BUCKNELL UNIVERSITY

A Comprehensive Assessment of Bucknell University's Energy Profile with Performance Simulations for Various Campus Facilities

An Honors Thesis in Environmental Science

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Thesis Submitted to the Honors Council

For Honors in Environmental Studies

April 11, 2008

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Acknowledgements

First and foremost I would like to thank Dr. Molly McGuire. Not only has she contributed enormously to the successful completion of this project but also, she has demonstrated an inordinate amount of faith in my individuality, creativity, and intellectual ability throughout the years. Thank you Dr. McGuire.

I would also like to thank several other people for their guidance and collaboration without which this project simply would not have been possible.

Jim Knight – Thank you for the wealth of data that you provided me about the campus' buildings' systems and energy usage statistics. Beyond that, thank you for being receptive to the concept of intelligent building design and for your willingness to continue the fight for increased energy efficiency on campus.

Dr. Peter Stryker – Thank you Dr. Stryker for both your sage technical advice during this project and your efforts to publicize this project amongst engineering students and faculty. It is my sincerest hope that this work is only the beginning of a formal institution wide effort to reevaluate how we use energy and what we can do to change.

Juliana Su – I appreciate all the time that you volunteered helping me learn how to use the Flash coding environment. Your help has been much appreciated.

Dr. Peter Wilshusen, Dina El Mogazi, & The Bucknell Environmental Center – Without first: your decision to initiate the campus wide environmental assessment, and second: your willingness to provide financial backing for the purchase of the VisualDOE software package this project certainly would not have gotten very far. Your efforts to promote environmental awareness and educate future environmental leaders are not in vain.

And finally, to my mother Pat, my father Paul, and my brother Bryan:

This, like everything, is for you.

Table of Contents

List of Tables

List of Figures

List of Images

Abstract

This two phase project involves [1] a comprehensive investigation of the composition and distribution of demand for thermal and electrical energy in Bucknell campus facilities and [2] the simulation of Taylor Hall's energy consumption profile using the energy analysis software VisualDOE 4.0. The first phase of this project culminated in the production of a color coded energy intensity map of the Bucknell Campus. In the second phase, VisualDOE simulations were used to evaluate the potential energy savings associated with various modifications to Taylor Hall's construction materials and reductions in the level of its overall electricity demand.

America's Energy Problem

> *There is no substitute for energy. The whole edifice of modern society is built upon it… It is not 'just another commodity' but the precondition of all commodities, a basic factor equal with air, water, and earth.*
>
> - E.F. Schumacher

This prescient statement from economist E.F. Schumacher clearly illustrates a reality that Americans are slowly beginning to appreciate. Energy permeates every facet of modern existence; it enables large scale food production, facilitates rapid communication and transportation, and fuels the engines of economic growth. Yet, even a cursory survey of the ways and extent to which we use our energy resources would wrongfully suggest that they were both cheap and in abundant supply.

Each year Americans consume more energy than the citizens of any other nation. How much more? Well, at 340 million Btu/person/year, in 2005 America's per capita energy consumption was roughly 4 times the global average and an astounding 21 times that of the average African citizen (EIA, 2006). According to data compiled by the World Resources Institute, in 2003, the average American consumed a quantity of energy equivalent to 7,795 kilograms of oil; a figure which works out to around 57 barrels of oil/person/year (WRI, 2006). Perhaps even more disturbingly, with energy consumption in the United States projected to grow at an annual rate of 1.3%/year, our total annual energy consumption is expected to increase from 100 to 133 quadrillion Btu's [quads] by the year 2030 (Table 1; EIA v, 2006).

Table 1: World Total Energy Consumption by Region

Table A1. World Total Energy Consumption by Region, Reference Case, 1990-2030
(Quadrillion Btu)

Region/Country	History			Projections					Average Annual Percent Change, 2003-2030
	1990	2002	2003	2010	2015	2020	2025	2030	
OECD									
OECD North America	**100.8**	**117.5**	**118.3**	**131.4**	**139.9**	**148.4**	**157.0**	**166.2**	**1.3**
United States[a]	84.6	98.1	98.1	107.9	114.2	120.6	127.0	133.9	1.2
Canada	11.1	13.1	13.5	15.6	16.6	17.5	18.4	19.2	1.3
Mexico	5.0	6.2	6.8	7.9	9.1	10.3	11.7	13.2	2.5
OECD Europe	**69.9**	**77.9**	**78.9**	**84.4**	**87.2**	**88.7**	**91.3**	**94.5**	**0.7**
OECD Asia	**26.7**	**36.5**	**37.1**	**40.3**	**42.8**	**44.4**	**46.1**	**48.0**	**1.0**
Japan	18.4	22.2	22.4	22.7	23.4	23.6	24.0	24.3	0.3
South Korea	3.8	8.4	8.6	10.9	12.3	13.3	14.4	15.5	2.2
Australia/New Zealand	4.4	6.0	6.0	6.6	7.0	7.4	7.8	8.2	1.2
Total OECD	**197.4**	**231.9**	**234.3**	**256.1**	**269.9**	**281.6**	**294.5**	**308.8**	**1.0**
Non-OECD									
Non-OECD Europe and Eurasia	**67.2**	**46.9**	**48.5**	**56.5**	**62.8**	**68.7**	**74.0**	**79.0**	**1.8**
Russia	39.0	28.1	29.1	33.3	36.5	39.6	42.4	44.8	1.6
Other	28.3	18.8	19.4	23.2	26.3	29.1	31.6	34.1	2.1
Non-OECD Asia	**47.5**	**78.4**	**83.1**	**126.2**	**149.4**	**172.8**	**197.1**	**223.6**	**3.7**
China	27.0	42.1	45.5	77.0	91.8	106.6	121.7	139.1	4.2
India	8.0	13.8	14.0	19.4	22.5	25.7	29.0	32.5	3.2
Other Non-OECD Asia	12.5	22.5	23.6	29.8	35.1	40.6	46.4	52.0	3.0
Middle East	**11.3**	**19.1**	**19.6**	**25.0**	**28.2**	**31.2**	**34.3**	**37.7**	**2.4**
Africa	**9.5**	**12.8**	**13.3**	**17.7**	**20.5**	**22.3**	**24.3**	**26.8**	**2.6**
Central and South America	**14.5**	**21.3**	**21.9**	**28.2**	**32.5**	**36.5**	**41.2**	**45.7**	**2.8**
Brazil	5.8	8.6	8.8	10.8	12.4	13.8	15.5	17.2	2.5
Other Central and South America	8.8	12.7	13.1	17.4	20.1	22.7	25.7	28.5	2.9
Total Non-OECD	**150.0**	**178.4**	**186.4**	**253.6**	**293.5**	**331.5**	**371.0**	**412.8**	**3.0**
Total World	**347.3**	**410.3**	**420.7**	**509.7**	**563.4**	**613.0**	**665.4**	**721.6**	**2.0**

[a]Includes the 50 States and the District of Columbia.

Notes: Energy totals include net imports of coal coke and electricity generated from biomass in the United States. Totals may not equal sum of components due to independent rounding. The electricity portion of the national fuel consumption values consists of generation for domestic use plus an adjustment for electricity trade based on a fuel's share of total generation in the exporting country.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2003* (May-July 2005), web site www.eia.doe.gov/iea/. **Projections:** EIA, *Annual Energy Outlook 2006*, DOE/EIA-0383(2006) (Washington, DC, February 2006), AEO2006 National Energy Modeling System, run AEO2006.D111905A, web site www.eia.doe.gov/oiaf/aeo/; and System for the Analysis of Global Energy Markets (2006).

One encouraging sign is that the number of people who have internalized this message and now feel compelled to do something about it is steadily on the rise. Indeed, this fact is evident by the increasing urgency of popular rhetoric condemning our national energy profligacy. Much like what happened in the United States during the mid to late 1970's in response to the OPEC oil embargo there is now a growing movement for both increased energy efficiency and decreased reliance upon imported foreign oil.

