

The Introduction section discussed the NZI process (Figure 1) and a number of tools commonly used to do integrated installation energy planning, where integrated means that building loads, distribution, and generation are all considered in the same analysis. For this paper, a computational framework is defined to mean a specification of data sets and computational tasks required to perform the NZI process. Each task performs operations on one or more data steps to produce one or more other data sets. In Figure 2, for instance, (a) is a data set (oval) containing parameters describing the physical geometry and systems for a building type, such as a barracks. A building energy simulation (b) can be applied to (a) as a computational task (rectangle) to produce a new data set of building electrical and thermal hourly loads for a year (c). In addition, set (a) can be modified by a computational task (d) using a set of EEMs to produce a new data set of parameters representing the building type with EEMs (e). Here also, simulation (b) can be applied to (e) to produce a new set of building loads (f) for the modified buildings. It follows that loads for the original building type (c) can be compared with loads for the improved building type (f) to assess the performance of the EEM set. To summarize, the NZI computational framework consists of data sets (ovals) and computational tasks (rectangles). Tasks are applied to data sets to create new data sets. Within the framework, there is no requirement that a computational task use a particular simulation or program (e.g., EnergyPlus, eQuest, TRNSYS), but only that the simulation be capable of transforming one type of data set into another. Thus, the intention is that the framework can be implemented with any number of appropriate tools and remain flexible to emerging tools.

Figure 3 shows the software architecture of NZI tool. The components are described below. NZI Tool is a web-based tool, using a commercial web browser plugin (Silverlight) to provide a near desktop experience in the user interface, connected to the NZI core acting as a web-based application server. Many of the essential computation tasks are provided as internet web services, which supply flexibility in scaling the service or in changing to new service providers. A web service is an application that is accessible via the internet and can respond to requests for tasks or data following a specified protocol.

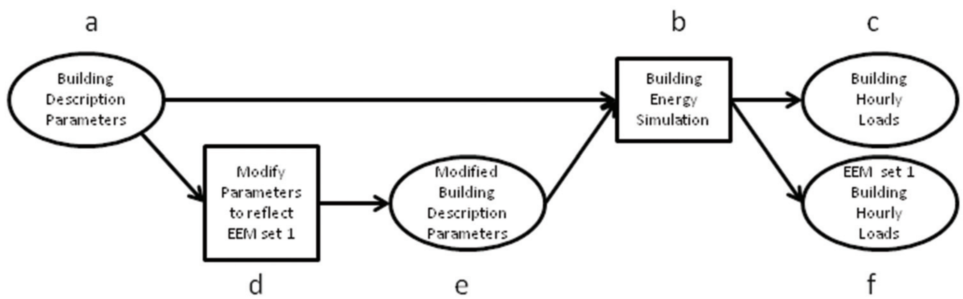

Figure 2 *Data sets (ovals) and computational task (rectangles) in a computational framework.*

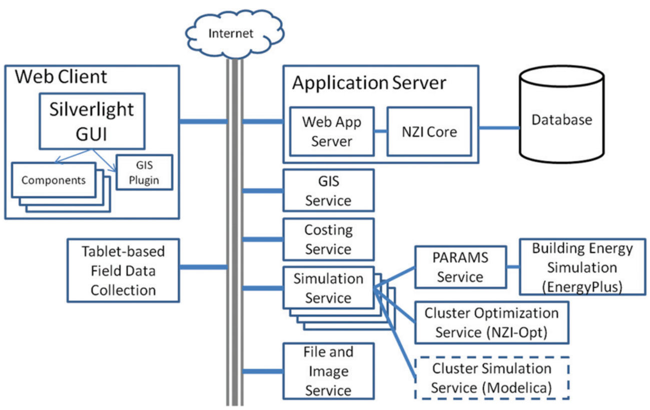

Figure 3 *The NZI tool software architecture. The cluster simulation service is under development and not yet available.*

The use of web services makes the framework robust and modular, allowing services to be upgraded without interruption to the system, so long as new versions adhere to the service protocol. Some such services include:

- **NZI core.** The NZI process flow and data structures are maintained in the NZI core and are implemented as a web application server and associated database. The principle function of the core is to organize the data, perform simple calculations, provide reporting functions, and control user access. Installation data is organized into studies and child alternatives, with the baseline and basecase being special forms of an alternative. Framing goals are set up in the core, linked to decision criteria, and quantitative data is used to compare alternatives. Geographical information system service (GIS) data is linked with the backend data, keeping track of which facilities belong to which building groups. The core also serves as a repository for all installation data used in a particular study, allowing field notes and images to be linked to particular facilities or systems. The intent of the framework is that the core is a module like any other, allowing other user interfaces and control logic to be developed in the future.
- **GIS.** Many energy-related calculations require geospatial information, so a GIS service is useful for mapping and displaying the location and footprint of buildings. This service, implemented using ESRI ArcGIS Server, provides data storage and organizing capability for building and energy networks.
- **Cost Engineering Service.** Estimating the cost of EEMs, energy network changes, supply devices, and storage devices is an important part of determining the economic feasibility of an alternative. The NZI tool implements a cost engineering service that contains cost models and associated data, responding to parameterized requests for cost information. The NZI core uses parameters stored in the baseline and each alternative to provide an estimated cost for that alternative.
- **Simulation Service.** Many computational tasks (building energy simulation, optimization, etc.) require powerful computational services to complete in a reasonable amount of time. The NZI framework provides a capability for distributed and asynchronous simulation using a job server. This is implemented on a server farm of virtual machines (VMs) with one master VM and ten identical client VMs colocated on a private network. The master VM hosts a web application that communicates with the NZI tool, queuing jobs and returning results. Each client's VM monitors the queue and executes up to four jobs concurrently. This allows the current job server system to run 40 analyses in parallel. However, because all client VMs are selfconfiguring, the number of simultaneous simulations can easily be expanded with additional server hardware and VMs.
- **Building Energy Simulation and Parametric Service.** Building energy simulation is performed by a combination of EnergyPlus and a pre- and postprocessor called PARAMS. The NZI core uses a set of parameters to describe the building based on a subset of input parameters accepted by building energy simulations such as EnergyPlus and eQuest. The current implementation of PARAMS is designed for EnergyPlus, but could be customized for other whole building simulation software, such as eQuest. PARAMS narrows the set of parameters that can be changed by the user to a subset that the authors consider practical at an installation planning level. These parameters are described in an eXtensibe Markup Language (XML) master definition file that the core requests from the simulation server and uses to

dynamically create the user interface. When the core requests simulation of a building type with a PARAMS input file, the simulation server passes the job to PARAMS, which generates input files, launches EnergyPlus, tracks the status of the job, retrieves the results, and postprocesses the results into a set of XML and comma-delimited loads files that are retrieved by the core as part of a data set. The PARAMS master definition file also describes the building simulation reference models that are available (e.g., barracks, dining facility, brigade headquarters, etc.). There are currently 16 EnergyPlus reference models available in the NZ planner, with more being added as needed. A custom model is available as well that allows the user to assemble a building model by specifying an area and fraction of different space types (e.g., classroom, administrative, hallway, etc.) that make up the building. For each reference model, default values of parameters such as orientation, window, wall, and roof overall heat transfer coefficient values (U), lighting types, roof emittance, equipment efficiency, and presence of day lighting controls are specified by PARAMs, with the user allowed to change them to suit conditions. Each reference model has an associated conditioned area, the intent being that the results be scaled to the actual area of the building. Determination of whether a model is appropriate to scale in this way requires some expertise and the research team is investigating options to set ranges of applicability for building reference models.

- **Cluster Optimization Service (NZI-Opt).** Cluster (or district) optimization is performed by the NZI-Opt Mixed-Integer Linear Programming model described in detail by Swanson et al. (2014). A cluster is a set of buildings to be optimized for energy supply and storage devices. The NZI core prepares a set of parameterized input files required by NZI-Opt, including definition of fuel prices, whether including wind and solar insolation, hourly cluster loads (electrical, heating, cooling, domestic hot water), available energy conversion and storage devices with costs, and constraints (minimum critical loads, percent renewable energy supply, green house gas limitations, etc.). NZI-Opt sets up a system superstructure, formulates the MILP problem using the open-source GNU Linear Programming Kit (GLPK), and solves for lowest cost subject to the specified constraints using a solver such as CPLEX or GLPSOL, a MILP solver from the GLPK. The basecase can be modeled by constraining NZI-Opt to use only devices and networks currently present in the community, in which case NZI-Opt will solve for most efficient operation. Table 1 shows an example of NZI-Opt output for a set of five alternatives and a single cluster. The time periods considered in the study is 30 years, with costs and performance annualized by summing them and divided by the study life.

