A Methodology to Sequentially Identify Cost Effective Energy Efficiency Measures:

Application to Net Zero School Buildings

by

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ABSTRACT

Schools all around the country are improving the performance of their buildings by adopting high performance design principles. Higher levels of energy efficiency can pave the way for K-12 Schools to achieve net zero energy (NZE) conditions, a state where the energy generated by on-site renewable sources are sufficient to meet the cumulative annual energy demands of the facility. A key capability for the proliferation of Net Zero Energy Buildings (NZEB) is the need for a design methodology that identifies the optimum mix of energy efficient design features to be incorporated into the building. The design methodology should take into account the interaction effects of various energy efficiency measures as well as their associated costs so that life cycle cost can be minimized for the entire life span of the building.

This research aims at developing such a methodology for generating cost effective net zero energy solutions for school buildings. The Department of Energy (DOE) prototype primary school, meant to serve as the starting baseline, was modeled in the building energy simulation software eQUEST and made compliant with the requirement of ASHRAE 90.1-2007. Commonly used efficiency measures, for which credible initial cost and maintenance data were available, were selected as the parametric design set. An initial sensitivity analysis was conducted by using the Morris Method to rank the efficiency measures in terms of their importance and interaction strengths. A sequential search technique was adopted to search the solution space and identify combinations that lie near the Pareto-optimal front; this allowed various minimum cost design solutions to be identified corresponding to different energy savings levels.

Based on the results of this study, it was found that the cost optimal combination of measures over the 30 year analysis span resulted in an annual energy cost reduction of 47%, while net zero site energy conditions were achieved by the addition of a 435 kW photovoltaic generation system that covered 73% of the roof area. The simple payback period for the additional technology required to achieve NZE conditions was calculated to be 26.3 years and carried a 37.4% premium over the initial building construction cost. The study identifies future work in how to automate this computationally conservative search technique so that it can provide practical feedback to the building designer during all stages of the design process.

DEDICATION

This work is dedicated to my parents and various members of my extended family. Their unending support, encouragement and prayers have always helped me overcome new challenges in life.

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1 INTRODUCTION

1.1 Problem Statement

Feedback from whole building energy simulation has become an invaluable component in the workflow of high performance building designs. Design teams carry out parametric studies of various efficiency measures on a trial and error basis and select combinations that provide the required cumulative energy savings. The economic feasibility of a planned option is usually assessed by simple payback analysis and is conducted at the very end of the design process. Steep energy performance targets and high capital investment are inherent in all net zero energy building (NZEB) designs requiring extensive energy and economic analysis to justify cost effectiveness. As the momentum behind NZE increases and more projects begin to demonstrate that NZE is an achievable goal, it is imperative that design teams examine cost control strategies and analytical processes that demonstrate the economic feasibility of a project.

Optimization techniques coupled with life cycle cost analysis can be an effective way to demonstrate that the design has achieved a balance between energy performance and economic returns. But the sheer number of building efficiency components and parameters makes traditional exhaustive optimization search methodologies cumbersome and difficult to integrate into the design process. At the same time, uncertainty in purchasing and maintenance cost data introduces a large amount of mathematical uncertainty into an unique optimum solution, and in many cases near-optimum solutions can be of equal value to the design team. Apart from taking account of the mutual interactions of parameters on building energy use, it is crucial that any such process also considers cost savings resulting from a reduction in system size when external and internal loads are reduced due to the implementation of higher efficiency options.

1.2 Objective

The objective of this study is to develop and demonstrate a process involving energy simulation, life cycle cost analysis and selective optimization search to determine a pathway leading to net zero energy use in a K-12 school building. This building typology was selected because K-12 school facilities, because of their low energy use intensity and greater roof and site area, have a greater advantage in achieving NZE condition over other building types. Further the benefits of efficiency features on the health and performance of school students is well documented. The study is conducted using DOE’s prototype building model (Deru et al, 2011) situated in a specific climate (Phoenix, AZ), and makes use of common off the shelve efficiency measures for which credible cost and maintenance data was available. A sensitivity analysis is also to be conducted to provide further validation of the optimization results.

By developing a net zero pathway, the study intends to determine the optimal combination of efficiency solutions and building design parameters that produces the highest life cycle cost savings compared to the ASHRAE 90.1 (2007) baseline case as well as the amount of additional investment that is required to develop a NZE school. By conducting additional sensitivity analysis, common efficiency measures can be ranked in terms of their interaction strengths thereby providing insights to the designer on which options to focus on first in order to reach quicker results.

1.3 Limitation

The range of the study was restricted by the lack of credible and accurate cost and maintenance data regarding energy design measures and by the inherent limitations of the energy simulation software used (eQUEST, 3.65). A reliable strategy for achieving NZE is to maximize energy savings by the use of conventional efficiency measures before shifting to renewable generation. In this study only measures with credible cost data were chosen for the initial set of parameters; the most effective combination was able to achieve 53% energy savings and decreased the building's energy use intensity (EUI) from an initial 66.8 kBtu/ft^2 to 32.3 kBtu/ft^2. This study did not consider several recently developed high efficiency secondary systems like decoupled ventilation, radiant cooling based systems etc. which could have reduced the EUI further. However, the main intention of this study was to highlight a process of achieving cost optimum conditions instead of achieving the highest possible energy savings.

A majority of the high performance schools that were studied incorporated strategies like clerestory lighting, tubular sky lighting, lighting shelves etc. Further, the low energy model selected during the preparation of the Advanced Energy Design Guide (ASHRAE) also had several south facing roof monitors. The energy conservation effects of innovative daylight design options were not included in this study due to modeling and daylighting analysis related limitations in the eQUEST simulation program.

2 THEORETICAL BACKGROUND

2.1 High Performance Schools

Sustainability and energy efficiency initiatives at schools, apart from reducing pollution and land fill waste, have been shown to provide health and economic benefits. Firstly, energy cost has been found to come second only to salaries in school budgets (ASE, 2003) and a study showed that 61% of public schools districts have reported a shortfall in funding to pay energy bills in the past years (Smith et al, 2003). High performance schools generally show annual energy savings in the range of 20-40% (Haberl et al, 2007) and hence can help alleviate this burden. The U.S. Department of Energy also estimates that high utility bills could be reduced by 25% if schools were to adopt readily available high performance design principles and technologies.

Secondly, high performance schools usually incorporate advanced daylighting principles and HVAC systems that can monitor and control indoor air quality more effectively. These two elements have been shown to directly influence student performance and absenteeism rates (CHPS, 2003). Hathaway et al, (1992) found that under the full spectrum of daylight, students learned faster, tested higher and had 1/3rd fewer absences due to illness when compared to children attending similar schools under normal lighting. Another study (Heschong Mahone Group 1999, 2003) found that students with daylighting in their classrooms progressed 20% faster on math tests and 26% faster on reading tests than students in the least daylight classrooms did over a one-year period. The connection between IAQ and student performance have also been highlighted by various studies.

Research on asthma in school children (Wargocki, 2000; Smedje, 1997) found that reported asthma cases were less common in schools that had installed new ventilation systems, as the new system resulted in higher air exchange rates and hence lowered the concentration of indoor airborne pollutants. The studies also recorded a correlation between higher concentration of pollutions and reduced performance among occupants.

Haberl et al, (2007) conducted an extensive survey of high performance schools around the country and documented the following characteristics:

- The annual energy savings from the application of energy efficient building components compared to less efficient components varies from 1% to 49%. However, most of the annual energy savings are in the range of 20- 40%.
- Ground source heat pumps and ice storage systems have been frequently adopted by schools to save energy and reduce kW demand.
- The EUI for high performance schools (K- 12 only) in the US DOE's EERE database is about 23 to 60 kBtu/sq.ft. (i.e., on average, 28.8 kBtu/sq.ft.).
- The average EUI for existing high performance schools from the EERE database is about 51% to 62% less than the national average for existing schools in the U.S.
- The average EUI for existing high performance schools from the EERE database is about 20% to 40% less than the schools compliant with ASHRAE 90.1-1999.
- The most popular choice of measures for high performance schools includes: high performance glazing (i.e., low SHGC), T5 or T8 fluorescent lamps, high R-values for walls and roofs, occupancy sensors to control lighting, photovoltaic (PV) systems, ground source heat pumps, and high AFUE (e.g., over 90%) boilers.

- Different strategies by different climate zones should be considered in the design phase of high performance schools.

2.2 Case Studies

During the course of this study, ASHRAE's high performance building database was used to analyze eleven documented high performing schools and the characteristics were found to be similar to that shown in the previous section (Haberl et al, 2007). Table 2-1 provides a summary of the findings.

Table 2-1 Summary of High Performance School Survey

Case#1		***Major Energy Conservation Features***
Name	Great Seneca Creek Elementary School	• Low-e glazing • Fiberglass window frames • Interior and exterior lighting controls • Vacancy sensors • Ground-coupled heat pump system • High efficiency boilers • Plug load control • Energy recovery
Location	Germantown, Md	
Size (sft)	82,511	
Occupancy	740	
Distinction	LEED_NC Gold	
Completion Date	2006	
EUI (kbtu/sft)	31.31	
Construction Cost ($/sft)	218.15	
Case#2		
Name	Northern Guilford Middle School	• Clerestory Daylighting • UFAD System • Light Shelves • Light Wells • Innovative Overhang Design • Lighting dimming sensor • Solar hot water system • Advanced metering and monitoring • PV system
Location	Greensboro, N.C	
Size (sft)	140,000	
Occupancy	950	
Distinction	ENERGY STAR Label	
Completion Date	2007	
EUI (kbtu/sft)	34.73	
Construction Cost ($/sft)	148	
Case#3		
Name	Plano Elementary School	• Geothermal HVAC: dual compressor units with distributive water pumping • Geothermal domestic water heating • DOAS • Occupancy controls • District energy management program
Location	Bowling Green, Ky	
Size (sft)	81,147	
Occupancy	435	
Distinction	ENERGY STAR Label (Score-99), Andromeda Star of Energy Efficiency	

Completion Date	2007	
EUI (kbtu/sft)	26.8	
Construction Cost ($/sft)	140	
Case#4		
Name	Twenhofel Middle School	• Advanced Daylighting features • Lighting dimming sensor • Geothermal HVAC PV system (22 kW) • Occupancy controls • DOAS • District energy management program
Location	Independence, Ky	
Size (sft)	112,000	
Occupancy	900	
Distinction	LEED Silver, ENERGY STAR Label	
Completion Date	2006	
EUI (kbtu/sft)	46	
Construction Cost ($/sft)	170	
Case#5		
Name	Two Harbors High School	• Advanced Daylighting features • Lighting dimming sensor • Occupancy controls • DOAS • Thermal displacement ventilation • Radiant floor heating • Energy recovery unit
Location	Two Harbors, Minn.	
Size (sft)	190,000	
Occupancy	800	
Distinction	2009 ASHRAE Technology Awards	
Completion Date	2004	
EUI (kbtu/sft)	56	
Construction Cost ($/sft)	128.94	
Case#6		
Name	Bethke Elementary School	• High performance envelope • Perimeter daylighting controls • Core daylighting with solar tubes • Thermal displacement ventilation in large volume spaces • High-efficiency boilers • Tower indirect cooling and direct evaporative cooling • Lighting dimming sensor • Energy recovery wheels • PV System (21kW) • Active load control
Location	Timnath, Colo.	
Size (sft)	63,000	
Occupancy	525	
Distinction	LEED Gold, Green Globes	
Completion Date	2008	
EUI (kbtu/sft)	42	
Construction Cost ($/sft)	151	
Case#7		
Name	Manassas Park Elementary School and Prekindergarten	• High performance envelope • Clerestory Daylighting • Special shading devices • Natural ventilation with induced stack effect • Ground source heat pump (one for each classroom) • BAS system • Lighting dimming sensor • Vacancy sensors • Tubular skylight
Location	Manassas Park, Va.	
Size (sft)	140,463	
Occupancy	840	
Distinction	LEED Gold, Energy Star (80)	
Completion Date	2009	
EUI (kbtu/sft)	37.28	

Construction Cost ($/sft)	199.53	
Case#8		
Name	Richardsville Elementary School	• High performance envelope • Clerestory Daylighting and light shelves • Geothermal HVAC • Demand control ventilation • BAS system • Lighting dimming sensor • Vacancy sensors • DOAS • PV System (348 kW producing 17.8 kBtu/sft equivalent energy)
Location	Richardsville, Ky	
Size (sft)	72,285	
Occupancy	460	
Distinction	1st Net Zero school in U.S	
Completion Date	2010	
EUI (kbtu/sft)	18.2 (0.39 considering PV generation)	
Construction Cost ($/sft)	206.5	
Case#9		
Name	Kiowa County Schools	• Clerestory Daylighting • High performance envelope • Geothermal HVAC • Demand control ventilation • Occupancy sensors • Wind turbine (50kW) • DOAS with energy recovery • High Efficiency Chiller
Location	Greensburg, Kan.	
Size (sft)	123,405	
Occupancy	410	
Distinction	LEED Platinum	
Completion Date	2010	
EUI (kbtu/sft)	29.2	
Construction Cost ($/sft)	238	
Case#10		
Name	Kensington High School for the Creative and Performing Arts	• Clerestory Daylighting • High performance envelope • Geothermal HVAC • Occupancy sensors • Lighting dimming sensor • DOAS with energy recovery • BAS System • Natural ventilation strategies
Location	Philadelphia	
Size (sft)	88,450	
Occupancy	440	
Distinction	LEED Platinum	
Completion Date	2010	
EUI (kbtu/sft)	39.74	
Construction Cost $/sft)	267	
Case#11		
Name	Sandy High School	• Clerestory Daylighting • High performance envelope • Translucent skylights • Modular heat recovery chiller • PV system (166 kW) • Special shading devices • Natural ventilation strategies • Displacement ventilation • Geothermal HVAC • Occupancy sensors
Location	Sandy, Ore.	
Size (sft)	310,000	
Occupancy	1,450	
Distinction	LEED Gold	
Completion Date	2012	
EUI (kbtu/sft)	35	
Construction Cost ($/sft)	273	

2.3 Cost effectiveness and cost control strategies

It is widely agreed that achieving cost effectiveness is one of the most crucial factors in achieving wider market penetration of NZE technology and practices. Pless et al, (2012) state that design teams and building owners commonly cite the incremental first cost of energy strategies as a significant barrier to realizing high performance in commercial construction projects. The common perception is that NZE is cost prohibitive and suitable only for special projects with large budgets. This conception partly arises because, in the past, project teams usually relied on simple payback analysis to justify energy-efficiency strategies. Components were analyzed in isolation and hence the impact of a change on other building systems were never credited. Designers have now begun to employ more comprehensive and integrated approaches to cost justification and capital cost control techniques and this is helping to make a case for NZEBs. Discussions during the Getting to Zero National Forum (2013) revealed that integrative design can allow for crucial design tradeoffs and keep the cost of NZE buildings within typical project budgets.

Recent reports published by the New Building Institute (2014) indicate that NZE has expanded from the domain of a few small demonstrational projects by universities or nonprofits to an increasing mainstream presence that spans a variety of building types and sizes. A 2012 study by the same institute found that NZE design and construction could be achieved at incremental costs of 10% in comparison to standard practices. Torcellini et al, (2010) report that ambitious performance goals and early planning and analysis was key in enabling NREL’s Research Support Facility (RSF) building to achieve both LEED Platinum certification and achieve NZE conditions while maintaining first cost competitiveness. The first phase of the project, 20400 m^2 office building, was completed at a cost of $\$2790/m^2$ and was within market acceptable rates. In fact, NREL's campus in Golden (Colorado) has six LEED Platinum buildings, all of which were constructed by using strategies and off the shelf technology that can be easily replicated anywhere. Leach et al, (2014) provide the following summaries of cost control strategies that NREL has compiled through its campus improvement efforts and ongoing discussions with industry cost control experts.

a. **Acquisition and delivery strategies:** A traditional design-bid-build approach can weaken integration between the project team members. A performance-based design-build procurement process can effectively balance performance, value and cost savings. A competitive procurement of an integrated project team (design team, contractor and trade partners) that is capable of achieving fixed and measured performance target should be sought. Energy efficiency expectations and performance goals should be incorporated into the project request for proposal (RFP). The performance based procurement process will establish clear energy performance and capital budget requirements from the outset and the cost of efficiency will drive the need for innovation in design.
b. **Design Strategies:** Integration of simple, passive energy-efficient strategies that require little additional costs are desirable. Building orientation, massing and layout should be optimized to reduce thermal loads without increasing material or construction costs. Passive design approaches like daylight redirection, thermal massing, solar shading, natural ventilation etc. An integrated design approach, that

considers cost tradeoffs across building systems, should be practiced from the beginning and whole building energy modeling should be used to inform design decisions. Modular and repeatable design strategies, that makes use of economies of scale, should also be used to overall design and construction costs.

c. **Construction Strategies:** Key trade partners should be integrated into the design process at an early stage to ensure that they fully understand the design intent and can collaborate to devise and implement construction cost control measures. Cost estimators should be made integral members of the team and a continuous value engineering process needs to be implemented so that the budget over-run do not occur and deleterious last minute value engineering practices are avoided. Modular designs and offsite construction should also be considered to reduce cost.

d. **Power Purchase Agreement**: Additional renewable power generation system adds considerable first cost to NZE projects. Third party power purchase agreements can be used to secure generation systems then the project budget is exceeded.