Many sage voices within the environmental community have expressed their concern about the direction which this movement is taking however. What I am referring to here is the fact that for the vast majority of Americans issues of energy efficiency are principally being framed in the context of the transportation sector. And indeed, there are practical reasons behind this. For most Americans, their only direct contact with global energy markets comes from a weekly visit to the local gas station. This is a fact well known to energy advocates in the public arena who have, quite successfully, been exploiting the ubiquity of this shared experience to deliver their message to the masses. For, even to the most naive among us, the linkages between transportation energy and things like national security or global climate change are readily apparent.

As the price of light sweet crude edges above $100/barrel we are seeing more and more popular support for policies designed to improve energy efficiency in the transportation sector. But while I agree that raising CAFE[1] requirements, providing increased funding for innovative public mass transit systems, and developing incentive structures to promote high efficiency and alternative energy vehicles are all long overdue steps towards reducing our national energy consumption; these measures represent but one component of the broader more comprehensive energy strategy that will be needed if we are going to adequately address this problem (NHSTA, 2006).

The popular perception that the majority of energy used in the United States is devoted to transportation is not only false but may prove to be dangerous as well. If one looks at a breakdown of sectoral energy demand in the United States they might be surprised to find that the largest single component of our national consumption profile goes to the heating,

[1] CAFE is an acronym for Corporate Average Fuel Efficiency Standards. They are established by the National Highway Traffic Safety Administration [NHTSA] and refer to “the sales weighted average fuel economy, expressed in miles per gallon [mpg], of a manufacturer’s fleet of passenger cars or light trucks with a gross vehicle weight rating [GVWR] of 8,500 lbs. or less, manufactured for sale in the United States, for any given model year.” (NHSTA, 2008)

cooling, and electrical needs of buildings (Table 2). Table 2: Buildings' Share of U.S.

Table 2: Primary Energy Consumption

Buildings Energy Data Book: 1.1 Buildings Sector Energy Consumption *September 2007*

1.1.3 Buildings Share of U.S. Primary Energy Consumption (Percent)

	Buildings						Total Consumption
	Residential	Commercial	Total	Industry	Transportation	Total	(quads)
1980 (1)	20%	14%	34%	41%	25%	100%	78.3
1990	20%	16%	36%	38%	26%	100%	84.7
2000	21%	17%	38%	35%	27%	100%	98.9
2005	**22%**	**18%**	**40%**	**32%**	**28%**	**100%**	**100.2**
2010	22%	18%	40%	32%	28%	100%	106.6
2015	22%	19%	40%	31%	29%	100%	112.4
2020	21%	19%	41%	30%	29%	100%	118.3
2025	21%	20%	41%	30%	29%	100%	124.5
2030	20%	20%	41%	29%	30%	100%	131.3

Note(s): 1) Renewables are not included in the 1980 data.
Source(s): EIA, State Energy Data 2004: Consumption, June 2007, Tables 8-12, p. 18-22 for 1980-2000; and EIA, AEO 2007, Feb. 2007, Table A2, p. 137-139 for 2005-2030 data and Table A17, p. 163 for non-marketed renewable energy.

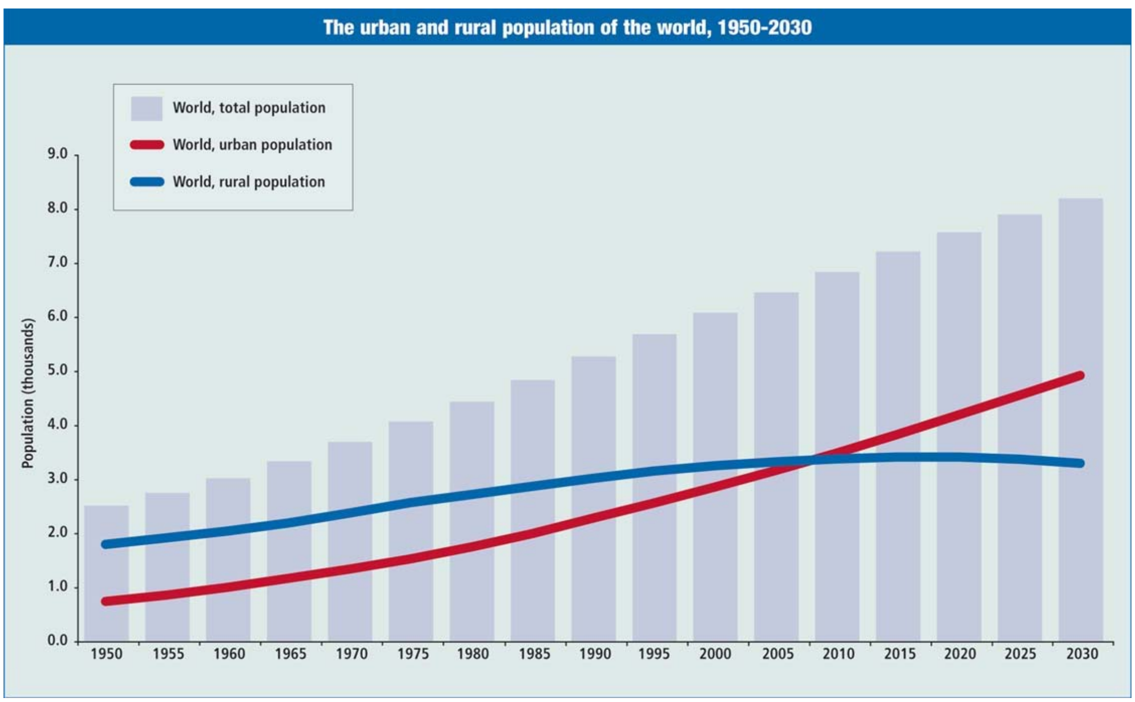
A full 40% of all the energy consumed in the United States each year services the requirements of commercial and residential structures. For some comparison, the transportation sector constitutes a mere 28% of the total national energy demand (EIA iv, 2006). The take home message from these statistics is this: relative to proposed changes in the transportation sector, for a significantly lower cost we can achieve equal or greater reductions in our national energy footprint through comparatively modest improvements in the energy efficiency of our buildings.

Energy Efficiency and the Built Environment

Based upon the previous section's analysis of America's current energy situation, we must now ask the question: if improved building design and construction practices really are "the low hanging fruit" in the quest for greater energy efficiency why then in the United States have only 2% of commercial structures and a paltry 0.3% of residential homes been built according to the principles of sustainable construction and design (Commission for Environmental Cooperation, 2008)?

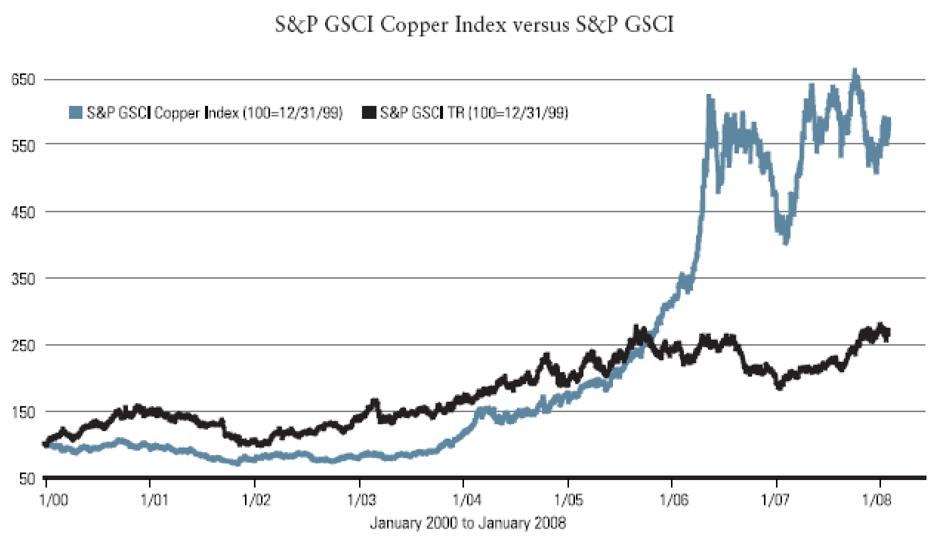
The vast majority of the buildings in American cities are dirty lumbering relics of a bygone era: a time when energy was cheap, space was abundant, and bigger was better. The world has changed significantly in the past 40 years however. Energy is certainly no longer cheap. The spot price of a barrel of oil, a popular benchmark for energy costs, has increased 670% over the same 40 year period (EIA ii, 2006). Similarly, space is no longer abundant. The global population has roughly doubled since 1970; with an increasing number of people choosing to live in urban rather than rural environments (Figure 1; United Nations Department of Economic and Social Affairs, 2005).