- Table 2 shows an example of devices selected for each alternative. NZI-Opt returns an optimal data set specifying energy conversion and storage devices to be used, including an optimal operation schedule.
- **Cluster Simulation Service (Modelica—Under Development).** In conducting studies at military installations, teams are often asked to assess the potential performance

Table 1. NZI-Opt Returns Performance Values for a Single Cluster and Five Alternatives

	Baseline	LEAC	LEACR	DBC	NZFFE
Total investment cost ($)	0/0	2.53 mil	1.96 mil	4.53 mil	11.28 mil
On-demand capacity:					
Heating, Btu/min (kW)	796,880 (14,000)	512,280 (9000)	910,720 (16,000)	NA	950,564 (16,700)
Cooling, Btu/min (kW)	380,226 (6680)	50,090 (880)	400,148 (7030)	NA	430,315 (7560)
Electricity, Btu/min (kW)	0/0	56,920 (1000)	56,920 (1000)	0/0	45,536 (800)
Hot-water storage, gal (L)	20,000 (75,700)	80,000 (302,800)	20,000 (75,700)	0/0	260,000 (984,100)
Chilled-water storage, gal (L)	20,000 (75,700)	70,000 (264,950)	20,000 (75,700)	0/0	20,000 (75,700)
Net electricity purchase, Btu (kWh)	30,444 (8.92) (mil)	1,775/0.52 (mil)	4,983 (1.46) (mil)	30,239 (8.86) (mil)	0/0
Electricity generation, Btu (kWh)	0 (0)	26,314 (7.71) (mil)	23,754 (6.96) (mil)	0 (0)	28,874 (8.46) (mil)
Natural gas use, Btu (kWh)	35,598 (10.43) (mil)	83,892 (24.58) (mil)	77,031 (22.57) (mil)	33,038 (9.68) (mil)	0 (0)
Biomass use, Btu (kWh)	0 (0)	0 (0)	0 (0)	0 (0)	78,260 (22.93) (mil)
Site FF-based energy use, Btu (kWh)	66,042 (19.35) (mil)	85,666 (25.10) (mil)	82,014 (24.03) (mil)	63,277 (18.54) (mil)	0 (0)
Source FF-based Energy use, Btu (kWh)	139,114 (40.76) (mil)	89,933 (26.35) (mil)	93,960 (27.53) (mil)	135,837 (39.80) (mil)	0 (0)
Renewable percentage	0 (0)	0 (0)	0 (0)	0 (0)	100
Equivalent annual cost, $	1.87 mil	1.62 mil	1.81 mil	1.93 mil	2.29 mil

Note: LEAC (lowest equivalent annual cost); LEACR (lowest equivalent annual cost with heating and cooling redundancy); DBC (decentralized boilers and chillers); NZFFE (net zero fossil fuel energy).

Table 2. NZI-Opt Returns a Selected Set of Energy Conversion and Storage Devices for a Single Cluster and Five Alternatives

	Baseline	LEAC	LEACR	DBC	NZFFE
Existing Boilers, 24,000 lb/h (7000 kW)	2	1	2		2
Biomass Heat-Only, 3800 lb/h (1100 kW)					1
Biomass CHP, 456 MBtu/min (800 kWe)					1
Natural Gas Reciprocating Engine w/Heat Rec., 57 MBtu/min (1000 kWe)		1	1		
Existing Air-Cooled Chillers, 950 ton (3340 kW)	2		2		2
Single Stage Absorption Chiller, 100 ton (350 kW)			1		
Single Stage Absorption Chiller, 250 ton (880 kW)		1			1
Photovoltaic System, 79,688 Btu/min (1400 kW)-peak					1
Decentralized Boilers for all Buildings				1	
Decentralized Chillers for all Buildings				1	
Hot Water Storage, 60,000 gal (227,100 L)		1			4
Cold Water Storage, 50,000 gal (189,250 L)		1			
Existing Hot-Water Distribution Network	1	1	1		1
Existing Cold Water Distribution Network	1	1	1		1