2.4 Sequential Optimization Search Technique

The use of energy simulations to facilitate decision making during both formative and detailed design phases have now become common practice. Energy simulation runs are often conducted on a trial and error basic, and hence the search for the optimal solution remains limited and vague.

Building energy optimization involves adjusting building components and system parameters until a minimum cost or energy use combination is achieved. Such optimizations are usually multivariate in nature and the parameter search spaces usually include options related to envelope, lighting, geometry etc. Genetic algorithms (GA) are most commonly used for building energy simulations; while most methodologies usually strive to identify the global optimum, some also seek to develop the Pareto Frontier-the set of cost-optimum solutions over a range of energy savings (Fig. 2-1). One common problem associated with this practice is that an exhaustive enumeration of all possible combinations can easily result in millions of options and can greatly increase the computational time required to generate results. Another issue is that theoretically optimal values can only be found for continuous building parameters. Building components being discrete in nature often have to be represented by continuous functions in an optimization cycle; after the analysis is completed, the discrete options closest to the optimal value are usually selected. It is also advantageous if the optimization process presents multiple optimal and near-optimal solutions. All cost assumptions also carry a level of uncertainty and so near optimal point can be equally as good as the optimal one.

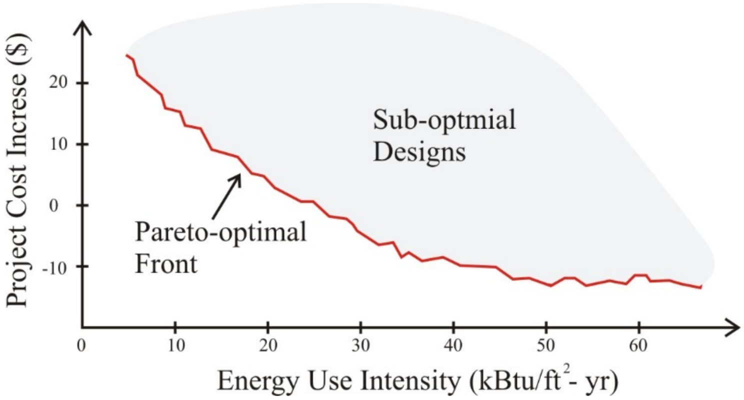

Figure 2-1 Pareto Front of Optimal Solutions

The sequential search optimization method was first described by Meier (1982) and is similar in nature to the technique used by Davis Energy Group in a Pacific Gas and Electric ACT2 project (DEG, 1993) and to the “energy code multiplier method” available in EnergyGauge-Pro (FSEC, 2001). A modified version of this technique was later incorporated into the BEopt software developed by the National Renewable Energy Laboratory (Christensen et al, 2006). The search methodology allows for the identification of intermediate optimal points for different target energy savings levels instead of the global optimum only. It also allows for discrete and realistic building options to be evaluated and helps in identifying near optimal alternative designs along the path. The method involves searching all categories (wall type, ceiling type, window glass type, HVAC type, etc.) for the most cost effective option at each sequential point along the path to ZNE. Starting with the base case, the effect of efficiency measures and design variables are assessed individually. Based on the results, the most cost-effective option is selected as an optimal point on the path and the baseline model is modified to incorporate this feature. This process is repeated over and over again and at each step the marginal cost of saved energy is calculated and compared with the cost of PV energy. When the cost of efficiency measures exceeds that of the PV option, the building design is held constant and PV capacity is gradually increased to reach ZNE.

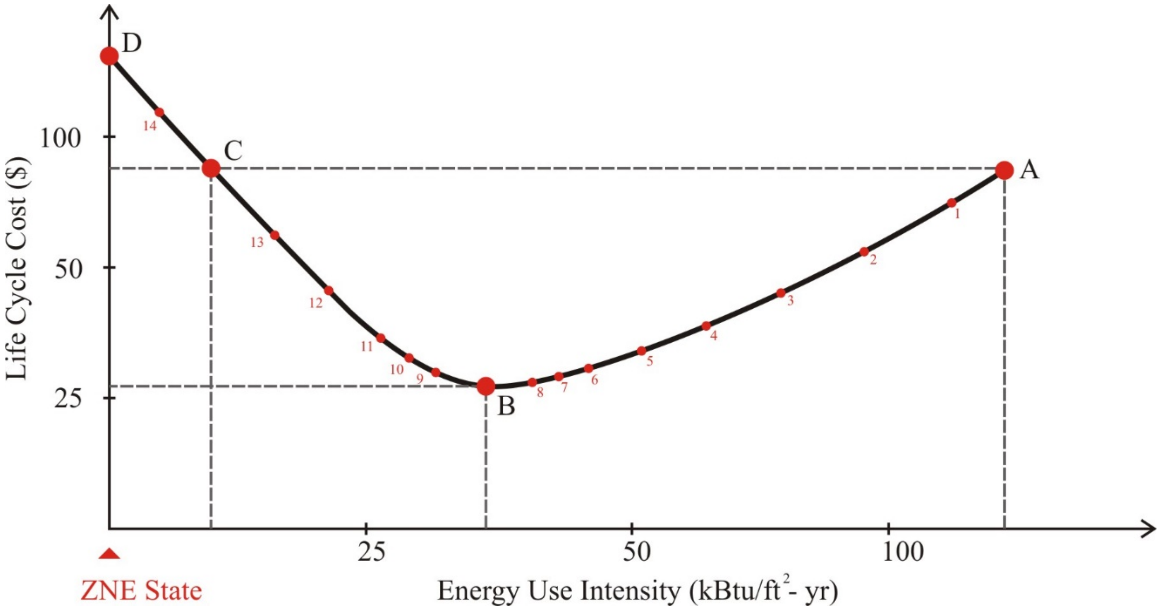

Figure 2-2 Conceptual Plot of the Path to ZNE

During the analysis, energy and cost results can be plotted in terms of annual, life cycle cost or net present value vs percentage energy savings (Fig 2-2). The path to zero net energy extends from a base case (e.g., an existing building, code-compliant building etc.) to an ideal zero energy condition with 100% energy savings. All the lower bound cost minimal points are connected to form the optimal path as shown in Fig. 2-2. Point A represents the base case, energy use is reduced by the application of efficiency measures and it seen by the downward slope and leftward progression of the cost curve. The lowest point in the path is point B, and it represents the cost optimal condition. Further addition of efficiency options has the tendency of increasing the life cycle cost for the building while producing energy savings. Point C represents the point where the marginal cost of saving energy equals the cost of producing PV energy. From that point on, the building design is kept constant and all remaining energy saving is achieved by increasing the PV system capacity until the point of ZNE (point D).

Later publications by Christensen et al, (2008) highlight several modifications that were incorporated into the sequential search technique used it the BEOpt Software. Three accuracy enhancing strategies namely large-step (LS) special case, invest/divest (I/D) special case and positive interaction special case are introduced to counter deficiencies in the previous process. Several speed strategies (10 in number) were also introduced that utilize various threshold criteria to eliminate ineffective combinations and hence decreases analysis speed time. A validation test was also conducted and the results of the sequential search process, while requiring 99% fewer runs, were generally consistent with those of a more exhaustive parametric search requiring 750,000 simulations.

2.5 Optimization Tools

The following section lists some of the tools that are commonly used to analyze building energy performance optimization problems. They incorporate a variety of techniques and are customized for use with either a single or multiple energy simulation engines.

2.5.1 Opt-E-Plus

This is a non-commercially available research tool that was developed by NREL to support the development of low and net-zero energy buildings by integrating simulation and optimization in the design process. It works specifically on EnergyPlus input and output files and has an inbuilt cost database of potential energy design measures (EDMs) spanning across as many as 40 major design parameters. Opt-E-Plus can employ both brute force and sequential search algorithms to find EDM combinations that best balance percent energy savings with life cycle cost when applied to the baseline building (Ellis et al, 2006). Opt-E-Plus does not support multidisciplinary optimization, and visualization of its tradespace is limited (Flager et al, 2008)

2.5.2 Gen-Opt

LBNL developed Gen-opt as a stand-alone optimization tool that can be coupled to any simulation program that depend on text inputs. It is capable of implementing a number of optimization algorithms such as generalized pattern search, particle swarm etc. and can handle both continuous and discrete variables (Wetter, 2004). Shortcomings include an absence of multi-objective optimization algorithms and constraint handling as well as the inability to interactively check for errors in the user's input (Palonen et al, 2013).

2.5.3 BEopt

This tool can be used to find cost-optimal solutions for residential buildings and was developed by NREL. Like Opt-E-Plus, it has a built-in data base of measures and the user is allowed to select the desired technologies to be used in the optimization process. It also uses EnergyPlus as a back-end engine to perform energy simulations and employs a modified sequential search optimization technique (Christensen, 2005) that helps to identify minimum-cost building designs at different energy-savings levels along the path to zero net energy.

2.5.4 TRNOPT

TRNOPT is an interface that couples the TRNSYS simulation engine with the generic optimization tool Gen-Opt. It is limited by Gen-Opt’s features and does not allow for detailed changes in the building simulation file (Palonen et al, 2013).

2.5.5 Design Builder Optimization

Design Builder is a popular simulation software that incorporates a graphical user interface (GUI) and uses the EnergyPlus simulation engine. It has an inbuilt design optimization and cost-benefit analysis module that can test over 120 different design variables including glazing type and amount, thermal mass, HVAC etc. It also allows for constrained multi-objective optimization, it provides a list of over 100 different key performance indicators, and uses the NSGA2 algorithm to develop the “Pareto Front” for specific problems (DesignBuilder Webiste).

2.6 Net Zero Energy Building Definition

Through the concept of net zero energy buildings is not new, the mainstream skepticism about the technical and economic viability of such projects have only recently begun to shift. This change is partly because more and more commercial projects are demonstrating that NZE is an achievable goal, and also due to the fact that policy makers have now started embracing NZEBs as a key strategy for meeting ever stringent energy and carbon goals of the future.

The commercial building stock being the highest consumer of energy has received the greatest attention in this field. The Energy Independence and Security Act of 2007 enabled U.S. Department of Energy (DOE) to develop the Net Zero Energy Commercial Building Initiative to promote the idea of net-zero energy for all new commercial buildings by 2030. This initiative also sets high targets like achieving net-zero energy for the entire U.S. commercial building stock by 2050. Prominent design professional societies like ASHRAE, AIA etc. have also followed suit. The ASHRAE Vision 2020 report emphasizes the requirement to develop tools by 2020 to enable commercially viable net zero energy buildings by 2030. AIA has launched the 2030 challenge with the goal of incrementally reducing existing building energy use by 50% first and then achieving further reduction targets by 2030. Government level policymakers have also widened the reach of NZEB’s to other building sectors. The recently signed Presidential Executive Order now requires all new federal facilities that are coming into service by 2020 to be designed as NZEBs. The California Public Utility Commission has also initiated an energy action plan to achieve net-zero energy for all new residential construction by 2020.

Even though the basic concept of NZEBs, a high efficient building with minimal energy demand that is capable of being mitigated by renewable technology, is well established; a common definition of the phrase “zero energy” is still missing. This is because the term zero energy can be defined in several ways depending on the goals and targets of the design team and building owner. Generally building owners and designers are concerned with site energy use as it directly relates to energy cost and is important for purposes of code compliance. Policymaking organizations like DOE is more concerned with national energy numbers and hence will be interested in primary and source energy information. Others concerned with pollution prevention will convert energy use can into carbon emission from power plants. The four commonly used definitions are as follows:

Net Zero Site Energy: The building produces at least as much energy as it uses in a year when accounted for at the site.

Net Zero Source Energy: The building produces at least as much energy as it uses in a year when accounted for at the source. This refers it the primary energy used to generate and deliver the energy to the site and calculations involve an appropriate site to source conversion multiplier.

Net Zero Energy Cost: In this case, the amount of money the utility pays the building owner for energy exported into the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.

Net Zero Energy Emissions: The building produces at least as much emission-free renewable energy as it uses from emission-producing energy sources.

Crawley et al, (2009) has also classified NZEBs in terms of renewable energy supply into the following:

NZEB-A: A ZEB that generates all energy from renewable energy sources that are located within the building's footprint and is directly connected to the building's electrical or hot/chilled water distribution system.

NZEB-B: A ZEB that uses renewable energy sources as described in ZEB-A as well as renewable energy sources available at the building site, and is directly connected to the building's electrical or hot/chilled water distribution system.

NZED-C: A ZEB that uses both onsite renewable technology like NZEB-A and B and makes use of offsite energy sources like biomass, wood pellets, ethanol etc. to generate energy on site.

NZED-D: A ZEB that makes use of all of the above renewable energy sources as well as off-site renewable options like Green-E or other equivalent renewable- energy certification programs.

2.7 Life Cycle Cost Analysis (LCCA)

Life cycle costing is an economic analysis method that takes into account the various costs incurred during the entire life of a measure and helps to form a holistic assessment of the total benefits of a design decision. This type of analysis is highly recommended for the identification of cost optimal building design options, and a low life-cycle cost (LCC) is a clear indication of the economic viability of a parameter. Other commonly used economic measures includes Savings to Investment Ratio (SIR), Internal Rate of Return (IRR) and Payback Period; these generally produce similar results if the same input parameters and study periods are used.

A complete LCC analysis takes into account numerous costs associated with acquiring, operating and disposing of a building component or system such as initial cost (purchase, construction cost etc.), fuel cost, operation and maintenance cost, replacement cost, residual values or salvage values, loan and interest payment, tax deductions etc. The time span of the analysis can vary widely and can be adjusted to include service and contact periods. Since different costs are incurred at different intervals and frequencies in the life of a component, LCC analysis makes use of the concept of time-equivalence and all cash flows are converted to present value by discounting them to a common point in time. The discount rate used often reflects the opportunity cost of the investment and is equivalent to the minimal rate of return of readily available investment options.

The Federal Energy Management Program (FEMP) of the U.S. Department of Energy has developed rules for carrying out LCC analysis of investments for energy and water conservation. National Institute of Standards and Testing (NIST) has further developed standardized nomenclature and conventions for the entire building industry to follow and these are documented in NIST handbook 135 (Life cycle costing manual for the Federal Energy Management Program). A computer program called BLCC (Building Life-Cycle Cost Program), which automatically applied the FEMP/NIST LCC conventions to an analysis, was also developed by NIST. The U.S. Department of Energy regularly publishes updates of price indices and discount factors incorporating the most recent energy price projections from the Energy Information Administration (EIA) and the most recent discount rates from FEMP and the Office of Management and Budget (OMB) Circular A-94 in the form of annual supplements to the NIST Handbook.

The basic Life-Cycle cost equation sums the present value of all components.

LCC= Initial Investment Cost + PV replacement costs + PV residual value+ PV energy costs+ PV OM & R (2-1)

The NIST Handbook stipulates the following steps for LCCA analysis.

Step 1: Selection of nominal discount rate

The nominal discount rate should be the investor’s Minimum Acceptable Rate of Return (MARR) and should be sufficiently large to make the investor indifferent to the new cash flow. If the investor borrows the capital needed to make the efficiency investment, the nominal discount rate should be the investor’s loan rate.