Figure 1: Urban and Rural Global Population Projections



And finally, bigger no longer means better. Surging costs for construction materials is contributing to the current collapse of the American housing market. The real value of the Standard and Poor Goldman Sachs Commodity Index [S&P GSCI], a popular commodities index containing several construction related materials, has increased by over 600% in just the past eight years (Figure 2; McGlone, 2008).

Figure 2: Historical S&P GSCI Performance



Improving energy efficiency in the built environment is a goal that has been within reach for quite some time now. The technologies, high performance materials, and construction know-how have all existed for decades. As proof of this fact, take the example of the home of energy analyst, physicist, inventor, and co-founder of the Rocky Mountain Institute, Amory Lovins (Fussman, 2006). Constructed in 1983, Lovins' home is located in Snowmass Colorado, an area of the country which annually experiences temperature extremes of -20º F during winter and as much as 100º F in the summertime (Ibid.). Yet in spite all of these factors however, through a combination of sensible design, high performance materials, and renewable energy generation systems [principally photovoltaic cells] Lovins' monthly home electric bill averages a meager $5/month (Ibid.). And, even with the area's highly variable climate, Lovins frequently boasts that the temperature inside his 4000 square foot home is such that he is able to grow bananas year round (Ibid.).

The example of Amory Lovins' Colorado home simply reinforces the need for the widespread application of these sorts of energy efficient building practices in the renovation and new construction of *every* building in the United States. Currently, energy efficient buildings are improperly viewed as high cost curiosities. This perception is inherently flawed and is merely an artifact of the impatience of the American people when it comes to economic decision making. As a society, we consistently favor economic decisions which deliver immediate returns over more sensible and ultimately more profitable long term strategies. Unfortunately, this sensibility ultimately lends itself to long term collapse and increased hardship.

The Future of Ecological Design

In the modern lexicon "Green" is a buzzword which has been used to describe the use of environmentally preferable practices and materials in the design, location, construction, operation, and disposal of buildings. As a general rule Green buildings strive to maximize energy usage efficiency and minimize deleterious environmental impacts. But, in order to consider what it means to be a "Green building" in a more analytical context it is important that the term be more narrowly defined. A government agency known as the United States Green Building Council [USGBC] has taken up the task of developing a certification system which aims to do just that (United States Green Building

Council, 2008). According to the USGBC, their Leadership in Energy and Environmental Design [LEED] Green Building Rating System™ encourages and accelerates [the] adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria." (Ibid.)

From an environmental perspective, the LEED certification system should be considered one of the single most important developments in the fields of architecture and construction in the last 25 years. The LEED system has tiered ranking schemes for a wide variety of different building types (Ibid.). From commercial structures and private residences to academic buildings and government headquarters, LEED certification provides an essential rubric with which to compare and evaluate different design strategies and construction methods (Ibid.). Significantly, as opposed to other regulatory methods, rather than constraining designers' creativity, the LEED system actually stimulates it, forcing them to develop innovative new solutions to address established problems of energy and materials consumption.

While energy efficiency is a primary consideration in the LEED certification process it is certainly not the only one. The LEED system involves a more comprehensive approach to the evaluation of a building's design, construction, and operation. According to the USGBC a LEED certified building will:

- Lower operating costs and increase asset value.
- Reduce waste sent to landfills.
- Conserve energy and water.
- Be healthier and safer for occupants.
- Reduce harmful greenhouse gas emissions.

- Qualify for tax rebates, zoning allowances and other incentives in hundreds of cities.
- Demonstrate an owner's commitment to environmental stewardship and social responsibility (Ibid.).

Partly due to the development of the LEED certification system, the once budding field of ecological design in now blossoming into a central feature of architectural school curriculums and practicing firms' design philosophies. The result has been a paradigm shift in what we perceive to be the functional role of the built environment. In the past, buildings were designed to satisfy only very basic criteria. For instance: they must have a low up front cost per square foot, they must provide adequate shelter from the elements and a comfortable internal environment, and they must conform to some sort of aesthetic standard. The new paradigm which has emerged imposes several new demands on our buildings. Firstly, the importance of up front costs has lost ground to more long term life cycle analyses. These take into account a building's construction, operation, maintenance, and even potential demolition. Secondly, the building's relationship with its natural environment has become a primary concern. A large number of modern building designs incorporate forms which embrace the natural features of the surrounding landscape (Brown *et al*., 2004). Contrast this with the modernist design aesthetic, which seeks the harshest possible contrast between a built form and its natural environment (Images 1 & 2).

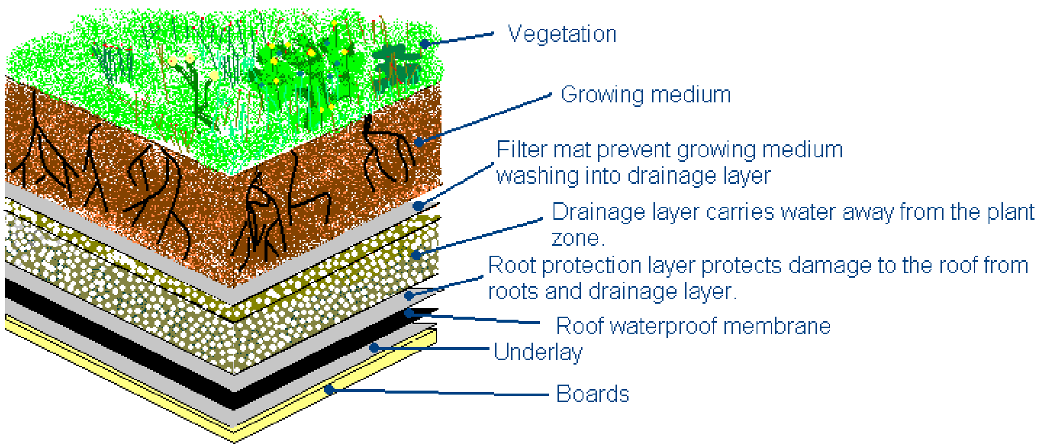
Images 1 & 2: Architectural Design Philosophy Comparison

Left, Douglas House: <http://blog.aia.org/mt-static/plugins/Ajaxify/tinymce/jscripts/tiny_mce/plugins/imagemanager/images/favorite_architecture_images/douglas_house_500_x_600.jpg>
Right, Falling Water: <http://www.galen-frysinger.ws/us/fallingwater62.jpg>

Description: On the left is famed modernist architect Richard Meier's Douglas House which was constructed in 1973 on a forested plot in Harbor Springs, MI. Contrast the Douglas House's relationship to its natural surroundings with that of Falling Water (1939), a home designed by Frank Lloyd Wright, an architect that many consider to be that father of ecological design.