of particular pieces of equipment, such as a particular type of heat pump or solar photovoltaic collection. Essentially, users would like to try out a piece of hardware or management practice. Optimization services such as NZI-Opt can be set up perform such trials, but they were not designed to do this and are limited by their need to use linear approximations for performance reasons. As a research objective, the authors are also interested in testing the optimized systems produced by NZI-Opt using nonlinear device performance characteristics and in performing sensitivity analysis. The cluster simulation service is being set up as a future capability to fulfill these requirements and will not be discussed further in this paper.

- **File and Image Service and Tablet-Based Field Data Collection.** When establishing the baseline, study teams gather data such as GIS, utility bills, and building drawings before visiting installations to verify conditions on the ground through building visits and staff interviews. As many who conduct site assessments know, organizing notes and images after site visits and making them available to the entire team can be a time-consuming administrative task. The NZI Tool includes a free-form service to store tagged files and associate them with facilities and systems in a study. A tablet-based application has been created to collect notes and images in the field. Data from the tablet can be automatically synchronized with facilities and infrastructure in a study.

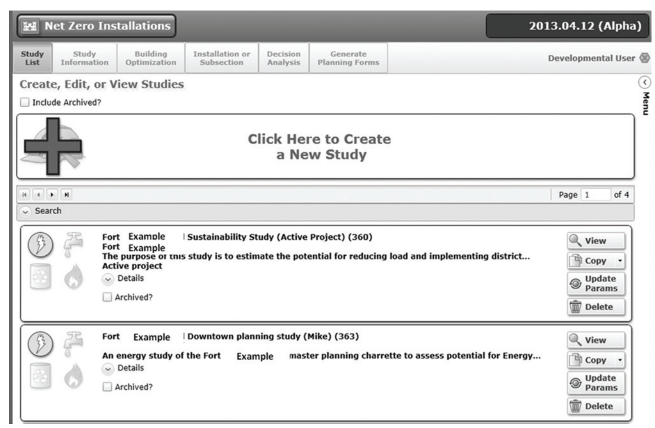

Figure 4 Each user sees a list of studies to which they have access in the NZI Tool.

IMPLEMENTATION EXAMPLE

The NZI framework and tool have been undergoing verification and validation at four military installations. The following example illustrates how the framework has actually been used in the field in conducting a study.

Framing Goals and Scope

One of the first tasks a study team faces in conducting a study in a community is coming to an agreement with the leaders on the scope and goals for the study. Table 3 shows an example set of framing goals for an installation. Figure 4

Table 3. Sample Framing Goals for an Installation Study

Parameter	Goal	Comments
Baseline year	FY 2007-2012	Based on average consumption
Analysis period	30 years	Based on sustainability plan
Efficiency improvement	30%	Integrate EEMs with major retrofits
Peak electrical load	170,606 MBtu/h (50 MW)	Hold the peak load below this value
NZ fossil fuel reduction	100%	NZ goal
Critical electrical load	102,364 MBtu/h (30 MW) On site	Requires contractual changes
Internal rate of return	3%	
Fuel flexibility	Natural gas/forest products	Available locally

shows a list of studies that a NZI tool user has access to. The major steps in the study process (study information, building optimization, installation or subsection, decision analysis, and generate planning forms) are shown as well. Each step has sub-steps listed below it. The user can proceed through each step and back up at any time, triggering possible resimulation at later steps. The study manager selects a location for the study in GIS and selects an appropriate Typical Meteorological Year, Version 3 (TMY3) format weather file for the region from data kept by the NZI core. The first step in establishing the scope occurs in the study information section of the NZI Tool. In Figure 4, the user selects facilities to be included in the study, defining the scope. All facilities in the study are kept in a master list. The user has the option to include or not include them in the baseline, basecase, and each alternative. The reason for this capability is to allow for alternatives that may require different combinations of buildings.