Step 2: Convert the nominal discount rate to a real discount rate Inflation should be treated implicitly and should be factored out of the nominal discount rate. This can be done by using the following equation:

$$\boldsymbol{d = \frac{1+D}{1+i} - 1} \tag{2-2}$$

d= the "real" discount rate, exclusive of inflation
i= the assumed rate of general inflation
D= the assumed "nominal" discount rate

Step 3: Estimate future costs using present costs

If a nominal discount rate is used, the future value of costs such as equipment replacements should be estimated from present costs and an assumed inflation using the following equation

$$\boldsymbol{F_t = P_0 \times (1 + i)^t} \tag{2-3}$$

F_t = *future value of a present cost,* P_0, *in year t*
P_0 = *present cost of goods or services in year 0*
i= the assumed rate of general inflation
t= future year assumed in the calculation

If a real discount rate is used (in Step 2), this step may be skipped.

Step 4: Discount single (discrete) future costs using the Single Present Value Factor (SPV)

The Single Present Value (SPV) factor should be used to discount future costs or savings to present value by using the following equations:

$$\boldsymbol{PV = F_t \times \frac{1}{(1+D)^t} = P_o \times \frac{1}{(1+D)^t}} \tag{2-4}$$

PV = present value of the future cost of goods/services

Ft= (future cost of goods/services in year t) = P0 if d is "real", where P_0 *the cost in year 0)*

t= future year assumed in the calculation

d= the assumed "discount rate"

Step 5: Discount annually recurring uniform future costs using the Uniform Present Value Factor (UPV), e.g., annual maintenance costs

Annually recurring future costs that are uniform, i.e., do not vary annually other than by the influence of general inflation (e.g., annual maintenance costs), a future cash flow stream should be discounted to its present value using the Uniform Present Value (UPV) Factor.

$$\boldsymbol{PV = A_0 \times \frac{(1+d)^n-1}{d(1+d)^n}} \tag{2-5}$$

PV = present value of the stream of annually recurring future costs of goods/services

A_0*= annually recurring cost of goods/services in year 0 (assumed to change only due to inflation)*

n= last year assumed in the analysis

d= the assumed discount rate (real)

Step 6: Discount annually recurring non-uniform future costs using the Modified Uniform Present Value Factor (UPV*), e.g., annual future utility costs that escalate at a uniform rate

For annually recurring future costs that are not uniform, i.e., that escalate annually, but which escalate at a uniform escalation rate, (e.g., annual utility costs that are projected to escalate at a uniform rate), a future cash flow stream should discounted to its present value using the Modified Uniform Present Value (UPV*) Factor.

$$\boldsymbol{PV = A_0 \times \frac{(1+e)}{(d-e)} \times (1 - \frac{(1+e)^n}{(1+d)})} \tag{2-6}$$

PV = present value of the stream of annually recurring future costs of goods/services

A1 = annually recurring cost of goods/services in year 1 (assumed to change due to inflation and uniform fuel price esclation)
A0 = annually recurring cost of goods/services in year 0 (assumed to change only due to inflation)
n= number of years assumed in the analysis period
t= future year assumed in the calculation
e= the assumed uniform (does not vary from year to year) energy price escalation rate (real)
d= the assumed discount rate (real)

Step 7: Discount annually recurring non-uniform future costs using the Modified Uniform Present Value Factor (UPV*), e.g., annual future utility costs that escalate at a uniform rate

For annually recurring future costs that are not uniform, i.e., that escalate annually, but which escalate at a non-uniform escalation rate, (e.g., annual utility costs whose projected escalation rates vary from year-to- year), a future cash flow stream should be discounted to its present value using the FEMP Modified Uniform Present Value (FEMP UPV*) Factor.

$$\boldsymbol{PV = A_0 \times \frac{(1+e_1)^1}{(1+d)^1} + A_0 \times \frac{(1+e_2)^2}{(1+d)^2} + A_0 \times \frac{(1+e_3)^3}{(1+d)^3} + A_0 \times \frac{(1+e_n)^n}{(1+d)^n}} \tag{2-7}$$

PV = present value of the stream of annually recurring future costs of goods/services
A_1 *= annually recurring cost of goods/services in year 1 (assumed to change due to inflation and uniform fuel price esclation)*
A_0 *= annually recurring cost of goods/services in year 0 (assumed to change only for inflation)*
n= number of years assumed in the analysis period
t= future year assumed in the calculation
e_1*= the assumed energy price escalation rate for year 1 (real, varies from year to year*
d= the assumed discount rate (real)

2.8 Morris Method

The Morris method (Morris, 1991) is a One-factor-at-a time (OAT) screening method that can be used to estimate the effect of changes brought about by individual parameters and can hence help to isolate the factors that (a) have negligible effects or (b) linear and additive effects on the simulation response. The methodology involves obtaining a sample of independently observed elementary effects and then subjecting them to a statistical analysis to measure the sensitivity of the simulation output for a particular input. This method is advantageous because it can handle large numbers of parameters, is economical in terms simulation requirement, the result interpretation is easy and graphical etc. It has been highlighted by various publications like Alam et al, (2004), Carrado et al, (2009), Sanchez et al, (2012).

First, the limits of all input parameters are characterized as a maximum (x_{max}) and minimum (x_{min}). The inputs are then transformed into dimensionless variables in the interval of (0:1) by using the following equation:

$$x_i' = \frac{x_i - x_{max}}{x_{max} - x_{min}} \tag{2-8}$$

The output function y(x) is expressed as a function of vector of real input parameters with k coordinates, where k is the number of input parameters. A series of random simulation trajectories, each defined as a sequence of k+1 points, is simulated and for every case one input parameter is changed by a predefined step Δ_i. The elementary effect (EE) for a point in a trajectory is calculated by the equation:

$$\boldsymbol{EE_i = \frac{y(x+e_i\Delta_i)-y(x)}{\Delta_i}} \tag{2-9}$$

Several trajectories (with r= total number) are analyzed to get a finite distribution of EE for each input variable. The mean (μ) and standard deviation (δ) of each effect are calculated by using the equations:

$$\boldsymbol{\mu_i = \frac{1}{r}\sum_{t=i}^{r} EE_{it}} \tag{2-10}$$

Sometimes the average of the absolute elementary effects is required to eliminate non-monotonic models. In these case, the mean (μ) is derived by using

$$\boldsymbol{\mu_i}^* = \boldsymbol{\frac{1}{r}\sum_{t=i}^{r} \left| EE_{it} \right|} \tag{2-11}$$

$$\boldsymbol{\delta_i = \sqrt{\frac{1}{(r-1)}\sum_{t=1}^{r}(EE_{it} - \mu_i)^2}} \tag{2-12}$$

The classification of the effect typology for each parameter can be done following the recommendation purposed by Sanchez et al, (2012):

- if $\frac{\delta_i}{\mu_i^*} \leq 0.1$, then linear effect
- if $\frac{\delta_i}{\mu_i^*} \leq 0.5$, then monotonic effect
- if $0.5 \leq \frac{\delta_i}{\mu_i^*} \leq 1$, then quasi-monotonic effect;
- if $1 \leq \frac{\delta_i}{\mu_i^*}$, then non-monotonic, non-linear effect.

3 METHODOLOGY

The methodology proposed can be broken down into two parts. An energy model of a prototype school building is first developed in a suitable building energy simulation program, in our case eQUEST. Building data and other specifications like occupancy and equipment schedules were selected from a NREL publication (Bonnema et al, 2013) that explained the development of the Advanced Energy Design Guide for K-12 School buildings (50% Energy Reduction) guide. The primary and secondary school DOE Commercial Reference Building models (Deru et al, 2010) were used as a starting point but various changes to the system types and schedules were made by the Steering Committee to comply with project objectives. The building model was then made compliant with the baseline modeling requirements of ASHRAE 90.1-2007. The baseline of AEDG-K12 models was based on the 2004 version, but the 2007 variant was selected for this study as it is currently used by many states to dictate their current energy codes. Further information about the model inputs and system specifications can be found in Appendix A

The first part of the study consists of a sensitivity analysis following the Morris method that is conducted with the purpose of gaining a thorough understanding of the range of the interaction effect of various energy efficiency measures under various conditions. This phenomenon is rarely examined during a trial and error based parametric study. A total of 19 separate parameters (Table 3-1) comprising of envelope, HVAC and other system factors have been considered. Each parameter was divided into three discreet values reflecting a low, medium and high range. This was easily implemented for parameters like window to wall ratio, over hang projection factors etc. but for HVAC parameters like energy recovery ventilation and indirect evaporative cooling, the discretization process was not so obvious. In the end, varying options like exchanger efficiency and the percentage of building area the measure was applied to was found to be an effective way of varying the magnitude of these measures. Then ten trajectories were developed randomly and 19 simulation runs were made for each trajectory. During each run, one parametric component was altered from one intensity range to another, and the annual energy cost of the run was recorded. At the end of the process, the changes in energy cost were calculated and assigned to the appropriate measure. A statistical analysis was conducted to compute the mean and standard deviations of the results. The classification method proposed by Sanchez et al (2012) was then used to rank the parameters in accordance to the strength and consistence of their interaction effects.

Table 3-1 Sensitivity Analysis Parameters and Discrete Values

No.	Parameter	Description	Discrete Values		
			A	B	C
1	Wall R-Value	R-value	13.00	17.00	23.00
2	Roof R-Value	R-value	20.00	29.00	36.00
3	Cool Roof	Reflectivity	0.30	0.55	0.70
4	Shade-Overhang	Projection factor	0.00	0.25	0.75
5	Window SHGC	SC, VT	0.29, 0.23	0.46, 0.48	0.29, 0.23
6	Window U-Value	U-value	0.73	0.56	0.43
7	Window WWR	Window to wall ratio (%)	35%	20%	5%
8	Skylight WWR	Skylight area ratio (%)	2%	1.5%	1%
9	LPD	Reduction (%)	0%	40%	60%
10	EPD	Reduction (%)	0%	13%	40%
11	Chiller Efficiency	cop	4.95	5.50	6.28
12	VFD Drive	Application	No	Yes	No
13	SA Reset	Max Temp (˚F)	55.00	65.00	55
14	Daylight Sensor	% area	0%	20%	40%
15	Boiler Efficiency	% Efficiency	80%	90%	80%

No.	Parameter	Description	Discrete Values		
			A	B	C
17	Evaporative Cooling	Application	No	Yes	No
18	Tower Efficiency	gpm/hp	38.20	40.20	38.20
19	Demand Control Vent	Application	No	Yes	No

During the second phase of the study, a sequential optimization methodology is used to develop a cost effective pathway that reduces life cycle cost and energy use intensity of the building. The analysis requires all possible options and variations to be tested one at a time during each iteration. Envelope decisions like roof insulation, widow to wall ratio etc. as well as system level decisions like LED lighting, high efficiency chillers, sensors etc. are converted to measures and compared to one another. The energy use, system capacity data etc. and other simulation results are then transferred to a separate spreadsheet in Excel and the life cycle cost benefit of each measure is calculated. Cost savings due to system capacity change are also considered. The best option is then selected and implemented permanently to the baseline and the process is repeated. This process is continued until the life cycle cost benefit of conventional measures become less attractive than that of renewable generation measures like photovoltaic (PV) systems. At this point, the PV system size is gradually increased to reach net zero conditions. Table 3-2 contains a list of the discreet parameters that were used in the analysis.

Table 3-2 List of Design Measures Used for Sequential Optimization Analysis

Category	Measure Names	Values				
ENVELOPE MEASURES	Exterior Wall Insulation	R-15	R-17	R-19	R-23	
	Roof Insulation	R-26	R-29	R-33	R-36	
	Roof Albedo	Reflectivity: 0.55		Reflectivity: 0.7		
	Window Overhangs	North (p.f)	0.1	0.2	0.3	
		South (p.f)	0.25	0.5	0.75	
		East (p.f)	0.25	0.5	0.75	
		West (p.f)	0.25	0.5	0.75	
	Window Properties	Type	S.H.G.C	V.T	U-Val	
		A	0.25	0.3	0.56	
		B	0.25	0.3	0.5	
		C	0.4	0.48	0.43	
	Skylight Glazing Properties	Type	S.H.G.C	V.T	U-Val	
		A	0.35	0.4	0.65	
		B	0.35	0.4	0.55	
		C	0.4	0.46	0.5	
	Window to Wall Ratio	55%	45%	25%	15%	5%
	Skylight to Roof Area Ratio	1%	3%	5%		
LOAD MEASURES	LPD Reduction	Occupancy sensors in daylight zones	10% Reduction			
		T-5 and T-5 HO lamps	40% Reduction			
		LED Lighting	60% Reduction			
	EPD Reduction	Receptacle Sensors	13% Reduction			
		Energy Star Rated Equipment	40% Reduction			
	Daylight Dimming	All Classrooms	All Classrooms + Ancillary Spaces			
HVAC MEASURES	Chiller Efficiency	0.64 kW/ton	0.56 kW/ton			
	Energy Recovery Wheel	Latent: 80% Effectiveness	Sensible:80% Effectiveness			
	Demand Control Ventilation	All Classroom, Library, Art Classroom, Gymnasium, Cafeteria				
	Variable Speed Drives	CHW, CW and HW water loop pumps + Cooling tower fan motor				
	HVAC Control Adjustment	Supply Air Temp Reset + Optimum Start and Stop				
	Evaporative Cooling	Indirect evaporative cooling in AHU				
	Cooling Tower Efficiency	Axial fans (40.2 gpm/hp)				
	Boiler Efficiency	Condensing Boilers with 90% efficiency				
PV MEASURE	Photovoltaic System	100 - 435 kW				

3.1 Details and Cost Assumptions of Efficiency Measures

3.1.1 Above Grade Wall Insulation Measures

The above grade wall of the baseline building was modeled with steel frame construction. The layers consisted of facing brick, plywood, fiberglass batt and gypsum board. An appropriate insulation R-value for continuous insulation (c.i.) was selected to meet the minimum wall insulation requirement listed in Standard 90.1-2007 (Table 5.5-2 of the standard).

The brick veneer metal frame wall consists of a 4” outer layer of facing brick, 1” air cavity, 1” Plywood, 3.5” Fiberglass Batt (R-9) and a 0.5” Gypsum board on the inside. The R-values of the inner and outer air films are considered as 0.17 and 0.68. The fiberglass batts were selected over other insulation options like mineral wool etc. because it offers low material and installation cost with good fire protection properties.

The initial cost of the wall assembly, including material and construction costs, is derived from a RS Means-2016 dataset option that closely matches construction type. It was assumed that subsequent increases in the R-value of the assembly will be brought about by changing the type and size of the fiberglass batt and the incremental cost increases are shown in Table 3-3. These assumptions were also tallied with the dataset used in PNNL’s Cost-effectiveness Study and were found to be comparable.

Table 3-3 Exterior Wall Insulation Measure Cost Data

Assembly R-Value	Insulation type	Total Cost of Assembly ($/ft^2)	Incremental Cost ($/ft^2)
Steel framed above grade wall, R-13	3.5” R-9 fiberglass batt, 15” Wide	18.58	
Steel framed above grade wall, R-15	3.5” R-11 fiberglass batt, 15” Wide	18.67	0.09
Steel framed above grade wall, R-17	3.5” R-13 fiberglass batt, 15” Wide	18.79	0.12
Steel framed above grade wall, R-19	6” R-15 fiberglass batt, 15” Wide	19.08	0.29
Steel framed above grade wall, R-23	6” R-19 fiberglass batt, 15” Wide	19.43	0.35

3.1.2 Roof Insulation Measures

A structural metal deck roof with rigid insulation is used in the baseline. The layers are assumed to consist of an outer ethylene propylene polymer membrane, 0.375” built up roofing, 3” thick rigid insulation (R-19), metal decking, airspace, structural members, 5/8” Gypsum board ceiling. Continuous and uninterrupted Polyisocyanurate insulation is selected because it has the highest R-value per inch of any rigid foam board insulation. An insulation R-value of 19 (3” thickness) was selected to meet the assembly maximum (U-0.048) roof insulation requirement listed in Standard 90.1-2007 (Table 5.5-2 of the standard).

The initial cost of the roof assembly, including material and construction costs, is derived from dataset used in PNNL’s Cost-effectiveness study. The cost of adding additional layers of Polyisocyanurate insulation is derived from RS Means-2016 data and is shown in Table 3-4.