Perhaps the most significant component of this new Green Building paradigm has been the realization that buildings should not only minimize their energy consumption and materials usage but that they should also perform ecological services in their local environment (Commission for Environmental Cooperation, 2008). The concept of ecological services was initially developed by ecosystem ecologists and it is used to describe those products and services which are provided by the regular functioning of natural ecosystems and have economic value to human society (Osborne, 2000). Some examples of ecosystem services include: the transformation of carbon dioxide into oxygen by photosynthesizing plants and the purification of water by natural wetland habitats (Ibid.). Drawing upon the example of these natural systems architects are now conceiving of buildings whose systems perform a similar suite of functions. One excellent example has been the increased use of what are called green roofs in modern sustainable designs. A green roof replaces traditional static roofing materials with a dynamic plant community capable of storing and purifying rainwater, moderating temperature extremes, and providing a therapeutic natural recreational environment (Images 3 & 4).

Image 3: Green Roof Cross Section



<http://www.delston.co.uk/images/Makeup.gif>

<u>Description:</u> The image shows a cross section of the typical construction design of green roof. The specific plant community composition is tailored to the environmental conditions of the environment in which the building is located.

Image 4: Chicago City Hall Green Roof Example

<http://static.howstuffworks.com/gif/green-rooftop-1.jpg>

<u>Description</u>*:* This photograph was taken of the rooftop of the Chicago City Hall which was installed as part of a recent city wide initiative for improved sustainability and energy efficiency. Note the contrast between the lush green vegetation of the rooftop as compared to the harsh grey tones of the surrounding sky scrapers in this dense urban environment.

Other prominent features of the new sustainable design ethos include: [1] combined use of high efficiency materials/design elements and renewable energy technologies to drastically reduce the energy required for heating, cooling, and lighting; [2] use of locally sourced and recycled materials; and [3] the use of active monitoring and control systems to minimize energy and resource consumption in day to day use.

The writings and professional practice of visionary architect and designer William McDonough have been vital in shaping the theory behind this new Green Building paradigm. In his recently co-authored book Cradle to Cradle, McDonough thoughtfully articulates a design philosophy which eliminates the very concept of waste (McDonough and Braungart, 2002). According to McDonough, our current economic system is predicated upon a terminal life cycle in which buildings, products, materials, etc. all move linearly from cradle to grave (Ibid.). Instead, he argues, these elements should all be designed to maximize recycle-ability without diminishing their quality or functionality. So far as buildings are concerned, this implies processes of adaptive re-use and the incorporation of design features previously mentioned in association with the LEED certification system (Ibid.). In this way, he maintains that we can transform the dynamics of our consumption and production into an endless cyclical process in which materials and resources are seamlessly transferred from “cradle to cradle.” (Ibid.)

Sustainability and the Campus Environment

The campus environment is unique amongst modern social institutions for its geographic unification of a diverse set of productive, intellectual, and cultural elements. University campuses around the world are a confluence of youthful exuberance, sage intellectual experience, and structured productivity (Creighton, 1998). Many college campuses have frequently and aptly been described as self contained cities (Creighton, 1998; DeCarolis, 2000). And indeed, the institutional structures which are in place to manage their operation closely mirror, albeit on miniaturized scale, the systems in place to manage many major metropolitan areas. It is of critical importance therefore to recognize the potential for university campuses to function as a proving ground for progressive structural policies designed for implementation on city and even nation wide levels (Creighton, 1998). This is especially true for initiatives whose perceived cost or complexity would make them undesirable for any rational electorate.

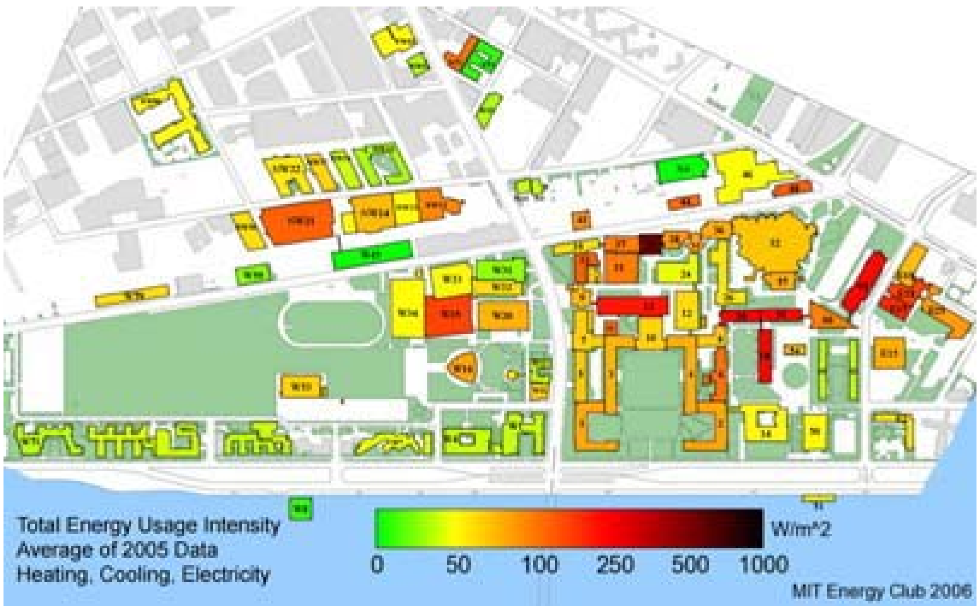
In the context of energy efficiency and sustainability the university setting would seem to be the optimum venue for the both the development and implementation of new technical and policy solutions (Creighton, 1998; DeCarolis, 2000). As a repository of knowledge and practical expertise they possess the basic engineering know-how required. With highly motivated student bodies that are desperate to conduct independent scholarly research, there is a vast pool of essentially free labor from which to draw upon for the implementation of potential projects. And finally, with their centralized structures, all that is needed to get a project off of the ground is the commitment of a few key administrative figures.

Currently, Bucknell University is working to put this idea into practice. As this thesis goes to press Bucknell is going into the final stages of a comprehensive sustainability assessment which has employed teams of students, faculty, and staff to evaluate and document baseline measures of environmental performance in a variety of categories. From energy and the built environment to water quality and the disposal of solid and hazardous wastes, the assessment program has been designed to inform the future action agenda of a forthcoming campus greening council which has been given a mandate to reduce the ecological footprint of the university's campus. The initiation of this process at Bucknell has come in response to a number of highly publicized campus greening initiatives which have taken place at universities across the country.

Mapping Bucknell's Energy Profile

In my role as a member of the "Energy Team" within Bucknell's campus environmental assessment I conducted a significant amount of research into campus sustainability initiatives which have taken place at other schools around the country. In this process I stumbled upon an article on the Massachusetts Institute of Technology [MIT] website which described a recent project devised by few student members of their campus' Energy Club (MIT News Office, 2007). These MIT students had developed software which converted campus utilities data for heating, cooling, and electricity into a color coded map of energy usage intensity in Watts /m^2 (Figure 3).