Baseline

The baseline data set consists of an inventory of buildings, data on past energy consumption and demographics, and energy profiles for all of the buildings, including electrical, heating, cooling, and domestic hot water. The first step in disaggregating the overall installation load is to group the facilities into building types, as shown in Figure 5. The NZI core currently has 16 standard building types into which it attempts to place facilities when they are imported from GIS data provided by the installation. The user then examines the data set to ensure facilities are in a building group with the correct representative energy model. This step requires a considerable amount of expertise and judgment on the part of the user, as well as an understanding of the building reference model.

Figure 5 *Grouping facilities into facility types.*

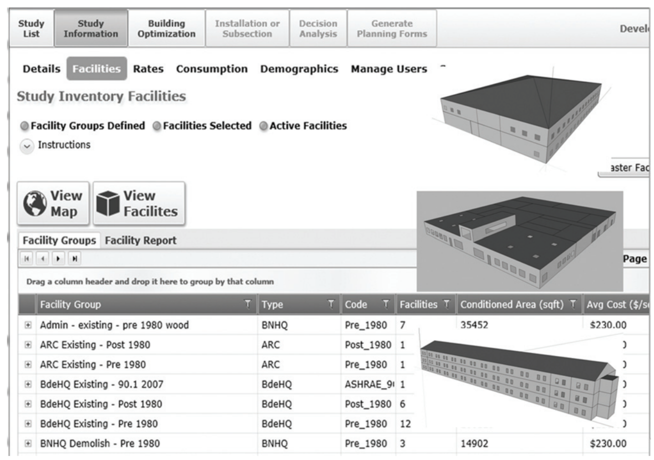

Figure 6 *Working from GIS data provided by the installation, the user selects buildings to be included in the project scope (shaded).*

Future work will attempt to find ways to simplify this step. Images have been overlaid in Figure 6 to illustrate sample building model types. In this study, about 500 buildings were divided into 35 building groups. Using the baseline data set, the NZI core automatically uses the simulation service, PARAMS, and EnergyPlus to simulate the performance of each of the building types, as shown in Figure 7. To get the performance of individual facilities, the standard model is scaled by the amount of conditioned space from the standard area of the reference model. Also note that the other alternatives, EEM sweep and basecase, are shown as tabs. Importantly, the user can opt not to use the built-in energy simulation for a particular building type and instead substitute results from another energy simulation program at this point. The authors have experimented using eQuest to simulate facilities not in the NZI tool library, have converted eQuest output to the PARAMS format, and have uploaded data with good results. There is also a customized model capability in the tool that

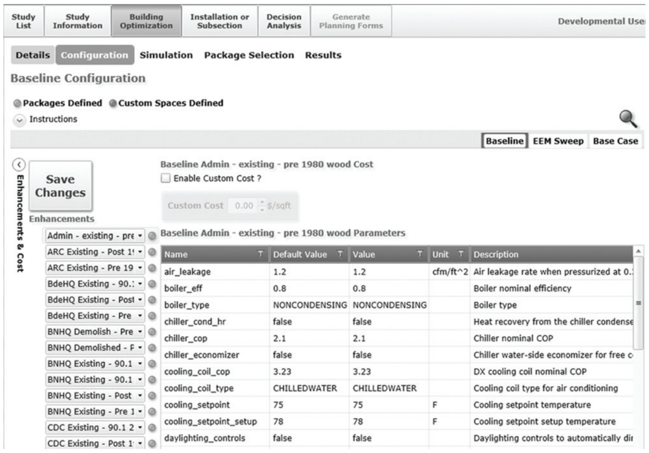

Figure 7 *The NZI core automatically sets up all of the facility types and simulations them on the NZI server farm using EnergyPlus. The user can review and change default parameters for each facility type.*