Table 3-4 Roof Insulation Measure Cost Data

Assembly R-Value	Insulation type	Total Cost of Assembly ($/sft)	Incremental Cost ($/sft)
Metal deck roof, R-21	3” R-19 Rigid Insulation	25.30	
Metal deck roof, R-26	3” + 1” rigid insulation	26.26	0.96
Metal deck roof, R-29	3” + 1.5” rigid insulation	26.45	1.15
Metal deck roof, R-33	3” + 2” rigid insulation	26.68	1.38
Metal deck roof, R-36	3” + 2.5” rigid insulation	26.95	1.65

3.1.3 Cool Roof Measures

Since Standard 90.1-2007 does not specify absorptance or other surface assumptions for roofs; the exterior finish for the roof of the baseline model is assumed to be a gray ethylene propylene polymer membrane with a solar reflectance of 0.3. The cool roof measure meets the prescriptive requirement of 90.1-2010 and improves the minimum solar reflectance to 0.55 and increases the thermal emittance of the surface to 0.75.

The incremental material cost of adding a cool roof option is estimated by the same process used in the PNNL Cost effectiveness study. The additional cost is assumed to be the difference between a typical ethylene propylene diene monomer (EPDM) that does not meet the requirements compared to the same corresponding materials that do meet the requirements. Labor cost is assumed to be the same for both the cases. The EPDM membrane requires a special finish to meet the high reflectance requirement and this adds $0.16/sq ft to the overall cost. This incremental cost is derived from DOE Building Technologies Guidelines for Selecting Cool Roofs (DOE 2010) with appropriate inflation related adjustments.

3.1.4 Overhang Measures

The baseline building is assumed to have glazing that is flush with the outside surface of the exterior wall with no projected overhangs. During the optimization runs various combinations of overhang measures ranging from projection factors of 0.25 to 1 are applied to different orientations.

The cost of adding overhangs in derived from the RS Means 2016 dataset. It is assumed to be similar to that of constructing a single span 4.5” deep steel deck, and is estimated as $7.97/sq ft of overhang surface.

3.1.5 Fenestration Measures

All vertical fenestrations in the baseline model is fitted with glazing having a solar heat gain coefficient (SHGC) of 0.25 and assembly U-value of 0.75 (Table 5.5-2, ASHRAE 90.1-2007). This is assumed to be equivalent to a double glazed low–e window option with aluminum framing. This then replaced with two other options that represents windows types having vinyl framing and triple glazing and hence have lower U-values. A glazing option with higher visual transmission is also included. The costs of the glazing options are derived from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and is shown in Table 3-5. The window to wall ratio is also varied between 5%-55%.

Glass skylights are modeled in spaces like classrooms, library, gymnasium etc. and cover 2% of the roof area in the base line model. During the sequential runs, this value is varied between 1%- 5%. Three other glazing variations are used during the sequential runs and is show in Table 3-5.

Table 3-5 Window and Skylight Measure Cost Data

Type	SHGC	U-Value	Cost ($/sft)
Window Type A	0.25	0.56	66.84
Window Type B	0.25	0.5	70.27
Window Type C	0.4	0.43	80.26
Skylight Type A	0.35	0.65	80.48
Skylight Type B	0.35	0.55	106.52
Skylight Type C	0.4	0.5	107.36

3.1.6 Chiller Efficiency Measures

The baseline model is equipped with a water cooled centrifugal chiller of 0.703 kW/ton efficiency as per ASHARE 90.1-2007 requirements. The measure replaces this with other centrifugal chillers with full load efficiencies ranging between 0.64-0.56 kW/ton. The costs of the chillers are derived from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and are assembled in Table 3-6. Labor and maintenance cost is assumed to be the same for similar sized chillers of different efficiency. The life of the chillers is taken to be 23 years.

Table 3-6 Chiller Efficiency Measure Cost Data

Full-load Efficiency		Material and Installation Cost ($)/ton
kW/ton	EER	
0.71	17	415
0.64	18.75	455
0.56	21.5	495

3.1.7 Variable Frequency Drives

Variable-speed drives are devices that can vary the rotational speed of motors by changing the alternating current frequency. The application of VFDs can produce substantial savings in comparison to constant speed or two-speed control mechanisms in the motors of fans, pumps and compressors. In this measure, variable frequency drives are applied to all pumps in the chilled water, condenser water and hot water loops as well as in the fan of the cooling tower.

The cost of this application is derived from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and shown in Table 3-7. The life of each device is considered to be 15 years and the replacement cost is assumed to be 25% greater than the initial cost due to future inflation in the cost of labor.

Table 3-7 Variable Frequency Drive Measure Cost Data

VFD Motor Size (hp)	Total material and installation cost ($)
1	1935
2	1958
3	2206
5	2532
10	3274
20	5233
50	9577
75	14017
100	16227

3.1.8 HVAC Control Measures

Two HVAC control strategies are bundled in this measure. Firstly, the supply air temperature is reset based on building loads. The system is allowed to reset to a set point of 65˚F to meet the cooling requirement of the warmest zone. The cooling loads are usually below the peak design condition for most periods of the system operation year. In such situations, an elevated supply air temperate satisfies the cooling load while decreasing both cooling and reheat energy. This measure also helps to increase the operational hours of the economizers. Optimum start and stop controls are also implemented and the HVAC system start-up is delayed as long as possible.

For cost assumptions, the VAV systems were assumed to include DDC systems including control of the VAV terminal units in each zone in order to comply with other VAV control requirements in Standard 90.1-2007 and Standard 62.1-2007. A DDC system can readily achieve the supply air temperature outdoor air reset and optimal start stop operations by activating a control sequence that is normally available without addition of any sensors, actuators, or other equipment. The ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) concluded that this strategy could be implemented without adding equipment or installation costs. An added cost for commissioning based on 4 man-hours of programming and 4 man-hours of commissioning for each affected VAV system was included. But since the zones which experience relatively constant loads may need to be designed for increased airflow in order to meet load at the fully reset supply air temperature; the study recommended an addition of $0.19 per square foot of interior building area served by HVAC systems affected by the control requirement to account for increased air distribution equipment.

3.1.9 Demand Control Ventilation (DCV) Measures

CO_2 sensors can be used to estimate the occupancy of a zone and reset the ventilation rate from the design occupancy down to the actual occupancy. This reduces energy wasted in conditioning excess outdoor air. This measure is most applicable in school spaces with dense occupancy and sporadic schedules like gymnasiums, cafeterias and auditoriums. Class rooms are also good candidates but are typically less cost effective due to their constant occupancy rates (CHPS, 2006).

The DCV measure was applied to all classrooms, the gymnasium, cafeteria and auditorium space in the model by developing an outdoor air schedule that is in sync with the occupancy schedule. The cost of individual sensors ranges from $250-500. The total cost of installing such a measure is taken from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and is considered to be $0.25/sq ft. The life of the system is assumed to be 15 years and the replacement cost is estimated as $0.31/sq ft due to inflation in labor charges.

3.1.10 Energy Recovery Measure

Energy recovery devices facilitate the transfer of energy between the exhaust and supply airstreams. In most applications, the two airstreams pass through an energy recovery wheel, a porous disk fabricated of materials having a specific heat capacity, and the rotation of the wheel helps to transfer energy from the higher energy airstream to the lower energy airstream. Hence the exhaust air preheats the supply air in the winter and precools it during the summer. The use of desiccant coatings also allows for the transfer of moisture.

For this measure, an enthalpy recovery wheel with a latent and sensible efficiency of 80% is applied in the model. The cost of adding an enthalpy recovery wheel to the air handling unit is taken from the RS Means 2016 dataset and is shown in Table 3-8. Maintenance of the ERV unit is similar to that for a packaged DX unit and includes lubrication, checking dampers, adjusting belts, replacing filters, checking door seals and cleaning coils. The ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) derived annual maintenance costs from two sources. RS Means Mechanical Cost Data 2015 provided a rough estimate for a set of routine packaged DX maintenance activities that total about 2.5 man-hours. Cleaning of the energy recovery media is also included in the maintenance cost, and can take about 15 minutes with frequency from every six months to 10 years depending on conditions; so the estimate included 15 minutes each year.

Table 3-8 Energy Recovery Ventilation Measure Cost Data

Outdoor Airflow (cfm)	Total material and installation cost ($)
8000	13039
10000	15418
20000	26782
25000	32509
30000	36738
40000	50217

3.1.11 Evaporative Cooling Measures

Direct and Indirect evaporative cooling uses moisture to reduces the dry bulb temperature of the outdoor air. The cooling process takes place across a constant line of enthalpy, and hence requires very little energy. In direct evaporative cooling systems, the water is exposed to the supply air steam and can reach an effectiveness of 80-90%. Indirect options are not as effective but do not add moisture to the supply air stream.

For this measure, an indirect cooling option of 70% efficiency is used in the energy model. The cost of the measure is taken from RS Means 2016 dataset and is calculated to be $0.75 per cfm of outdoor air. The life of the system is assumed to be 15 years and a yearly maintenance cost equivalent to 5% of the initial system cost is added.

3.1.12 Cooling Tower Efficiency Measures

The heat rejection device in the baseline model is an axial fan cooling tower with two speed fans. The maximum flow rating of the tower divided by the fan name plate rated motor is set at 38.2 gpm/hp as per the requirements of ASHRAE 90.1-2007. For this measure the minimum efficiency is increased to 40.2 gpm/hp. The additional cost of the measure is derived from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and is shown in Table 3-9. No additional labor or maintenance cost is considered. The life span of the cooling towers is considered to be 25 years.

Table 3-9 Cooling Tower Efficiency Measure Cost Data

Size of Chiller Cooling Load served (tons)	Incremental Cost ($)
233	*233*
354	354
467	467

3.1.13 Boiler Efficiency Measures

The baseline building is modeled with two natural draft boilers with an efficiency of 80%. The boiler efficiency measure replaces this baseline with condensing boilers of 90% efficiency. These boiler types are more efficient because they recover energy by condensing waste water vapor. Market surveys revealed that condensing boilers usually have a cost premium of 30% over conventional natural draft boiler prices; this fact was used to modify the cost estimates from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and is shown in Table 3-10. Condensing boiler usually have a higher maintenance requirements and is considered to be equal to 3% of the initial cost. The life of the measure is estimated to be 35 years.

Table 3-10 Boiler Efficiency Measure Cost Data

Capacity (Million Btu/h)	Incremental Cost ($)
0.3	1913
2.5	5960
7.5	17049
15	42622
25	55518

3.1.14 Daylight Sensor Measures

No daylight controls are added to the base model as per the requirements of Standard 90.1-2007. The two measures add daylight sensors in an incremental sequence to various spaces that decreases the design lighting power to a minimum of 35%. One photo-sensor is included per space and the same sensor is used to control both the primary and side-lighted areas. The primary school multi-classroom pods are divided into separate classrooms based on the corner classroom area. Labor, material and maintenance cost calculations are derived from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and RS Means 2016 dataset.

The material costs included the cost of the sensor, wiring and powerpack. Labour cost is calculated based on the number of sensors and number of fixtures to be wired to the controller. Five minute installation per fixture was estimated. Replacement and commissioning costs are included and involved the cost of photo-sensor and power pack; the functional testing costs included commissioning and calibration of photo-sensors.

The total area of perimeter spaces that can benefit from daylighting controls is assumed to be 57126 sft; corridor areas, the mechanical room and other service zones are excluded. The combined installation and material cost of the measure is assumed to be \$1.82/sft. The life of the measure is assumed to be 15 yrs and replacement cost is assumed to be \$2.2/sft and takes account of inflation.

3.1.15 Occupancy Control Measures

Both infrared and ultrasonic sensors are used to provide automatic lighting controls in spaces. These along with dimmable ballasts can be used to modulate the intensity and power consumption of lighting fixtures in accordance to occupancy and provide automatic turning on/off actions. Automatic lighting control is assumed to decrease the lighting power density by 10% in the applied areas, this estimate is taken from Table G3.2 in Standard 90.1-2007.

The cost of this measure is estimated to be $0.70/sq ft and is derived from the methodology used in the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013). All fixtures are assumed to have dimmable ballasts. The type and number of sensors required is estimated for representative spaces in the school building and the cost is later averaged. The commissioning cost of the lighting controls is assumed to be 7% of the system cost. And the life span is considered to be 15 years.

3.1.16 Plug Receptacle Control

Both time schedules and occupancy sensors can be used for receptacle controls. Many new codes like ASHRAE-90.1 (2010) and California Title 24 (2013) now require spaces with high plug loads to automatically shutoff selective devices when there is no use. The cost effectiveness of the measure is increased if occupancy sensors are already installed in the spaces.

This measure was applied to all class rooms, library and office spaces in the model (48% of total area). The methodology suggested in the ASHRAE 90.1 Determination of Energy Savings study (Halverson, 2014) is used to estimate the energy savings of this measure.

The fractions of the time during which the candidate spaces are unoccupied during regularly occupied hours are calculated. Then the fraction of the plug-in equipment that is likely to be plugged into a controlled receptacle in each space is calculated. A diversity factor is also added to account for equipment that could be turned off but is not plugged into a controlled receptacle and is shown in Table 3-11. These factors and area fractions are combined to produce two reduction fractions and are applied to the equipment schedule of the spaces. The combined savings is estimated to be equivalent to a 13% reduction in the total equipment power density of the building.

The cost of adding this measure is considered to be $2.20/sq ft and the estimate is derived from the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013). It includes the cost of wiring for controlled receptacles, power pack controllers and occupancy sensors. The life span is assumed to be 15 years.

Table 3-11 Receptacle Control Measure Assumptions

<table>
<tr><th colspan="4">Area fraction for Space Types added by 90.1-2010 for the Primary School prototype building</th></tr>
<tr><td>Classroom</td><td colspan="2">Break Room</td><td>Conference Room</td></tr>
<tr><td>48.44%</td><td colspan="2">0.13%</td><td>0.51%</td></tr>
<tr><th colspan="4">Factors Used to Calculate Reduction Fraction for Equipment Schedule</th></tr>
<tr><td>Factors</td><td>Classroom</td><td>Break Room</td><td>Conference Room</td></tr>
<tr><td>Unoccupied fraction during occupied hours</td><td>0.32</td><td>0.15</td><td>0.33</td></tr>
<tr><td>Fraction of plug loads that could be turned off</td><td>0.55</td><td>0.37</td><td>0.45</td></tr>
<tr><td>Diversity factor</td><td>0.75</td><td>0.75</td><td>0.75</td></tr>
</table>

3.1.17 Lighting Power Density Measures

A reduction in the lighting power density (LPD) can be brought about by using efficient lighting fixtures fitted with LED and T-5 type lamps that have high efficacy. Hence, less energy is consumed to maintain the required illuminance levels in the spaces. LPD reduction also reduces the heat dissipated from lighting fixtures and brings about a reduction in the cooling load.

For the baseline LPD estimation, data from Standard 90.1-2007 (Table 9.6.1) and the space by space methodology was used. The cumulative lighting power density (LPD) was deduced to be 1.18 W/sq ft. For determining the cost associated with LDP reduction the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) assigned each space of a building with up to four lighting systems, each of which provided an assigned percentage of the overall total illumination of the space. These percentages determined the quantity of fixtures required and cost estimates were developed for each fixture and lamp types.

During this study, a simplified approach is applied to determine the cost of reducing lighting power load. Best Practices Manuals from CHPS and DOE are used to determine the required illumination levels in each functional zone. It is assumed that the whole facility is equipped with one homogenous type of luminaire and that variation in illumination levels is brought about by increasing or decreasing fixture counts in spaces. The Quick Lighting Calculator tool from Siemens was used to calculate the number of fixtures that were needed. The working plane was fixed at 2.5 feet and the reflectance of the ceiling, walls and floors are kept at 80%, 40% and 20%. Reduction in lighting power density is brought about by switching to fixtures that offer higher efficacy. The cost of the lamps/luminaires used is derived from manufacturer catalogs (Grainger 2016), the labor rates for delamping operation is taken from RS-Means (2016) and is assumed to be $53.5 per hour and no additional lighting design cost is associated with switching from one measure to another. SPV factors are used to convert intermittent delamping costs into a yearly maintenance cost for all cases.

40% LPD Reduction: It is assumed that all spaces in the baseline building have 4’ by 2’ lighting fixtures equipped with four legacy T-8 type fluorescent lamps each having an efficacy of 58 lumens/Watt. The total number of fixtures require is calculated to be 512 and the rated life of the lamps is assumed to be 20,000 hours. In this measure, these are replaced by fixtures having T-5 lamps of 93 lumens/watt efficacy and 30,000 hours rated life. The delamping time for both fixture types are assumed to be 10 minutes. Table 3-12 shows further details.