Figure 3: MIT Campus Energy Intensity Map



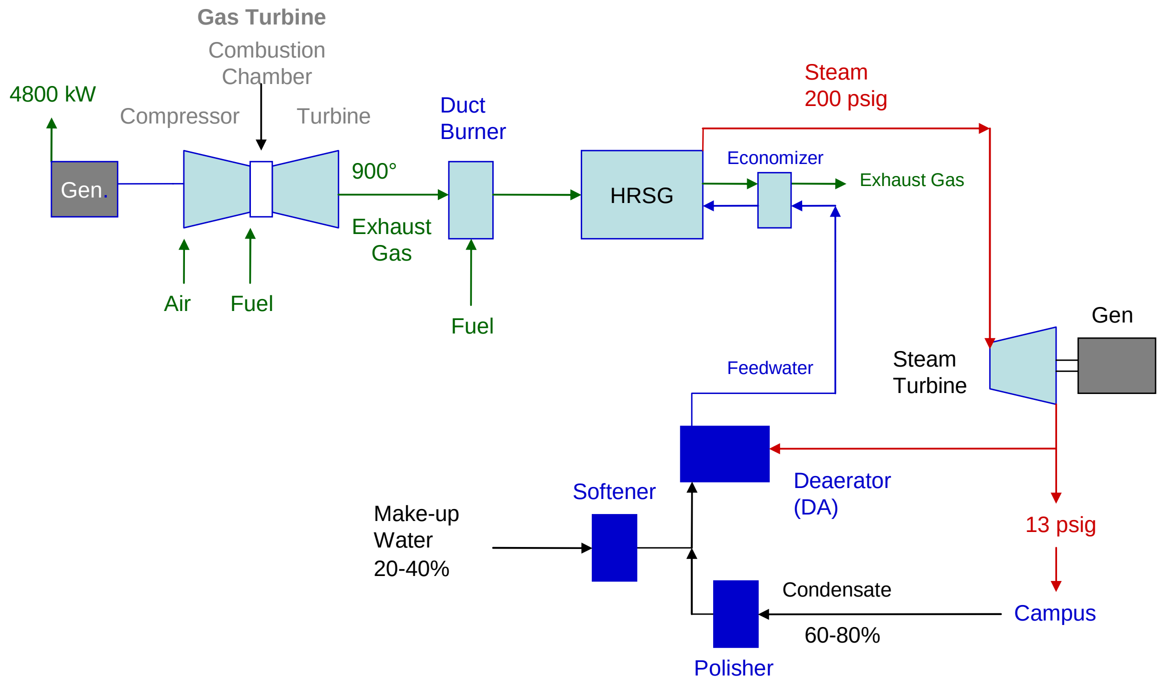
After perusing the map for a short while I began to get frustrated by the lack of information about the specific building usage patterns or construction details. Without this information, it was extremely difficult for an outsider like me, who is not familiar with the MIT campus, to ascertain why any particular building consumed so much or so little energy.

For the modeling component of this thesis project I knew that I was going to need access to Bucknell's campus utilities data. Consequently, I felt that this project would be the perfect opportunity to develop a similar energy intensity map for Bucknell. Only I wanted to make a map that could be hosted on the university Environmental Center's website and that would provide enough information so as to be intelligible even to those individuals who are not part of the Bucknell community. To do this, I decided to develop a simple flash-based user interface which would combine the visual information displayed on the map with written descriptions containing each building's construction date, construction materials, and the composition of its dominant energy loads.

After deciding to make this map I sat down and had a conversation with Jim Knight, Assistant Director of Utilities and Co-generation, about obtaining the necessary data [building square footages and building-specific electricity, heating/cooling, and fuel consumption]. As Jim began to describe the campus' energy system however, it became clear to me that it was going to be difficult to make a map that was identical to the one produced by the MIT students.

The difficulties arise from the fact that Bucknell has historically generated the majority of the energy used for the campus' heating, cooling, and electrical needs. Prior to 1998, there was a coal fired power plant with 5 megawatt electrical production capacity. In 1998, the University made the decision to replace this antiquated system with a high efficiency co-generation plant. Co-generation refers to a process which derives two forms of energy from a single fuel source (Knight, 2008). Bucknell's cogeneration plant has what is known as a combined cycle design, meaning that it not only produces electricity from the initial combustion of natural gas in the turbine engine, but it also produces electricity from the steam that is produced as a byproduct of this initial combustion process (Figure 4; Knight, 2008).

Figure 4: Cogeneration Power Schematic



The new co-generation plant has several significant advantages over its coal-fired predecessor. First and foremost is its improved efficiency. Under optimal conditions Bucknell's co-generation facility is capable of converting up to 75% of the energy contained in its fuel source into electricity and usable thermal energy. Yet another significant benefit of co-generation technology is the fact that it produces significantly lower levels of noxious atmospheric emissions than alternative forms of energy production. With the construction of the new plant in 1998 came an immediate 50% decrease in the campus' carbon emissions. Also, the production of sulfur dioxide, nitrogen dioxide, and particulates decreased between 75% and 99% from their previous levels.

At peak operating capacity Bucknell's 6 megawatt co-generation facility is capable of accommodating about 95% of the campus' electricity demand [the other five percent is obtained from Citizen's Electricity Company with the associated carbon emissions being offset by the purchase of nationally certified wind energy credits] (Ibid.). The plant has a peak steam production capacity of 140,000 pounds per hour [pph] with 50% redundancy [two 70,000 pph boilers operating with one 70,000 pph backup boiler] (Ibid.). This system was designed with this level of redundancy because the majority of the campus' buildings' only source of heat is the steam which is piped in from the central plant.

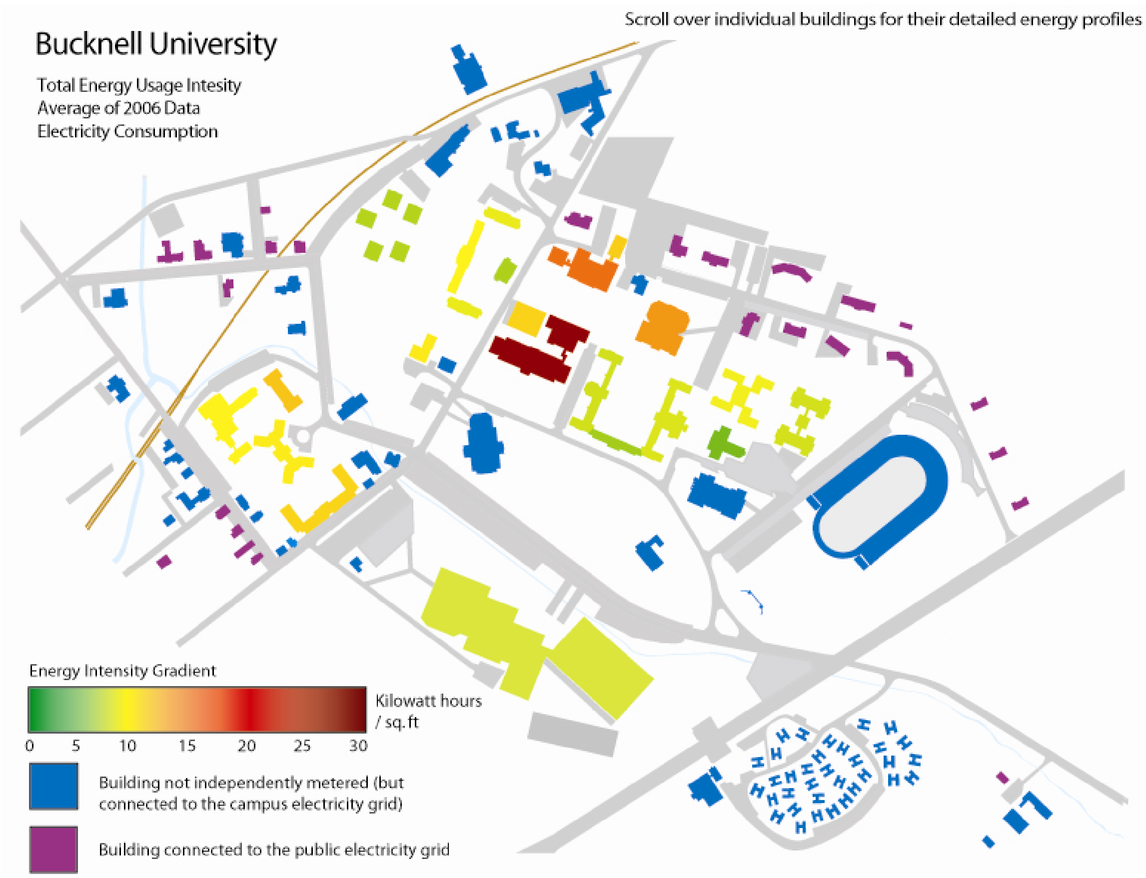
Owing to the fact that Bucknell's energy needs have always been supplied by a central independent source, so long as energy costs remained relatively low, the University had little incentive to install expensive metering equipment on individual buildings. The rationale of University Officials was this: if total energy consumption falls within a certain acceptable range it doesn't really matter how that energy is distributed among individual campus buildings. Unfortunately however, this attitude has resulted in a situation where very little is actually known about the composition of energy use on this campus. And, to be sure, while the major consumers like Dana Engineering or Rooke Chemistry Building can easily be identified, the limited building-specific metering capacity for electricity, chilled water, and especially steam, makes it virtually impossible to quantify their consumption.