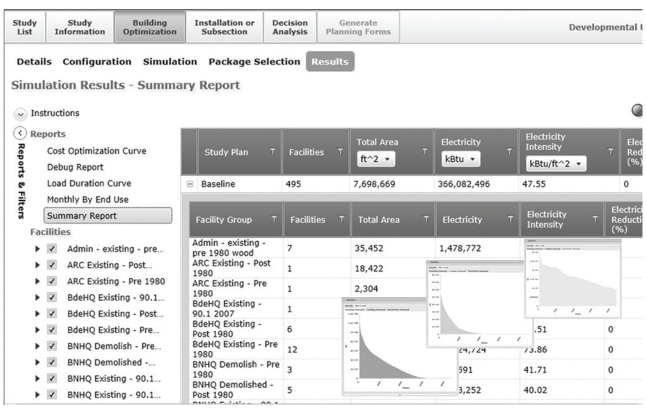

Figure 8 *Reports in the building optimization section give data on facility energy consumption for the baseline and all alternatives. Load duration curves are inlaid as an example.*

allows the user to break down a building type by space use type and approximate the performance of a custom building as well. Figure 8 shows the optimization report page, which yields statistics about the baseline in total and broken down by building type. Load duration curves are overlaid for illustration, although they would be found in a different report. At the end of this step, the user starts the calibration step in which model results from the simulation are compared with utility bills and as much meter data as is available. Unfortunately, there is currently no automated approach to calibration, although such a capability has been discussed. This problem is common to many tools, including FEDS and the former REEP. One danger of an automated approach is that it might calibrate a model for an incorrect reason, such as automatically adjusting air infiltration when some other phenomena such as overlooked internal loads is causing the model to be in error. If the modeled results are significantly different then metered data, the user must decide which part of the model is most in error and take steps to correct it. For instance, they might find that the buildings have much higher infiltration than the standard model or that the plug loads are significantly higher than expected. The goal is not to model each building exactly, but rather to find the facilities or processes that are using the most energy so that the focus can be turned on them.

Basecase

A building group can be tagged as *existing*, *demolish*, or *planned*. Facilities marked *existing* or *demolish* will always be shown in the baseline. Facilities marked *existing* or *planned* will be shown in all other alternatives, including the basecase, to indicate a future situation at the end of the study life. A finer-grained option in a temporal sense, although not implemented, would be to allow the user to step through a study year by year. A basecase is created as a type of alternative with no EEMs applied. New facilities are constructed to a specified standard, such as ASHRAE Standard 90.1-2007 or 90.1-2010 (ASHRAE 2007; 2010).

Building Optimization

The NZI tool saves substantial time when conducting studies through its ability to automatically apply *packages* of EEMs to building types. Packages are put together by subject matter experts with experience in building optimization and organized by building type and era of construction (e.g., built to ASHRAE Standard 90.1-2007). The NZI tool obtains the EEM package from the PARAMS server in an XML format and dynamically modifies the user interface to display them to the user. The NZI Tool displays packages of EEMS, such as lighting, high efficiency equipment, and airtightness (infiltration) (Figure 9). Up to 12 different sets of packages might be applied, although there is no limit in the framework. Packages can depend on each other. For instance, the HVAC package could depend on the infiltration and lighting package. The user can review the EEM parameters or accept the defaults for a first pass, coming back later to refine the EEMs and possibly reflect newer technology. The inset graphic in Figure 9 shows the comparison matrix containing the baseline, basecase, and EEM sweep. Note that the number of facilities and area increases from the baseline, but the energy intensity goes down significantly in the EEM sweep. The user can review the results of each EEM package set, including costs retrieved from the cost engineering service, and select the desired package set of EEMS. At the end of the building optimization step, the NZI tool contains a data set for each alternative with a full set of building load profiles. At least some of the alternatives contain reduced loads after application of EEM package sets. At this point, the user is ready to consider supply and distribution options.

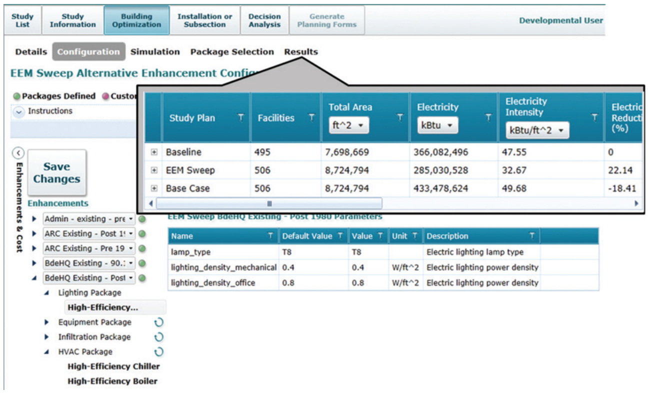

Figure 9 *The NZI tool automatically applies different packages of EEMs to each facility type, according to their type and era of construction. The inset shows results from the baseline, basecase, and the EEM sweep alternative.*