60% LPD Reduction: All lighting fixtures are converted to LED type lamps with an efficacy of 118 lumens/watt and 50000 hours rated life. The delamping time for each fixture is assumed to be 1 hour and the replacement cost is assumed to be half of the initial fixture. Table 3-12 shows further details.

Table 3-12 Lighting Power Density Reduction Measure Assumptions

Details	**Baseline Case**	**40% LPD Reduction Case**	**60% LPD Reduction Case**
Lamp type	T-8 (Legacy)	T-5 & T-5 HO	LED Tubes
Watt/lamp	42	28	18
Number of lamps per fixture	4	4	4
Number of Fixtures	512	492	492
Efficacy (Lumens/Watt)	58	93	118
Cost of Fixture ($)	160	250	492
Cost of Lamp ($)	4	12	30

Details	Baseline Case	40% LPD Reduction Case	60% LPD Reduction Case
Lamp Rated Life (hrs)	20000	30000	50000
Cost of Ballast ($)	60	60	-
Ballast Rated Life (hrs)	50000	50000	-
Delamping time per fixture (hrs)	0.18	0.18	1
Cost of labor ($/hr)	53.5	53.5	53.5
First Cost ($/sft)	1.11	1.66	2.20
O&M ($/sft)	0.098	0.145	0.127

3.1.18 Equipment Power Density Measures

The equipment power density for the baseline model was derived from the assumption used in the development of the AEDG design guide for K-12 School buildings (Bonema et al, 2013). It was assumed that the primary schools had one instructional computer per 3.8 students (Education Week 2005), so for 650 students 171 instructional computer units (150 W desktop and a 50 W monitor) was considered. It was also assumed that there would one staff member for every student and each staff member apart from using one computer would use other equipment like a refrigerator, microwave etc. and total of 1065W of miscellaneous loads were assigned per staff. In addition to this, 85 W per staff was included for items like task lights, printers and other office equipment. The school was also assumed to have a 65 W server with a 1.9 power usage effectiveness. The cumulative equipment power density was calculated to be 1.32 W/sq ft.

For the 40% reduction measure, all instructional and staff computers were replaced with Energy Star rated units (32 W mini desktop and 18 W LED backlight monitors). An energy efficient server, 48 W per connection with a power usage effectiveness of 1.2, was also used. The cost difference between the equipment used was derived from manufacturer catalogs and the incremental cost was calculated to be $2.06/sq ft. The life of the equipment was assumed to be 10 years and the maintenance cost was considered to be similar for both cases.

3.1.19 Photovoltaic Generation

NREL's PVWatts Calculator was used to deduce the amount of electricity generation that can expected from a standard, crystalline Silicon with 15% efficiency, 100 kW PV system for a location in Phoenix, Arizona. The system loss was assumed to be 14% and the inverter efficiency was set at 96%. The software estimated that a new 100 kW fixed array system would generate 172842 kWh of electricity for the first year. The PV system was assumed to have a 25 year commercial warranty period, and hence an annual degradation of 0.5% was factored into the calculation (Jordan et al, 2012). The final average generation for the 30 year study period was estimated to be 160310 kWh/year.

The system was also assumed to be connected to the grid and did not include battery storage. The cost of the full system including material cost for the PV panels, racks (surface penetrating steel frames), wiring, combiner box, DC to AC inverter and the installation cost was estimated to be $8686/kW and was derived from RS Means 2016 dataset. PV systems are known to commonly outlast their warranty periods and the life span of the measure was assumed to be 35 years. An annual maintenance cost equivalent to 0.10% of the system first cost was also included.

3.2 LCCA Methodology

The life cycle cost analysis was conducted based on the Federal Energy Management Program (FEMP) LCCA method (NIST 1995). One area of departure from the FEMP method was the use of a 30-year study period instead of the prescribed 25 years. This is the study period used by the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013) and is also widely used for LCCA in government and industry.

The DOE nominal discount rate is used and energy price escalation rates are taken form the Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis-2013 report (Rushing et al, 2013). Updated regional energy costs are taken from the EIA database.

Table 3-13 Life Cycle Cost Analysis Parameters

Economic Parameter	Value	Source
Nominal Discount Rate Real Discount Rate	2.5% 3 %	*Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis - 2013, NIST annual update – (Rushing et al, 2013).*
Inflation Rate	-0.5%	
Electric & Gas Prices	$0.1014/kWh $0.99/therm	*EIA-database (2014)*
Energy Price Escalation	UPV	*Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis - 2013, NIST annual update – (Rushing et al, 2013).*
	Electricity 20.18 Nat Gas 24.22	*The NIST uniform present value factors are multiplied by the first year annual energy cost to determine the present value of 30 years of energy costs and are based on a series of different annual real escalation rates for 30 year*

3.3 System cost adjustment due to Equipment Capacity Change

HVAC capacity changes due to energy efficiency measures can contribute substantially to the life cycle savings by reducing the HVAC system costs. The primary sources of capacity changes are reductions in cooling and heating loads due to changes in lighting power and controls, energy recovery, infiltration, automatic outdoor damper control during morning warm-up and roof reflectance etc. During the ASHRAE 90.1 Cost-effectiveness study (Thorton et al, 2013), costs were developed for a range of equipment sizes corresponding to the models. In most cases, the equipment costs were derived from estimates provided by multiple manufacturers and the average was used. For the piping and ductwork costs, schematic level single line representatives were developed for the ductwork and piping for each prototype and detailed costs were estimated.

For this study, regression equations were developed between capacity (e.g. tons of cooling, outdoor airflow etc.) and the reported equipment costs listed in the ASHRAE 90.1 Cost-effectiveness study workbook. The capacities of the various system components were extracted from each simulation run and the system cost was derived. This was then compared to the baseline HVAC system and adjustments were made to the overall life cycle cost estimate to incorporate any changes in HVAC system first cost. The interpolations and estimates are shown in Appendix B.

4 RESULTS

4.1 Sensitivity Analysis

As described earlier in Sections 2.8 and 3, the Morris method provides sensitivity analysis and is an effective way of screening parameters in terms of importance and interaction strength. The methodology section further describes the procedure implemented and in total 19 trajectories (200 simulations) were used. The mean versus standard deviation (σ vs μ^*) plots of the results are shown in Fig. 4-1, 4-2 and Table 4-1 also assembles summaries and parameter rankings. The parameters located on the bottom left of the chart have negligible interaction and have negligible energy saving performance. The parameters on the bottom right have a tendency to produce high energy savings in all conditions and are less likely to deviate due to the effects of interaction with other measures. The points on the upper right portions of the chart produce strong results but are more liable to interact with other measure. The analysis was able to successfully rank the parameters in accordance to the mentioned criteria. Later during the sequential search process, a close correlation as observed between the order of the selected measures and the ranking developed during this analysis.

- Reductions in lighting power density (LPD) and equipment power density (EPD) consistently registered high energy savings during the various trajectory runs. Measures having these parameters were selected at the 2nd and 4th iteration of the sequential search process.
- Parameters like window to wall ratio, chiller efficiency, demand control ventilation and window overhangs produced high mean and standard deviation values. Hence

these options were likely to register strong results as well as show greater interaction when coupled with other measures. Measures comprising of these parameters where selected early during the sequential search process. Since first cost is an important component of LCCA analysis, measures registering lower first had an advantage over more expensive options. Window to wall ratio reduction produced significant first cost savings, because the cost of glazing options was must higher than that of opaque walls, and was selected as the first option during the sequential selection process.

- Parameters like evaporative cooling, supply air temperature reset, variable frequency drives and skylight area ratio had lower mean and standard deviation value. Hence these measures were selected in a sequential manner between the 6th and 9th iterations.
- Parameters like roof insulation and cool roof membrane options registered the lowest importance and were not selected during the search process in phase 2.

Table 4-1 Sensitivity Analysis Results

Rank	Parameter	Mean (μ*)	Standard Deviation (δ)	Important & Linear	Important & Non-linear	Non-important & Linear	Non-Important & Non-linear
1	LPD	24088	1076	✓			
2	EPD	16978	3025	✓			
3	Window WWR	7298	4063		✓		
4	Chiller Eff	6054	3406		✓		
5	DCV	5510	4052		✓		
6	Shade-Overhang	3810	2729		✓		
7	Evaporative Cooling	3670	1734	✓			
8	SA Reset	3307	1566	✓			
9	Window SHGC	1766	1641				✓
10	VFD Drive	1761	528			✓	
11	Daylight Sensor	1741	1260				✓
12	ERV	1494	1357				✓
13	Skylight WWR	1335	475			✓	
14	Window U-Value	1038	367			✓	
15	Wall R-Value	852	424			✓	
16	Boiler Efficiency	667	149			✓	
17	Roof R-Value	395	173			✓	
18	Tower Eff	57	35			✓	
19	Cool Roof	9	5			✓	

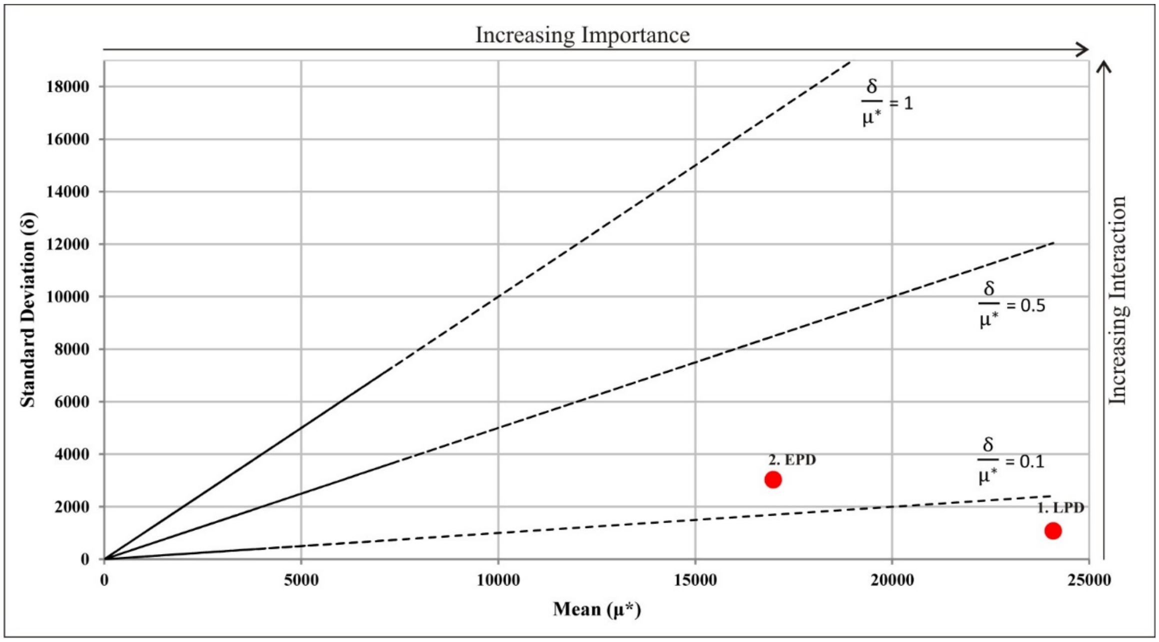

Figure 4-1 Mean (μ*) vs Standard Deviation (δ) -First Two Parameters

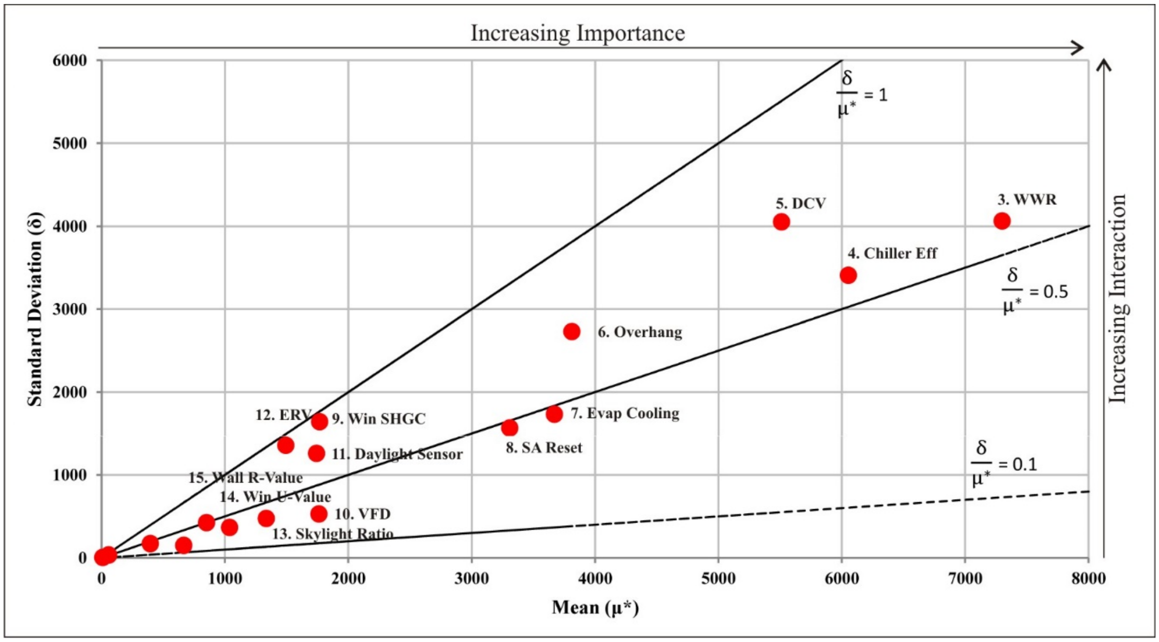

Figure 4-2 Mean (μ*) vs Standard Deviation (δ)

4.2 Sequential Search Process

The sequential search methodology has previously been described in Sections 2.4 and 3. A total of 20 sequential iterations comprising of 865 separate simulations were conducted (Fig 4-5) and each time the option with the greatest life cycle saving potential was selected. This technique enabled the benefits of each strategy or design measure to be weighed against its associated cost and included interactions between technology.

The cost optimal combination was identified as the point after which life cycle savings are no longer economically feasible with the given set of measures. This is termed as the minimal life cycle cost point (point B). This combination was found to reduce the building EUI from 66.8 kBtu/ft^2-yr to 35.5 kBtu/ft^2-yr (47% reduction) and produced an incremental life cycle savings in the range of $1.278 million. A window to wall ratio of 5% was selected at the beginning due to the fact that glazing options had much higher first cost than opaque walls; the energy cost savings from heat gain reduction was also substantial for the hot arid climate of Phoenix. A minimal skylight to roof area ratio of 1% was also found to be optimal. Other envelope measures that were selected included higher insulation for the exterior walls and overhangs for the East, West and North facades. Overhang measures showed higher propensities for interaction and induced daylighting related penalties. Overall the measures that produced the highest life cycle savings included those that reduced the lighting and equipment power loads. For the HVAC system, measures like higher efficiency chillers (0.56 kW/ton), indirect evaporative cooling, variable frequency drives in pumps and fans, demand control ventilation in classrooms and other densely occupied spaces, control measures like supply air temperature reset were all found to be cost effective and produced subsequent life cycle cost savings. Measures like energy recovery ventilation and receptacle sensors were not found to be cost effective. The total annual energy cost savings was estimated to be $64,587. The cumulative first cost of the optimal set of measures was estimated to be $104,485 and the total net savings is estimated to be $ 1,278,939. The simple payback for this set of efficiency measures was estimated to be 1.6 years and proved to be a suitable investment. It has to be noted that the payback period would have been as high as 7 years if the cost savings related to reduction in glazing area was not considered. Table 4-2 provides additional details.

The neutral life cycle cost combination (point C) is the set of measures that produces zero life cycle savings for the study period. The maximum saving combination (point D) was achieved with the addition of a 435 kW photovoltaic generation system. The additional cost of getting the building from the minimum ASHRAE 90.1 state to net zero energy conditions was estimated to be $4,013,753. The simple payback for the additional investment was estimated at 26.3 years and was not found to be economically lucrative. Given that the average cost of construction for a similar one storied school building is $145/ft^2 (RSMeans 2016), this amount equates to a 37.4% increase in first cost.