Jim Knight indicated that while several of the more recently constructed buildings on campus had been fitted with appropriate utilities meters the vast majority of the older buildings on campus were still without them. He bemoaned the lack of funding in the Utilities department budget for a fully automated institution wide monitoring network like that which exists on the MIT campus.

Taking into consideration all of these factors, the final energy usage intensity map which I was able to create for Bucknell's campus only features campus electricity consumption for the 2006 calendar year. The map uses a color gradient to indicate electricity consumption intensity [Kwh/ ft^2] for all buildings connected to the campus grid and outfitted with the necessary monitoring equipment. For easy identification, buildings that are connected to the campus electricity grid but do not have monitoring capacity are colored blue. Similarly, the buildings that are not connected to the campus grid are colored purple. Unlike MIT's map, it was impossible to incorporate heating and cooling energy usage because the specific heating and cooling energy intensities of our campus buildings are simply unknown and will continue to be so until the University invests in adequate monitoring equipment.

Campus Energy Intensity Analysis

Figure 5: Bucknell University Energy Intensity Map



There are a total of 122 facilities with independent utilities systems on campus. Of these, 25 (20.5 %) are not connected to the campus electrical grid and receive their power from the local utility company (Figure 5). An additional 71 facilities (58.2 %) are connected to the campus electrical grid but are not equipped with independent metering equipment (Figure 5). This leaves 26 remaining facilities (21.3 %) which are connected to the campus electrical grid and possess independent monitoring equipment (Figure 5). Using a list of building square footage data obtained from Ray Kaycon in Bucknell's internal planning department I calculated the electrical usage intensity for these 26 facilities on a Kwh/ ft^2 basis. I then converted the data range into a color spectrum which was used to color code each building according to its specific electricity consumption intensity.

Among the buildings represented in this data set are classrooms, offices, laboratory facilities, an athletic center, administrative buildings, and residential dormitories. The following list describes some significant trends that were observed in the data (all energy intensity figures listed from greatest to least and are quoted in Kwh/ ft^2):

- The three monitored facilities which were found to consume the most electricity per square foot were the Science Complex [29.5], Dana Engineering [21.4], and Bertrand Library [16.8].
- The three monitored facilities which were found to consume the least electricity per square foot were the Carnegie Building [8.1], Freas Hall [6.2], and the Weis Music Center [2.4].
- Through consultation with Jim Knight, the three unmonitored facilities suspected to have the largest electricity consumption intensity were the Langone Center, the Weis Performing Arts Center, and Seventh Street Café.
- Similarly, the three unmonitored facilities suspected to have the lowest electricity consumption intensity were Kristy Mathewson-Memorial Stadium, Rooke Chapel, and the Stadler Poetry Center.

There are a number of different factors which appear to be related to the energy usage intensity. These include the following:

- *Load Composition*: The number and type of electrical loads contained in a particular campus facility has a significant bearing on the intensity of its energy consumption. Both Rooke Chemistry and the Biology Building in the Olin Science Center contain numerous pieces of energy hungry laboratory equipment; a few of which, including the large nuclear magnetic resonance spectrometers, on their own can consume as much electricity as an entire small building. Consequently, there proved to be a significant positive trend between a building's laboratory space/amount of laboratory equipment and its electricity usage intensity.

- *Usage Schedule*: Just as important as the size of the individual loads is the frequency with which they are used. A lower quality load, with smaller power requirements, can consume just as much energy as a larger load if it is being used more often. This fact is evident in both the consumption intensities of Dana Engineering and Bertrand Library as they are two of the most heavily utilized buildings on campus. While Bertrand is open daily from 8 am to 2 am, Dana is available 24 hours a day; a fact which clearly contributes to its status as Bucknell's second largest known energy consumer.
- *HVAC System Configuration*: The majority of the heating and cooling requirements for Bucknell's campus facilities are satisfied by low pressure steam and chilled water that is pumped in from the physical plant on the Southeast corner of campus. Some facilities however posses composite systems which rely partly upon electrical components to satisfy their heating, ventilation, and cooling needs. Dana Engineering is one such facility. In addition to a heat exchange system for processing steam and chilled water, Dana is outfitted with a complex electrical heat pump system which greatly contributes to its energy consumption intensity.
- *HVAC Load Size*: This term describes the volumetric area which is being heated and/or cooled by a facility's HVAC system. Larger individual thermal

zones necessitate more powerful intake and return fans which demand greater quantities of energy to power their electric motors. Bertrand library, with its seven large unpartitioned floors necessitates an oversized HVAC system to deliver responsive thermal control.

- *Construction Date*: Energy intensity appears to be positively correlated to building age as older buildings were found to have higher energy intensities than more recently constructed buildings with similar energy loads and usage schedules. For instance, the ratio of classroom area, offices, and laboratories in Breakiron Engineering is roughly the same as that of Dana Engineering. However, Breakiron, which opened in 2004, has significantly lower electricity usage intensity than Dana [1940] because it was built using modern construction techniques and high efficiency materials.

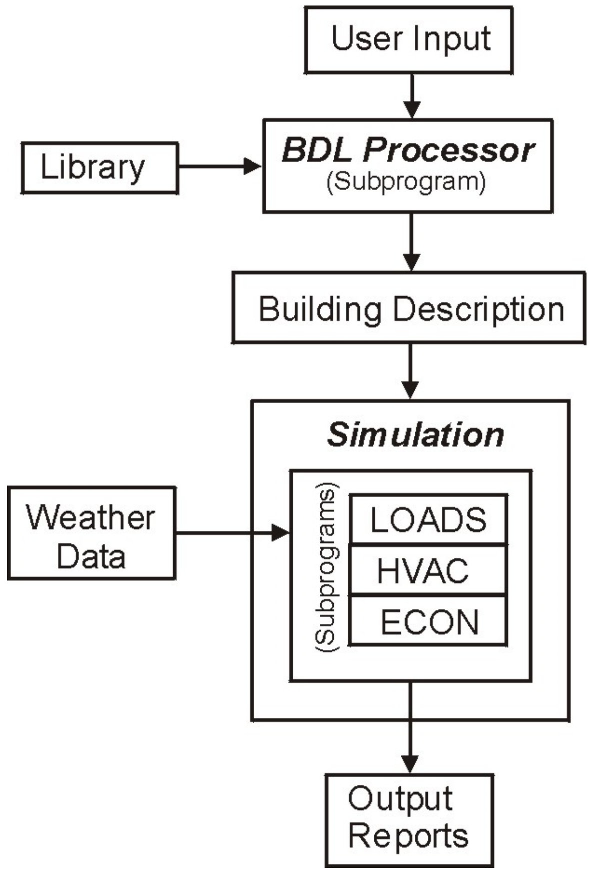
VisualDOE and the Computational Simulation of Building Energy Consumption

The second phase of this thesis project involved attempts to simulate the energy usage of several campus buildings using the energy analysis software VisualDOE. VisualDOE is a propriety version of DOE-2, a software package initially developed by a consortium of software engineers and building energy specialists working at the Lawrence Berkeley National Laboratory (Department of Energy, 2007). The DOE-2 program on which VisualDOE is based is described by the Department of Energy as "an up-to-date, unbiased computer program that predicts the hourly energy use and energy cost of a building given hourly weather information and a description of the building and its HVAC equipment and utility rate structure." (Department of Energy, 2007) VisualDOE was therefore selected for this project because its well-developed graphical interface lends itself to more effective use by non-experts than DOE-2's code-based format (AEC, 2004).