Figure 10 *The user can select facilities to include in a small or large district energy system, called a cluster. As facilities are added or removed, statistics on number of buildings, loads, and energy density are updated.*

Cluster Optimization

Installations have several options when it comes to meeting their heating, cooling, and electrical needs. In a decentralized approach, electricity, and natural gas are commonly run to each building, which has its own dedicated heating and cooling equipment. This has a drawback in that the equipment in each building must be sized to meet the peak loads and may be under-used much of the year. Alternatively, if the facilities are close enough in a geospatial sense, heating and cooling networks may be run and common district or cluster equipment may be shared. In addition, cogeneration or poly-generation may be used, increasing the source fuel efficiency considerably. The NZI Tool, using NZI-Opt, is set up to make it easy to test alternative strategies of decentralized versus cluster strategies. In Figure 10, the user has selected a set of facilities that are on an existing 4-pipe hot-water and chilled-water network with centralized boilers and chillers. Since the NZI tool has load profiles for all of the buildings from the previous step, it can display the cluster heating, cooling, domestic hot water, and electrical load, as well as the density of the load based on a polygon encompassing the selected buildings. As a rule of thumb, the higher the energy density, the better a candidate the system is for a cluster supply strategy. The user can accept defaults for running NZI-Opt (Figure 11), including editing energy conversion and storage devices in screen 11.1, setting up constraints in screen 11.2. Screen 11.3 is shows the status of instances of NZI-Opt on the simulation server, indicating that five have been completed and that one is still running. Heating and cooling networks are modeled as storage devices, with estimated values for standby and operational thermal losses due to ground conduction and for pumping losses. Study teams often make assumptions for network losses based on rules of thumb for energy density between 3% (for very dense, well insulated systems) to more than 20% (for older and less dense systems). The NZI tool has a capability to import energy networks from GIS or

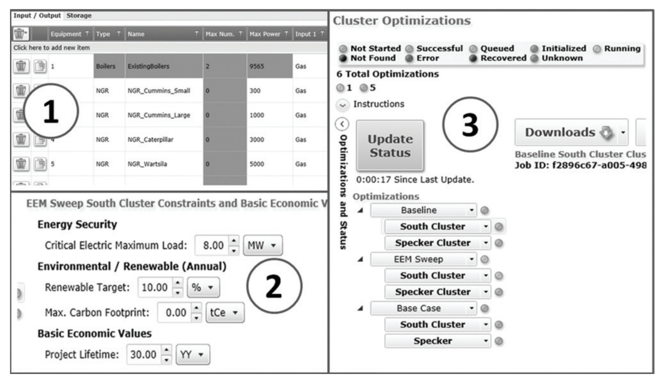

Figure 11 *Running cluster optimization from the NZI tool. In screen 1, the user can accept the default set of energy conversion and storage devices, or can add new ones. In screen 2, the user can set constraints. Screen 3 shows the simulation control page. Each of the alternatives is shown and a total of 6 instances of NZI-Opt are run (5 are finished, 1 is still running).*

to draw them in and then to export to EPANet to calculate pressure drop and assist in sizing networks (Figure 12). Following the completion of the NZI-Opt runs, the performance of each cluster is combined with those buildings that are not in a cluster and presented together in a table similar to Table 1 so that the user can make an informed choice between the basecase and alternatives. Here again, the NZI tool provides estimated costs for the recommended devices in each alternative. A new module is currently under development to provide MCDA support and screens that will allow users to compare alternatives in a decision matrix that adds criteria weighting and qualitative factors.

Figure 12 Thermal networks can be drawn in or imported from GIS. The costing service has the ability to estimate costs to install networks using a variety of burial techniques in different ground types. It can also export an EPANet formatted file to estimate pressure drop using the simulation service.

SUMMARY AND DISCUSSION

It is always a challenge to attempt to automate steps in processes that rely a great deal on professional expertise and experience. Many talented professionals express the opinion that the task is impossible and the authors would agree that it is certainly difficult. However, the NZI team has learned a great deal from the experience of putting together a framework and tool that has substantially accomplished its goals, but still has room for improvement.