Figure 4-4 and 4-5 shows the energy end use break down after the addition of the selected measure during each iteration. It has to be noted that the percentage of energy reduction per addition of new measure reduces drastically after the first few iterations. The first five selected measures produce energy savings of 38% over the initial baseline, while the 15 measures selected afterwards were only able to reduce the total energy used by an additional 10%. This asymptotic trend is commonly seen when measures are coupled together during energy simulations and is a result of the fact that energy use reduction becomes more difficult with increasing levels of energy efficiency.

Figure 4-3 shows the relationship between the observed net savings and the incremental capital cost associated with the measure. It can be seen that the reduction in energy use intensity produced by measures selected between iterations 9-18 is not high but carries a considerable first cost. Hence if there is budgetary constraint, it is advisable to implement only the first eight measure to achieve an energy saving of 44%.

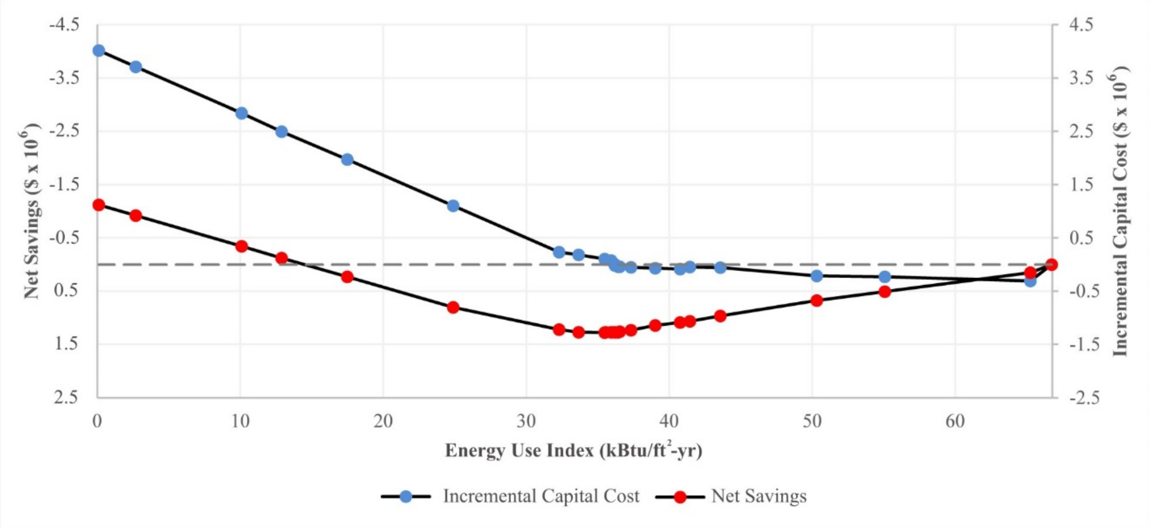

Figure 4-3 Energy Use Intensity vs Net Savings and Incremental Capital Cost

Table 4-2 Sequential Search Process Results

No	Measure Selected	Incremental LCCA Savings ($)	EUI (kBtu /ft^2-yr)	Savings %	Energy Cost Savings ($)	Incremental First Cost ($)
A	**(Baseline)**		66.76			
1	WWR-5%	151,750	65.26	2.2%	1,663	-3,08,428
2	LPD Reduction-60%	504,846	55.09	17.5%	25,627	80,619
3	Demand Control Ventilation	675,481	50.32	24.6%	33,219	18,491
4	EPD Reduction- 40%	965,195	43.58	34.7%	71,944	1,52,362
5	Chiller Efficiency- 0.56 kW/ton	1,064,532	41.44	37.9%	54,676	13,740
6	Skylight Area Ratio-1%	1,084,703	40.77	38.9%	55,750	-40,901
7	SA Reset and Optimum Start	1,142,081	39.03	41.5%	57,411	16,688
8	Indirect Evaporative Cooling	1,231,747	37.32	44.1%	61,195	18,705
9	VFD in Pumps and Fans	1,258,845	36.55	45.3%	62,918	10,000
10	E-Wall R value-15	1,268,674	36.45	45.4%	63,096	1,561
11	Cooling Tower Efficiency	1,270,813	36.40	45.5%	63,191	2,000
12	East Overhang (p.f-0.75)	1,270,940	36.22	45.7%	63,579	20,826
13	North Overhang (p.f- 0.2)	1,271,067	36.21	45.8%	63,626	15,707
14	E-Wall R Value-17	1,271,576	36.18	45.8%	63,665	3,641
15	West Overhang (p.f-0.25)	1,271,824	36.16	45.8%	63,702	6,942
16	Daylight Dimming in Classrooms	1,272,167	35.95	46.1%	64,153	66,962
17	Boiler Efficiency-85%	1,272,447	35.54	46.8%	64,452	16,900
18	E-Wall R Value-19	1,272,987	35.48	46.8%	64,587	8,670
B	**(Minimum Life Cycle Cost Combination)**					
	Energy Use Intensity (kBtu/ft2-yr)	35.48				
	Total Savings (%)	46.80%				
	Life Cycle Cost Savings ($)	1,278,939				
19	Recepticle Sensor	1,271,043	33.67	49.6%	68,672	78,824
20	Occupancy Sensor	1,220,363	32.30	51.6%	71,944	51,773
21	PV System (100kW)	802,770	24.9	62.7%	88,200	868,660
22	PV System (200kW)	229,707	17.5	73.8%	104,455	1,737,320
23	PV System (260 kW)	0	14.7	80.4%	114,208	2,258,516
C	**(Neutral Life Cycle Cost Combination)**					
	Energy Use Intensity (kBtu/ft2-yr)	14.7				
	Total Savings (%)	80%				
	Life Cycle Cost Savings ($)	0				
24	PV System (300kW)	-343,356	10.1	84.9%	130,464	2,605,980
25	PV System (400kW)	-916,419	2.7	95.9%	146,719	3,474,640
26	PV System (435kW)	-1,116,991	0.1	99.8%	152,409	3,778,671
D	**(Maximum Savings Combination)**					
	Energy Use Intensity (kBtu/ft2-yr)	0.1				
	Total Savings (%)	99.8%				
	Life Cycle Cost Savings ($)	-1,116,990				

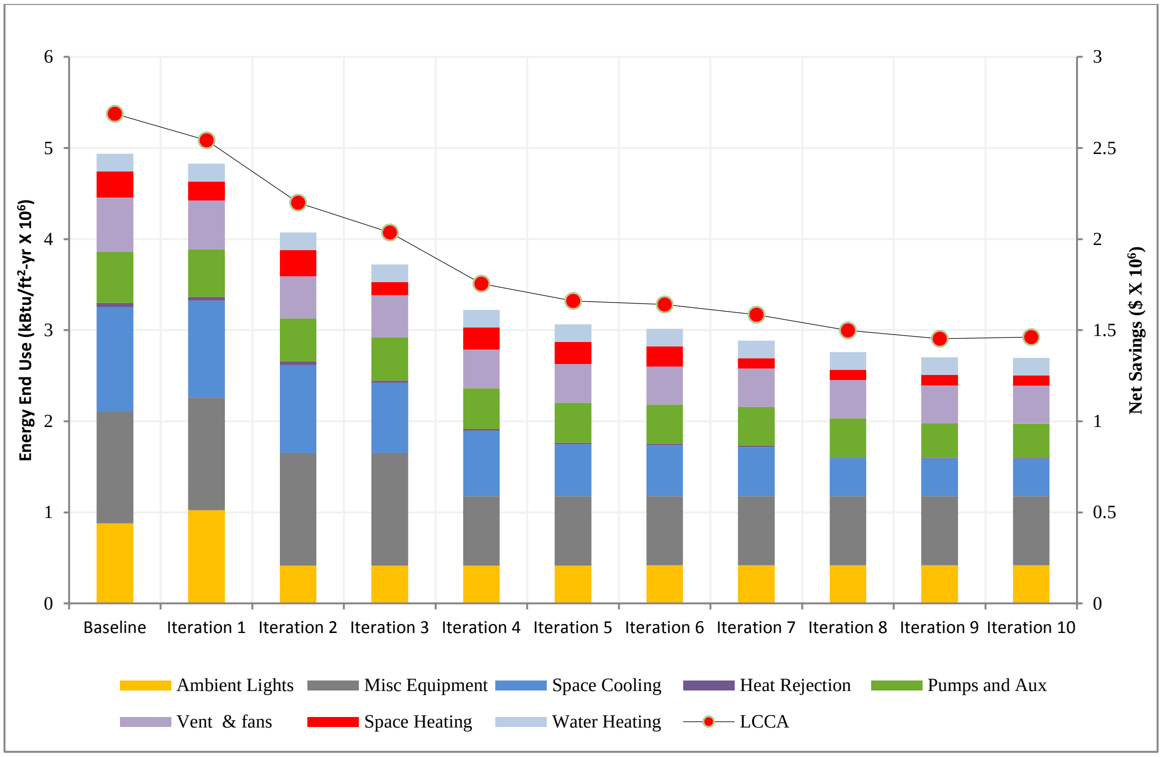

Figure 4-4 Energy end use vs Net Savings (Iteration 1-10)

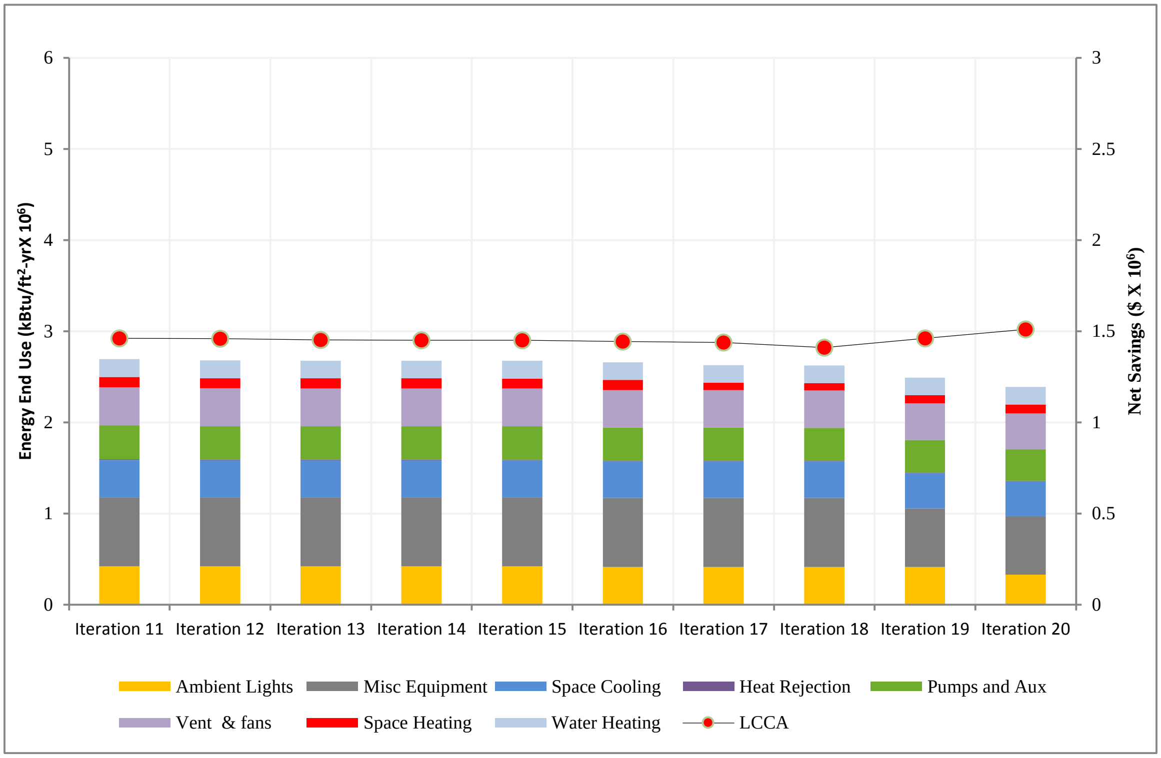

Figure 4-5 Energy End Use vs Net Savings (Iteration 11-20)

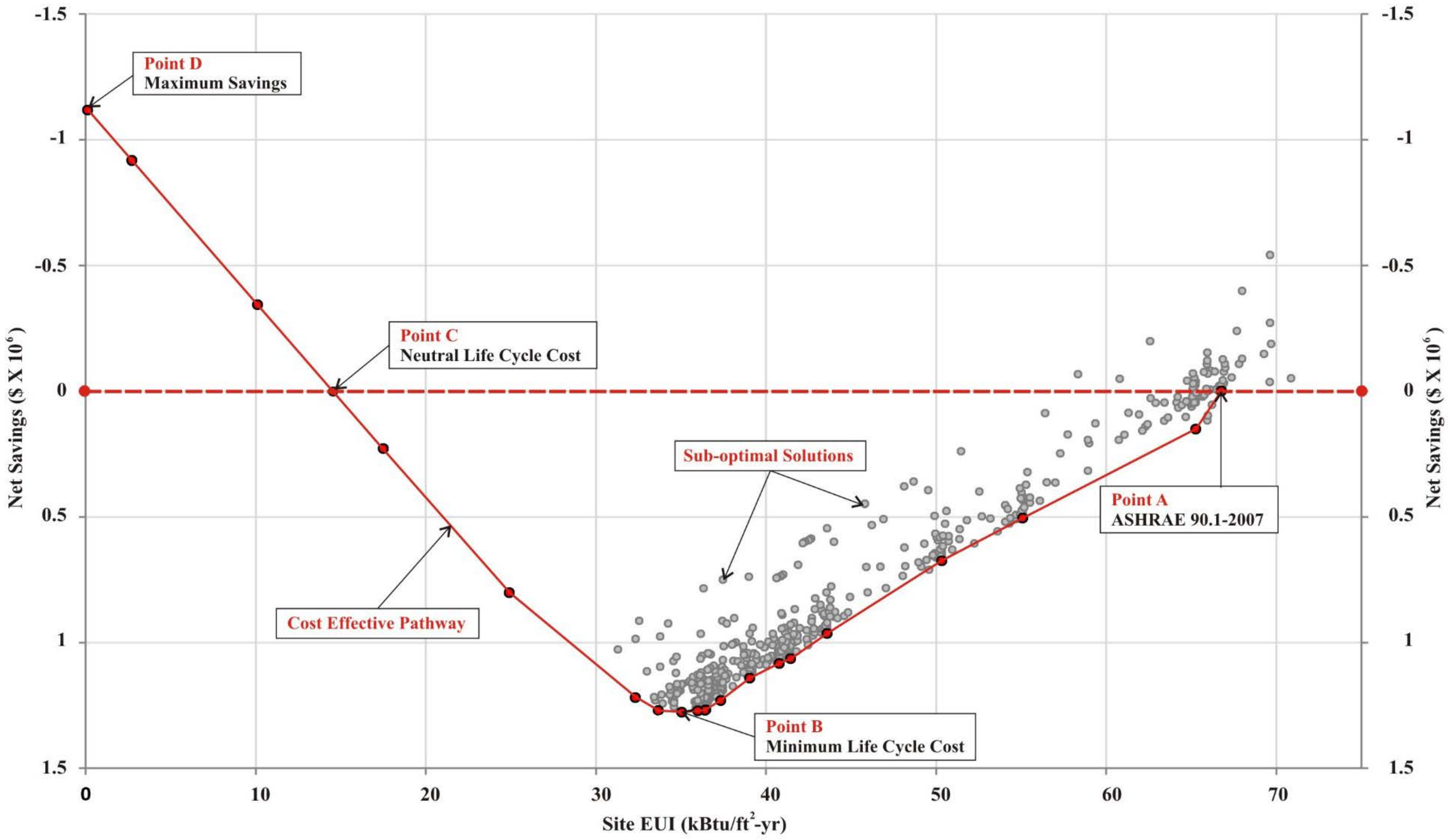

Figure 4-6 Energy Use Intensity vs Net Savings

5 CONCLUSION AND FUTURE WORK

This research demonstrated how the sequential search methodology can be used to identify a cost optimum pathway towards net zero conditions in a school building located in Phoenix, Arizona. The methodology included a special step wherein accurate economic data of various ECM measures were determined, this allowed us to compare and justify the incorporation of these measures for the proposed building. The process provided an estimate of the extra investment required to achieve different levels of energy efficiency compared to a baseline and allowed the determination of feasible payback time periods. It was realized that such types of analysis can be used to persuade investors to agree to higher initial costs since they would lead to greater life cycle savings from the reduced utility bills.