The advantages of this energy analysis tool in the context of Bucknell are twofold. Firstly, because Bucknell currently does not have metering equipment installed on every one of its campus buildings the models that were generated can provide a rough baseline for per-square-foot energy consumption on the basis building design, age, and usage type (Reddy, 2007; Smith, 2007; Steadman, 1975; Stein, 1977). By comparing model outputs to records of campus wide energy consumption, calibrated estimates can be made for the individual energy consumption profiles of buildings without metering equipment (Reddy, 2007).

The second major advantage of the software package is the ability to quickly and accurately compare the energy performance and cost effectiveness of current design elements to various high efficiency alternatives (AEC, 2004). For instance, when modeling an individual building a base profile is created that is accurate to the current design. In addition to this however, alternate profiles, building off of this base profile, can be developed to examine the potential benefits of energy efficient design modification or changes in the load management schedules (Figure 6; Ibid.).

Figure 6: General VisualDOE Workflow Diagram



The differences in energy consumption associated with these alternative profiles are then computed into utilities costs using user determined values for fuel and utilities prices (Ibid.).

The initial selection of buildings from potential candidates for evaluation in this project was accomplished via consultation with Bucknell's associate director for utilities, Jim Knight and associate professor of mechanical engineering and a computational thermodynamics specialist, Dr. Peter Stryker. The selection criteria which were agreed upon through our discussions were as follows:

- The buildings to be selected must be representative of the different usage types present on campus. These include: educational/research spaces, office/administrative spaces, mixed use areas, and residential spaces.
- Buildings must also represent a cross section of ages. This is meant to reflect the potential efficiency differences associate with advances in materials and construction techniques.
- A single building for which accurate utilities data is available must be modeled. Comparisons between real data for this building and the model projections will allow us to calibrate model input parameters and accurately interpret output projections (Reddy, 2007).
- The nature of structural design elements, utilities systems, and construction materials for selected buildings must all be amenable to the capabilities of the software. This requirement is meant to eliminate the introduction of unnecessary error associated with inaccurate depiction of the building's base profile.
- Campus buildings suspected of being the largest energy users or those that are currently slated for near future term efficiency renovations should be given priority in the selection process.

On the basis of these criteria, the buildings that were selected for further investigation in this study were Breakiron Engineering, Kress Hall, Smith Hall, Ellen Bertrand Library, the science center [Rooke Chemistry and the Biology Building], and Taylor Hall.

The Modeling Process

The criteria that were used to select buildings as candidates for study in this project occurred prior to the purchase of the VisualDOE software. As neither I nor anyone with whom I had consulted in the development of this project had any experience with VisualDOE or any other DOE-based energy simulation software the time requirements for the modeling of even a single building were essentially unknown. Also, there were several unforeseen obstacles involved with the modeling process that needed to be resolved before energy simulations could be conducted. While a brief overview of my experience will be given in the following discussion, for brevity's sake, the excruciating details of working with such a powerful computational tool as VisualDOE have been reserved for a comprehensive procedural write-up that has been included in an accompanying document. This procedure contains detailed descriptions of the informational requirements for both the building of models within VisualDOE and the design of performance simulations. Additionally, it includes some practical advice aimed at minimizing wasted effort and maximizing the accuracy of models that are being constructed within VisualDOE.

When I had initially conceived of this project my main goal was to conduct a study that would be as useful as possible to the Bucknell community. And, I believe that this goal is reflected in the previous discussion of the rationale behind the building selection criteria. In retrospect however, the decision to model six buildings could be considered overly ambitious given the project's short timetable and my inexperience with performing energy analyses using VisualDOE.

The modeling process within VisualDOE is iterative and requires the successful completion of several progressive phases before simulations are able to be run. The first phase involves the creation of what are known as blocks. Within the model, blocks represent unique floor plans inside a building. A multi-floored building can be made up of a single block [repeated several times] or several different blocks stacked up over one another. There are several different ways to create these blocks: one can select from a template of pre designed blocks, use a simplified drafting application within VisualDOE to draw them from scratch, or import a drawing file that had been creating using a third party computer aided drafting [CAD] program. For existing buildings, like the ones that I had chosen to model, CAD drawings provide the most accurate description of a building's layout and thus, it is highly recommended that they be used if available.

Fortuitously, Bucknell's internal planning department had CAD drawings on file for all six of the buildings that I had chosen to model. These had been created either during the buildings' initial design and construction or as part of a recent renovation. These CAD drawings had been generated in AutoCAD[2] and depict the building precisely as was constructed, showing every room in minute detail. However, VisualDOE requires that the floor plans depict only what are known as "closed contiguous thermal zones". Typically, a closed contiguous thermal zone is composed of several rooms that are regulated by a single thermal control [i.e. a thermostat]. In order to adapt the existing CAD files into viable block designs for each block I sat down with a printout of the corresponding HVAC schematic and drew-over the existing floor plan lines to depict the closed contiguous thermal zones. As an additional requirement, each of these thermal zones must be drawn as contiguous closed polygons within the drafting program. Any overlapping surfaces or

[2] AutoCAD is a proprietary computer aided drafting software that is licensed and developed by the Autodesk Corporation.

"holes" in block design resulted in an error message when importing the CAD file into visual DOE. As a result of these and other difficulties, this first phase of the modeling process proved enormously time intensive. Indeed, just learning how to work with AutoCAD, itself an exceptionally complicated drafting tool, involved a steep learning curve.

After successfully completing the block designs for all six buildings I was able to move onto the next phase in the modeling process; specifying the buildings' facades. This phase involves determining the precise materials and insulation ratings associated with a building's external walls, roof coverings, windows and doors. These characteristics were determined via a combination of site visits and construction data obtained from Bucknell's planning office. Once again however, this phase required significant amount of detailed information and manual editing. For instance, the position and characteristics of each individual window had to be individually determined through a custom editing process that involved selecting window type, size, and glazing.

Up until this point my strategy had been to work on all six buildings simultaneously. However, the various difficulties that I encountered during the first two phases of modeling had consumed a significant amount of my available research time and suggested that the remaining modeling phases would be accompanied by similar unforeseen problems. Consequently, I decided that rather than working on all six buildings at once I should instead concentrate my efforts on the completion of as many individual buildings as possible. As a result of this change in approach, the first building that I chose to focus on was Taylor Hall. I selected Taylor Hall first because of all the buildings that I was working with it possessed several features which made it amenable to the modeling process in VisualDOE:

- Small size
- Simple floor plans
- A Simple HVAC system
- Non commercial loads
- Standard load schedules

The decision to abandon work on the other five models was not an easy one; however, it was made per the recommendation of my thesis advisor and several other engineering professors with whom I had been consulting because of the enormous amount of work associated with the modeling and simulation of just one large facility.

After specifying the building facades for Taylor Hall, the next modeling phase involved determining the building's load characteristics. This portion of the modeling process requires that you specify what are known as "standard" and "process loads". A standard load refers to fuel or electrical loads which are metered but do not necessarily contribute to zone heating/cooling loads. Alternatively, a process load contributes to zone heating/cooling loads but does not go to meters (Knight, 2008). As an instructive example, the electricity consumed by a classroom projector constitutes a standard load and any ambient heat that may be given off by the projector's lamp will contribute to the room's process loads [this is because it affects the heating/cooling loads of the room] (Zhang, 2007).

In order to specify the standard and process loads for Taylor Hall I conducted several site visits. Using print-outs of the block designs that I had created in AutoCAD I documented the number and characteristics of every electrical appliance [lights, computers, printers, copy machines, etc.] contained in each of the building's rooms [the determination of some standard loads and all process loads was made via the use of a

Department of Energy report entitled Energy-Use of Miscellaneous Plug Load Equipment] (Robertson, 2004). Then, using the building's hours of operation and class schedules as guides I made approximations of the usage schedules associated with the various loads. All of this information was incorporated into a custom designed load schedule for each room of Taylor Hall within VisualDOE.