In testing the process, framework, and tool at four installations, it has proven useful in selecting facilities and automatically setting up energy simulations using EnergyPlus. This process can take weeks and involves a great deal of manual file organization and careful attention to keeping simulation runs in the right place and associated with the right facilities. For each installation following the site visit, the process of grouping facilities into appropriate building types typically took about eight hours of work for an experienced team. Once the models were set up, running them using the coarsely parallel server farm could be accomplished in about an hour for 500 facilities divided into 15 types. The real acceleration occurred in applying EEM package sets. Between 8 and 13 EEM package sets were applied to 15 building types, resulting in a set of 555 EnergyPlus simulations to be run. A caching capability was added to the NZI tool so that once a simulation had been run with a particular set of input parameters in any study, the results are saved in a database. As an outcome, the tool runs large sets of simulations much faster than would be possible for an individual on a desktop computer. Typically, the simulation runs take about 2 hours for a simulation set of that size the first time. Subsequent runs are much faster as minor changes are made to simulations. In the authors' experience, the same process performed outside of the tool took three to four weeks.

Perhaps a greater improvement is made possible by the ability of the framework and tool to keep results organized and to recalculate summary results when changes are made to the initial models runs. When working with experienced teams running simulations on their own computers and compiling results using spreadsheets, we found that there is increasing resistance to making changes to the original models and recompiling the results as studies progress. This is understandable due to the additional work and the danger of introducing errors as numbers are cut and pasted in spreadsheets. When working in the tool, however, it is almost trivial to add or remove facilities and to change key assumptions such as air infiltration rate or envelope thermal conductivity. The simulation can be rerun very quickly and the results compiled quickly. This proved to be a very useful capability during calibration with utility bills and led to exploration of more options.

There were certainly data sets and tasks for which the tool was not as immediately useful, although the NZI computational framework still applied. In some cases, such as preparing reports to view data in a certain way, the tools were not ready or the report was a new requirement and the turn-around time to get software engineers to prepare a report was too long or expensive. Additionally, the teams that performed studies frequently encountered difficulties in sharing data (spreadsheets, photos, drawings, notes, etc.) between team members. Much of the data required access control and could not be stored on publically available file sharing sites. This led to the addition of the file and image service together with the tablet-based field data collection. The rationale was that data, images, and free-form files should be linked to data sets and computational tasks in the NZI tool. Thus, if there is an unusual condition or a need for a new graph or analysis, the data can be downloaded into a spreadsheet, the work performed, and the results attached to a particular data set in and alternative where it is relevant. No tool is likely to cover all of the possible conditions it will be used under. Incorporating an ability to associate free-form files maintains flexibility.

The NZI framework and tool continues to evolve. The research team is actively documenting the schema for data sets and computational tasks with a goal of sharing them with energy professions with an interest in standardizing processes and analyses used in community energy planning. This schema is scheduled for publication in the fall of 2013. Many of the components used in the reference implementation are open source and the authors are interested in collaboration with individuals or organizations that have in interest in evolution of the framework to accommodate their own tools. There are several areas of active research interest, including incorporation of coupled energy, water, and waste systems, non-linear simulation using Modelica, and finer-grained phasing of energy plans to optimize the order and timing of sub-project execution.

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DISCUSSION

Lawrence Markel, Principal, SRA, Knoxville, TN: You have discussed facility requirements and needs, but have you incorporated mission-oriented resource use yet? For example, in consolidating data center servers and utilizing the cloud, you can compare energy use from multiple data centers (original) with energy used by fewer data centers (after consolidation).

In your case, if an air base is expanding with more aircraft operations, can you look at the trade-off of constructing more electricity-intensive simulators versus the mission-oriented aviation fuel you save by replacing some training flights with simulator use? Do you have plans to combine mission-oriented options and resource use with facility-related resource planning?

Michael Case: The computational framework represents mission-oriented resource usage as energy density for lighting, information technology, major equipment, and other plug loads. For instance, if data centers were consolidated, the energy density would decrease in some buildings and increase in others. The framework does not currently consider trade-offs with mission-oriented fuels, although this is an excellent suggestion. Non-mission transportation fuel is scheduled to be included in 2015.