The measures selected as the Pareto optimal building design were also found to be congruent to the ranking results of the sensitivity analysis (Morris Method) conducted in the first part of the study. The top ten ranked measures were selected during the initial iterations and the lower ranked options were not selected at all. This provides further validation to the selection process. As mentioned earlier (Section 1.3), the study was limited in its scope and future work in this area should focus on the following aspects:

- The hot and arid climate (Phoenix, Arizona) selected for this study is cooling intensive. Buildings situated in this climate zone usually register higher energy use intensities in comparison to buildings located in milder climates. This factor usually results in an increase in the size of the renewable systems and hence decreases the economic incentives behind the development of net zero buildings. Future studies can consider making a comparison with milder climates to assess the full impact of this factor.

- The effects of a wider set of measures should be investigated, this study was limited by the unavailability of adequate cost data, and greater effort in the collection of data from manufactures and market sources can broaden the initial set of parameters.
- Given the fact that the price of building components tends to fluctuate due to innovation and other market drivers, future analysis should try to incorporate uncertainties of performance and cost of various measures considered in the analysis.
- Study can be extended to include for different HVAC systems. Systems like Fan Coil Units (FCU), Water Source Heat Pumps (WSHP), Geothermal Heat Pumps (GHP) etc. have been widely used in high performance school buildings. Different measures will likely effect each system differently and hence the cost optimum combination can vary for each case.
- Cost effective energy reduction pathways can be formulated for school types with larger conditioned areas and greater program level diversity. This study only focused on the primary school prototype model and future work can include DOE’s secondary school prototype.
- The process can be automated further by the use of tools like RMI’s Model Manager (RMI Website). This Excel-based tool makes use of the batch processing feature in eQUEST and is ideal for investigating large numbers of parameters. The

tool’s post-processing component also allows for various output data like performance metrics, building plant and system size etc. to be extracted and compared side by side in a single interface.

- The compatibility of this methodology with parametric analysis features of other simulation software like the Parametric Analysis Tool (PAT) in OpenStudio can be investigated. The Parametric Analysis Tool leverages the flexibility of OpenStudio measures and the Building Component Library (BCL) and hence can be used to analyze complicated system level strategies like decoupled ventilation etc.

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APPENDIX A

ENERGY MODEL DATA

This Appendix assembles the various architectural design and HVAC system related details of the primary school prototype building used in this study. Building data and other specifications like occupancy and equipment schedules were selected from NREL publications like Bonnema et al. (2013) and Deru et al. (2010).

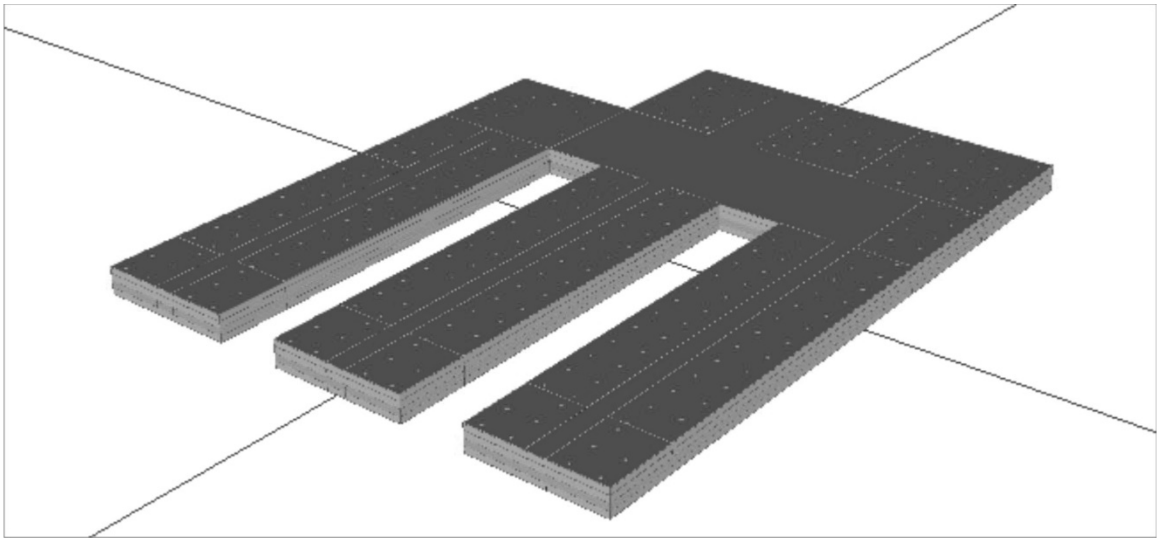


Figure A-1 Screen Capture of Model Geometry in eQUEST

Table A-1 Primary School Zone Geometry Breakdown

Zone Type	Space Type	Qty.	Dimensions (ft × ft)	Zone Area (ft²)	Total Area (ft²)
Corner classroom	Classroom	6	36.09 × 29.53	1,066	6,396
Large classroom group	Classroom	5	173.88 × 29.53	5,134	25,670
Small classroom group	Classroom	1	114.83 × 29.53	3,391	3,391
Art classroom	Art room	1	59.06 × 29.53	1,744	1,744
Classroom corridors	Corridor	3	209.97 × 9.84	2,067	6,201
Lobby	Lobby	1	62.34 × 29.53	1,841	1,841
Main corridor	Corridor	1	42.65 × 137.80	5,877	5,877
Mechanical room	Mechanical	1	19.69 × 137.80	2,713	2,713
Restrooms	Restroom	1	62.34 × 32.81	2,045	2,045

Media center	Library/media center	1	62.34 × 68.90	4,295	4,295
Offices	Office	1	68.90 × 68.90	4,747	4,747
Gym	Gym/multipurpose room	1	68.90 × 55.77	3,843	3,843
Kitchen	Kitchen	1	68.90 × 26.25	1,808	1,808
Cafeteria	Cafeteria	1	68.90 × 49.21	3,391	3,391

Table A-2 Building Component Characteristics

Item		Component	Values	
Envelope	Roof	Insulation entirely above deck	R-20.0 c.i.	
		Solar reflectance index (SRI)	0.3	
	Wall	Steel Framed	R-13	
	Slabs	Unheated	N.R	
	Doors	Opaque	U-0.700	
	Vertical Glazing	Metal Framing (all other)	Assembly Max. U	Assembly Max SHGC
			U-0.75	SHGC-0.25
		Window and Wall Ratio	35%	
	Skylight	Skylight with Curb	Assembly Max. U	Assembly Max SHGC
		0%-2.0%	U-1.98	SHGC-0.36
		2.1%-5.0%	U-1.98	SHGC-0.19
		Skylight to Roof Ratio	2%	
	Shading	Overhangs	None (windows are flushed with exterior walls)	
Lighting	Interior Lighting Power density	Space Type	LPD (W/ft$^{2)}$	
		Auditorium	0.9	
		Art Room	1.4	
		Cafeteria	0.9	
		Classroom	1.4	
		Corridor	0.5	
		Gym/multipurpose room	1.4	
		Kitchen	1.2	
		Library/media center	1.2	
		Lobby	1.3	
		Mechanical room	1.5	
		Office	1.1	
		Restroom	0.9	
		Calculated whole building LPD	1.18	
	Exterior Lighting	Exterior Lighting Total	5547 W	
	Controls	Automatic lighting controls	None	
Plug and Process	Plug and Process loads	Space Type	Electric Loads (W/ft^2)	Gas Loads (Btuh/ft^2)
		Auditorium	n/a	
		Art Classroom	6.3	

		Cafeteria	0.5	
		Classroom	1.4	
		Corridor		
		Gym/multipurpose room		
		Kitchen	16.7	57.8
		Library/media center	0.5	
		Lobby		
		Mechanical room		
		Office	0.5	
		Restroom		
		Calculated whole building	1.3	
HVAC	System Summary	Type	VAV with reheat	
		Fan Control	VAV	
		Cooling Type	Chilled Water	
		Heating Type	Hot water fossil fuel boiler	
	AHU	Preheat Coils	n/a	
		Ventilation rate per Space Type	As per ASHRAE 62.1-2007	
		Economizer	Included	
		Economizer High-Limit Shutoff	75˚F	
		System Fan Power	P_{fan}= bhp X 746/ Fan Motor Efficiency	
	Chiller	Type	Water-cooler Centrifugal	
		Number	2	
		Minimum Efficiency	6.10 COP, 6.40 IPLV	
		Chilled-Water Supply Temp	Supply: 44˚F, Return: 56˚F	
		Chilled-Water Supply Temp Reset	44˚F when OA> 80˚F, 54˚F when OA< 60˚F	
		Chilled-Water Pump Efficiency	22 W/gpm	
	Boiler	Type	Natural Draft	
		Number of boilers	2	
		Minimum Efficiency	80% AFUE	
		Hot-Water Supply Temp	Supply: 180˚F, Return: 130˚F	
		Hot-Water Supply Temp Reset	180˚F when OA< 20˚F, 150˚F when OA> 50˚F	
		Hot-Water Pump Efficiency	19 W/gpm	
	Heat Rejection	Type	Axial fan cooling tower with two speed fans	
		Condenser Water Design Supply Temp	85˚F	
		Condenser-Water Pump Efficiency	19 W/gpm	
		Fan Performance	38.2 gpm/hp	
SWH	Service Hot Water	Type	Gas storage water heater	
		Thermal Efficiency	80%	
Others	Schedules	Occupancy, Cooling Set Points, Lighting Equipment use, Electrical Equipment use etc.	As per AEDG development guide.	

APPENDIX B

SYSTEM SIZING AND COMPONENT COSTS CORRELATIONS

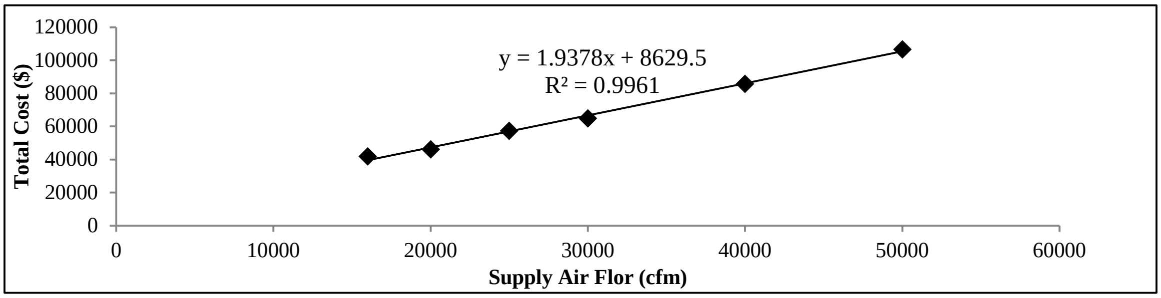
This appendix assembles the costs of various HVAC components that were used to develop regression based equations to determine changes in system sizing during the sequential search process. The ASHRAE 90.1 Cost-effectiveness Study was the primary source of cost data and the process is further elaborated in Section 3.3. The following datasets are included:

Table B-1 Material and Installation Costs of Air Handling Units.
Table B-2 Material and Installation Costs of Air Distribution Systems.
Table B-3 Material and Installation Costs of Chiller Units.
Table B-4 Material and Installation Costs of Cooling Tower Units.
Table B-5 Material and Installation Costs of Boiler Units.
Table B-6 Material and Installation Costs of Primary Pumps.
Table B-7 Material and Installation Costs of Hot Water Piping System.
Table B-8 Material and Installation Costs of Chilled and Condenser Water Piping Systems.

VAV Air Handling Unit

Table B-1 Material and Installation Costs of Air Handling Units

Supply Air Flow (cfm)	Material and Installation Cost ($)
16000	41817
20000	46097
25000	57400
30000	64784
40000	85736
50000	106688



Duct Work and Zone Air Distribution

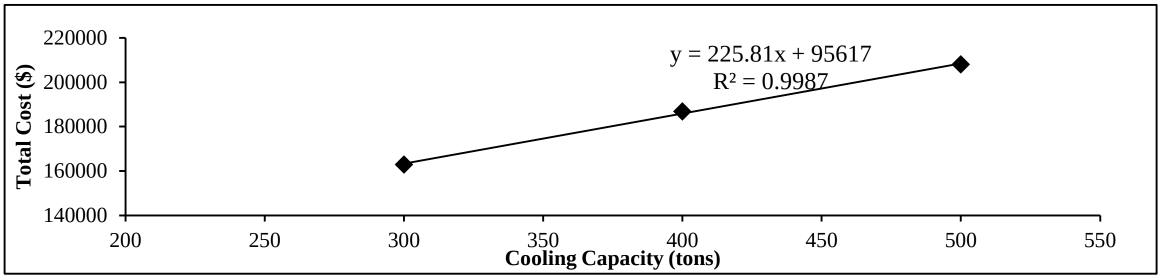
Table B-2 Material and Installation Costs of Air Distribution Systems

Material Cost ($) vs System Airflow (cfm)	Labor Cost ($) vs System Airflow (cfm)
y = 0.2902x + 4511.3 $R^2 = 0.8963$	y =1.576x + 9922.5 $R^2 = 0.9473$

Chillers

Table B-3 Material and Installation Costs of Chiller Units

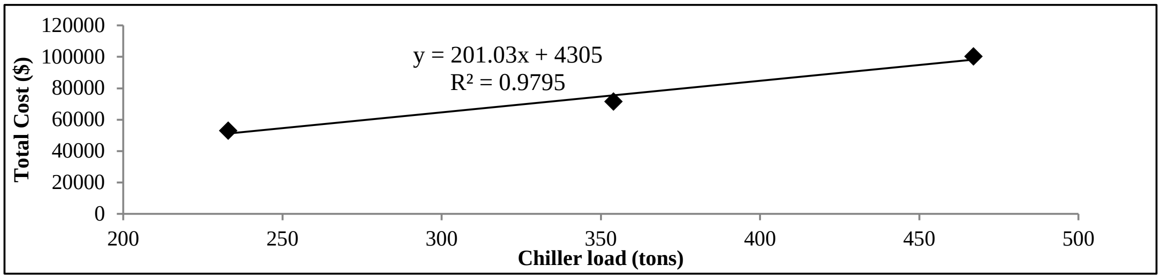
Cooling Capacity (tons)	Material and Installation Cost ($)
300	162887
400	186888
500	208049



Cooling Tower

Table B-4 Material and Installation Costs of Cooling Tower Units

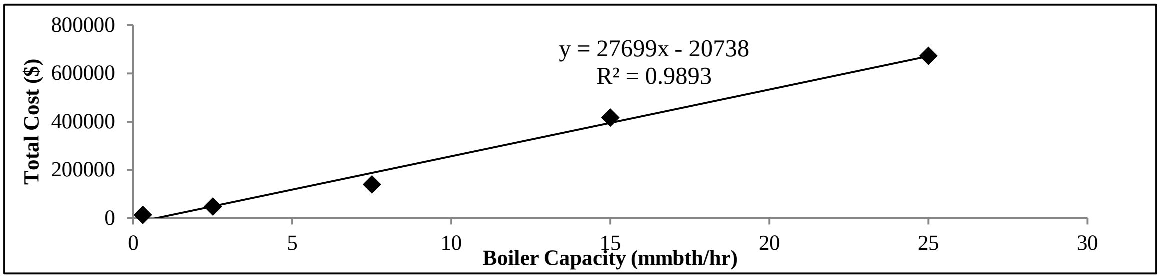
Size of Chiller Cooling Load Served (tons)	Material and Installation Cost ($)
233	53042
354	71540
467	100217



Boilers

Table B-5 Material and Installation Costs of Boiler Units

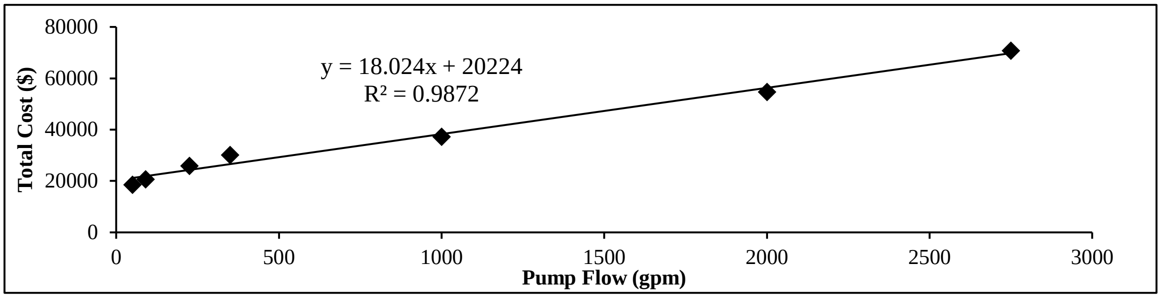
Boiler Capacity (mmbtu/hr)	Material and Installation Cost ($)
0.3	12883
2.5	47344
7.5	139909
15	417279
25	672172



Primary Pumps

Table B-6 Material and Installation Costs of Primary Pumps

Flow (gpm)	Total Cost
50	18561
90	20715
225	25933
350	30173
1000	37225
2000	54676
2750	70805



Hot Water (HW) Piping

Table B-7 Material and Installation Costs of Hot Water Piping System

Material Cost ($) vs HW Coil Flow (gpm)	Labor Cost ($) vs HW Coil Flow (gpm)
$y = 4.756x^2 - 768.94x + 63199$ $R^2 = 0.8013$	$y = 1.546x^2 - 245.21x + 35280$ $R^2 = 0.8505$

Chilled Water (CHW) and Condenser water (CW) Piping

Table B-8 Material and Installation Costs of Chilled and Condenser Water Piping Systems

Material Cost ($) vs CHW Flow (gpm)	Labor Cost ($) vs CHW Flow (gpm)
$y = 97.92x - 34003$ $R^2 = 0.9709$	$y = -0.0604x^2 + 302.95x - 267225$ $R^2 = 0.9872$

APPENDIX C

SENSITIVITY ANALYSIS TRAJECTORY RUNS

This appendix assembles all the simulation results of the various trajectories used for the sensitivity analysis (Morris Method). A total of 10 trajectories (200 simulations) were conducted and the energy conservation effects of each parameter was recorded separately. Section 2.8 and 4.1 has further details of the process. Tables C-1 to C-10 shows all the trajectories used and lists the energy cost change produced by each parameter.

Table C-1 Simulation Runs of Trajectory 1

																				Electricty Use (X1000 kWh)	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,398	562	147282	
2	1b	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,395	561	146964	1
3	1b	2b	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,395	583	147270	2
4	1b	2b	3b	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,395	583	147260	3
5	1b	2b	3b	4b	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,374	565	144882	4
6	1b	2b	3b	4b	5b	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,418	580	149533	5
7	1b	2b	3b	4b	5b	6b	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,413	561	148804	6
8	1b	2b	3b	4b	5b	6b	7b	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,352	501	142012	7
9	1b	2b	3b	4b	5b	6b	7b	8b	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,346	490	141334	8
10	1b	2b	3b	4b	5b	6b	7b	8b	9b	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,176	559	124774	9
11	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,116	592	119016	10
12	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12a	13a	14a	15a	16a	17a	18a	19a	1,084	592	115792	11
13	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13a	14a	15a	16a	17a	18a	19a	1,065	594	113912	12
14	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14a	15a	16a	17a	18a	19a	1,055	474	111646	13
15	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15a	16a	17a	18a	19a	1,045	471	110638	14
16	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16a	17a	18a	19a	1,046	415	110123	15
17	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17a	18a	19a	1,016	412	107073	16
18	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18a	19a	966	413	102072	17
19	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19a	966	413	102040	18
20	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	19

Table C-2 Simulation Runs of Trajectory 2

																				Electricty Use (X1000 kWh)	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	**1a**	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,398	562	147282	
2	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,330	583	140614	10
3	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15a	16a	17a	18a	19a	1,300	585	137616	11
4	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13a	14a	15a	16a	17a	18a	19a	1,279	588	135497	12
5	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14a	15a	16a	17a	18a	19a	1,266	482	133172	13
6	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15a	16a	17a	18a	19a	1,248	482	131357	14
7	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15b	16a	17a	18a	19a	1,249	419	130763	15
8	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15b	16b	17a	18a	19a	1,224	414	128164	16
9	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15b	16b	17b	18a	19a	1,171	415	122867	17
10	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15b	16b	17b	18b	19a	1,171	415	122827	18
11	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	1,154	261	119575	19
12	1a	2a	3a	4a	5a	6a	7a	8a	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	996	290	103846	9
13	1a	2a	3a	4a	5a	6a	7a	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	991	284	103328	8
14	1a	2a	3a	4a	5a	6a	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	951	258	98983	7
15	1a	2a	3a	4a	5a	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	957	251	99531	6
16	1a	2a	3a	4a	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	971	250	100954	5
17	1a	2a	3a	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	954	248	99221	4
18	1a	2a	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	954	248	99216	3
19	1a	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	952	242	98877	2
20	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	1

Table C-3 Simulation Runs of Trajectory 3

																				Electricty Use (X1000 kWh)	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	**1a**	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15a	16a	17a	18a	19a	1,398	562	147282	
2	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15a	16a	17a	18a	19b	1,250	510	131818	19
3	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15a	16a	17a	18b	19b	1,250	510	131747	18
4	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15a	16a	17b	18b	19b	1,213	516	128079	17
5	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15a	16b	17b	18b	19b	1,222	516	129013	16
6	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14a	15b	16b	17b	18b	19b	1,223	438	128318	15
7	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13a	14b	15b	16b	17b	18b	19b	1,205	438	126470	14
8	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12a	13b	14b	15b	16b	17b	18b	19b	1,177	260	121899	13
9	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	1,154	261	119585	12
10	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11c	12b	13b	14b	15b	16b	17b	18b	19b	1,130	261	117162	11
11	1a	2a	3a	4a	5a	6a	7a	8a	9a	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	1,009	283	105134	10
12	1a	2a	3a	4a	5a	6a	7a	8a	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	852	324	89623	9
13	1a	2a	3a	4a	5a	6a	7a	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	848	318	89122	8
14	1a	2a	3a	4a	5a	6a	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	810	288	85029	7
15	1a	2a	3a	4a	5a	6b	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	816	280	85524	6
16	1a	2a	3a	4a	5b	6b	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	829	279	86829	5
17	1a	2a	3a	4b	5b	6b	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	814	277	85269	4
18	1a	2a	3b	4b	5b	6b	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	814	277	85264	3
19	1a	2b	3b	4b	5b	6b	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	811	268	84922	2
20	1b	2b	3b	4b	5b	6b	7b	8b	9b	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	808	266	84545	1

Table C-4 Simulation Runs of Trajectory 4

																				Electricty Use (X1000 kWh)	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,398	562	147282	
2	1b	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,395	561	146964	1
3	1b	2b	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,395	583	147270	2
4	1b	2b	3b	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,395	583	147260	3
5	1b	2b	3b	4b	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,374	565	144882	4
6	1b	2b	3b	4b	5b	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,418	580	149533	5
7	1b	2b	3b	4b	5b	6b	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,413	561	148804	6
8	1b	2b	3b	4b	5b	6b	7b	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,352	501	142012	7
9	1b	2b	3b	4b	5b	6b	7b	8b	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,346	490	141334	8
10	1b	2b	3b	4b	5b	6b	7b	8b	9b	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,176	559	124774	9
11	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,116	592	119016	10
12	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19b	1,057	485	111928	19
13	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18b	19b	1,056	485	111867	18
14	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17b	18b	19b	1,021	493	108444	17
15	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16b	17b	18b	19b	1,029	493	109226	16
16	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15b	16b	17b	18b	19b	1,030	420	108584	15
17	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14b	15b	16b	17b	18b	19b	1,020	419	107541	14
18	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13b	14b	15b	16b	17b	18b	19b	986	240	102323	13
19	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12b	13b	14b	15b	16b	17b	18b	19b	965	241	100270	12
20	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98507	11

Table C-5 Simulation Runs of Trajectory 5

																				Electricty Use (X1000 kWh)	Gas Use (X 10E6 Btu)	Energy Cost ($)	Attribute
1	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,398	562	147282	
2	1a	2a	3a	4a	5a	6a	7a	8a	9a	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,337	585	141327	10
3	1a	2a	3a	4a	5a	6a	7a	8a	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,170	673	125257	9
4	1a	2a	3a	4a	5a	6a	7a	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,164	661	124566	8
5	1a	2a	3a	4a	5a	6a	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,125	604	120043	7
6	1a	2a	3a	4a	5a	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,121	588	119451	6
7	1a	2a	3a	4a	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,141	596	121629	5
8	1a	2a	3a	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,121	579	119392	4
9	1a	2a	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,121	579	119391	3
10	1a	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,120	593	119443	2
11	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11a	12a	13a	14a	15a	16a	17a	18a	19a	1,116	592	119016	1
12	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12a	13a	14a	15a	16a	17a	18a	19a	1,084	592	115792	11
13	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13a	14a	15a	16a	17a	18a	19a	1,065	594	113912	12
14	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14a	15a	16a	17a	18a	19a	1,055	474	111646	13
15	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15a	16a	17a	18a	19a	1,045	471	110638	14
16	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16a	17a	18a	19a	1,046	415	110122	15
17	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17a	18a	19a	1,016	412	107083	16
18	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18a	19a	966	413	102078	17
19	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19a	966	413	102047	18
20	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98507	19

Table C-6 Simulation Runs of Trajectory 6

Trajectory6																				**Electricty Use (X1000 kWh)**	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	
2	1c	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	945	240	98196	1
3	1c	2c	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	944	238	98047	2
4	1c	2c	3c	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	944	238	98043	3
5	1c	2c	3c	4c	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	931	237	96745	4
6	1c	2c	3c	4c	5c	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	925	240	96143	5
7	1c	2c	3c	4c	5c	6c	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	921	236	95731	6
8	1c	2c	3c	4c	5c	6c	7c	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	907	233	94294	7
9	1c	2c	3c	4c	5c	6c	7c	8c	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	901	232	93646	8
10	1c	2c	3c	4c	5c	6c	7c	8c	9c	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	820	239	85483	9
11	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16b	17b	18b	19b	701	268	73744	10
12	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	686	268	72188	11
13	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13b	14b	15b	16b	17b	18b	19b	702	268	73874	12
14	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14b	15b	16b	17b	18b	19b	728	520	79007	13
15	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15b	16b	17b	18b	19b	728	520	78976	14
16	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16b	17b	18b	19b	727	613	79802	15
17	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17b	18b	19b	721	612	79154	16
18	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18b	19b	743	600	81276	17
19	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19b	743	600	81320	18
20	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	790	694	86959	19

Table C-7 Simulation Runs of Trajectory 7

Trajectory7																				**Electricty Use (X1000 kWh)**	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	
2	1b	2b	3b	4b	5b	6b	7b	8b	9c	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	869	254	90627	9
3	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11b	12b	13b	14b	15b	16b	17b	18b	19b	747	288	78578	10
4	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12b	13b	14b	15b	16b	17b	18b	19b	729	288	76819	11
5	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13b	14b	15b	16b	17b	18b	19b	748	287	78650	12
6	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14b	15b	16b	17b	18b	19b	776	549	84076	13
7	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15b	16b	17b	18b	19b	770	548	83486	14
8	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16b	17b	18b	19b	769	646	84396	15
9	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17b	18b	19b	762	646	83621	16
10	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18b	19b	786	635	85951	17
11	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19b	786	635	86004	18
12	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	833	727	91692	19
13	1c	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	830	724	91301	1
14	1c	2c	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	828	726	91174	2
15	1c	2c	3c	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	828	726	91171	3
16	1c	2c	3c	4c	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	817	719	89954	4
17	1c	2c	3c	4c	5c	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	812	734	89593	5
18	1c	2c	3c	4c	5c	6c	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	820	725	90339	6
19	1c	2c	3c	4c	5c	6c	7c	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	802	708	88359	7
20	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	791	697	87125	8

Table C-8 Simulation Runs of Trajectory 8

Trajectory8																				**Electricty Use (X1000 kWh)**	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	
2	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17b	18b	19b	945	241	98176	16
3	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18b	19b	993	240	103025	17
4	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19b	993	240	103082	18
5	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	1,046	415	110123	19
6	1b	2b	3b	4b	5c	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	1,029	411	108455	5
7	1b	2b	3b	4b	5c	6c	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	1,026	403	108015	6
8	1b	2b	3b	4b	5c	6c	7c	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	1,010	381	106151	7
9	1b	2b	3b	4b	5c	6c	7c	8c	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	1,003	369	105317	8
10	1b	2b	3b	4b	5c	6c	7c	8c	9c	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	921	395	97323	9
11	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16c	17c	18c	19c	801	447	85602	10
12	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12b	13b	14b	15b	16c	17c	18c	19c	772	447	82712	11
13	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13b	14b	15b	16c	17c	18c	19c	788	446	84334	12
14	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14b	15b	16c	17c	18c	19c	796	587	86554	13
15	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15b	16c	17c	18c	19c	796	587	86498	14
16	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	795	683	87354	15
17	1c	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	792	687	87104	1
18	1c	2c	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	790	687	86950	2
19	1c	2c	3c	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	790	688	86948	3
20	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	790	694	86959	4

Table C-9 Simulation Runs of Trajectory 9

Trajectory9																				Electricty Use (X1000 kWh)	Gas Use (X 10E6 Btu)	Energy Cost ($)	Attribute
1	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	
2	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19c	966	413	102040	19
3	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18c	19c	966	413	102072	18
4	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17c	18c	19c	1,016	412	107073	17
5	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16c	17c	18c	19c	1,046	415	110123	16
6	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15c	16c	17c	18c	19c	1,045	471	110638	15
7	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14c	15c	16c	17c	18c	19c	1,037	469	109743	14
8	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13c	14c	15c	16c	17c	18c	19c	1,047	587	111954	13
9	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12c	13c	14c	15c	16c	17c	18c	19c	1,065	585	113803	12
10	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11c	12c	13c	14c	15c	16c	17c	18c	19c	1,030	585	110234	11
11	1b	2b	3b	4b	5b	6b	7b	8b	9b	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	909	665	98778	10
12	1b	2b	3b	4b	5b	6b	7b	8b	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	833	727	91701	9
13	1b	2b	3b	4b	5b	6b	7b	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	829	715	91186	8
14	1b	2b	3b	4b	5b	6b	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	801	685	87955	7
15	1b	2b	3b	4b	5b	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	800	682	87833	6
16	1b	2b	3b	4b	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	797	687	87616	5
17	1b	2b	3b	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	804	693	88363	4
18	1b	2b	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	804	693	88361	3
19	1b	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	802	696	88259	2
20	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	791	697	87125	1

Table C-10 Simulation Runs of Trajectory 10

Trajectory10																				**Electricty Use (X1000 kWh)**	**Gas Use (X 10E6 Btu)**	**Energy Cost ($)**	**Attribute**
1	1b	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	948	241	98500	
2	1c	2b	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	945	240	98196	1
3	1c	2c	3b	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	944	238	98047	2
4	1c	2c	3c	4b	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	944	238	98043	3
5	1c	2c	3c	4c	5b	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	931	237	96745	4
6	1c	2c	3c	4c	5c	6b	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	925	240	96143	5
7	1c	2c	3c	4c	5c	6c	7b	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	921	236	95731	6
8	1c	2c	3c	4c	5c	6c	7c	8b	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	907	233	94294	7
9	1c	2c	3c	4c	5c	6c	7c	8c	9b	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	904	233	93919	8
10	1c	2c	3c	4c	5c	6c	7c	8c	9c	10b	11b	12b	13b	14b	15b	16b	17b	18b	19b	822	240	85750	9
11	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16b	17b	18b	19b	702	269	73858	10
12	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16b	17b	18b	19c	715	450	76976	19
13	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16b	17b	18c	19c	715	450	76996	18
14	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16b	17c	18c	19c	763	448	81779	17
15	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15b	16c	17c	18c	19c	796	448	85174	16
16	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14b	15c	16c	17c	18c	19c	796	506	85709	15
17	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13b	14c	15c	16c	17c	18c	19c	796	506	85674	14
18	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12b	13c	14c	15c	16c	17c	18c	19c	805	699	88590	13
19	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11b	12c	13c	14c	15c	16c	17c	18c	19c	820	694	89997	12
20	1c	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c	13c	14c	15c	16c	17c	18c	19c	790	694	86959	11