After scheduling the loads, I was finally able to proceed to the fourth and final phase of the modeling process: editing the central plant and HVAC system components. For this phase, I sat down with Jim Knight in facilities and went over the precise nature of Bucknell's central physical plant. From him, I obtained the utility rates that the University pays for the surplus electricity it obtains from the local utility as well as prices for the diesel oil and natural gas that are used for power generation. I then had him proof schematics that I designed in VisualDOE describing both the central utility plant and Taylor Hall's independent dual-duct HVAC system.

The Simulation Process

Similar to my experience with the creation of the building models, my effort to develop a viable simulation for Taylor Hall was beset by difficulty and required a painstaking process of trial and error. Much of the difficulties encountered here had to do with the fact that VisualDOE often presents the user with a choice between several mutually exclusive operations or design features; however, the software does not always give the user immediate notification that an erroneous overlapping selection has been made. As a result, I eventually learned that it is essential to conduct periodic checks of what are known as the "model definitions." The code embodied in the model definitions fundamentally describes the model design making it impossible to even access the simulation menu if there are errors.

A viable model forms what is known as the “base case” and is intended to be an accurate representation of the buildings’ existing design and usage characteristics. In addition to the base case however, VisualDOE allows for the creation of alternative design cases which can incorporate a combination of different design features and usage regimes. This feature is intended to allow energy analysts to compare the performance of different construction features or the impact of various load management scenarios.

When designing the alternative cases for the Taylor Hall simulation I only considered design changes or load management scenarios that did not require extensive structural modifications to the building or costly changes to the HVAC system layout. In this way, my hope was to demonstrate the potential benefits of short term low cost measures that could be immediately applied to improve the energy efficiency of buildings across Bucknell’s campus. In addition to the base case therefore, I developed three alternative cases with the following basic characteristics:

Alternative 1:	20% reduction in lighting power density
	20% reduction in equipment power density
Alternative 2:	Alternative 1 modifications plus -
	Replacement of all single pane non-glazed exterior windows with double pane 3/12/3 mm high efficiency windows
Alternative 3:	Alternative 2 modifications plus -
	Decrease the heating activation temperature from 70º F to 67º F
	Increase the cooling activation temperature from 75º F to 78º F

Each progressive alternative was intended to build upon the efficiency savings of the previous iteration. The efficiency gains associated with these measures require minimal effort for implementation and, at most, only minor changes in the building's material construction or usage scheduling. For instance, achieving the 20% reductions in light and equipment power densities targeted in *Alternative 1* could easily be achieved, and likely exceeded, through the installation of light emitting diode [LED] light fixtures and the purchase of ENERGY STAR[3] rated office equipment and appliances. Similarly, the replacement of external windows proposed in *Alternative 2* does not require an enormous capital investment yet could potentially yield enormous dividends in terms of energy savings. Finally, *Alternative 3* involves small changes to the heating and cooling regimes of the building that would likely be imperceptible to any of its occupants.

Simulation Results Summary: Taylor Hall

The simulation results for Taylor Hall revealed Alternative 2 to be the most energy efficient of the three Alternative model cases. This result came as somewhat of a surprise because it was expected that the alterations in the heating and cooling activation temperatures, however minor they were, would result in a decrease in the energetic demands being placed on the HVAC system.

[3] ENERGY STAR is an innovative energy performance rating system for a wide variety of products and practices. It has been developed through cooperation between the U.S. Environmental Protection Agency and the U.S. Department of Energy and is designed to help businesses and consumers save money and protect the environment (Environmental Protection Agency, 2008).

The total combined annual energy cost [electricity and fuel] for each of the four cases is given below:

Base Case = $22,397

Alternative 1 = $13,116

Alternative 2 = $10,582

Alternative 3 = $12,893

The annual energy savings associated with the implementation of the different iterative building modifications were as follows.

Alternative 1: 20% reduction in lighting power density

20% reduction in equipment power density

= $9,281

Alternative 2: Alternative 1 modifications plus -

Replacement of all single pane non-glazed exterior windows with double pane 3/12/3 mm high efficiency windows

= $2,534

Alternative 3: Alternative 2 modifications plus -

Decrease the heating activation temperature from 70º F to 67º F

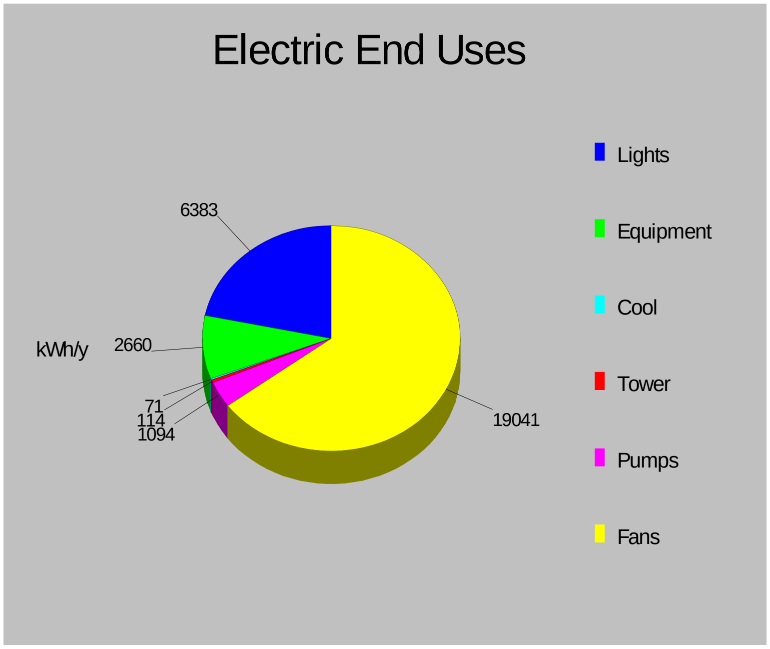
Increase the cooling activation temperature from 75º F to 78º F

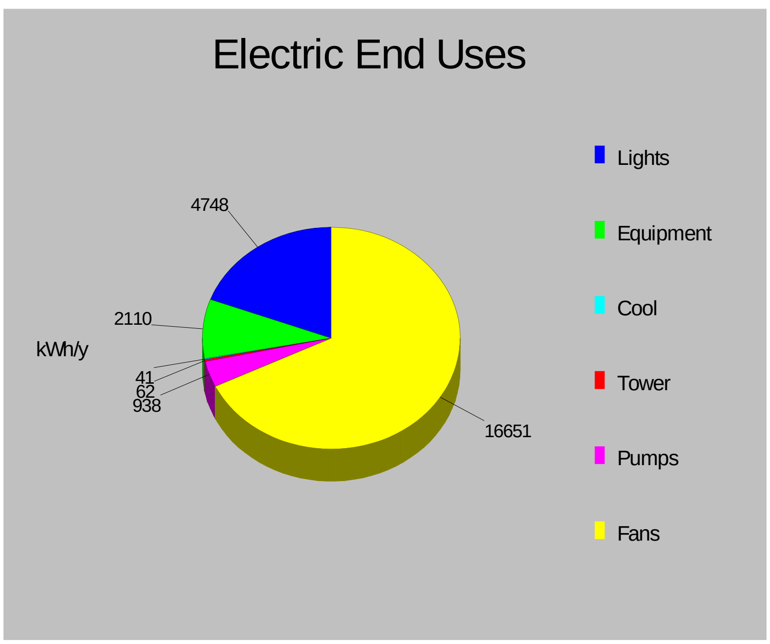
= - $2, 311

As these figures demonstrate the largest annual energy cost savings were associated with the 20% reduction in lighting and equipment power densities. Beyond this, the simulated replacement of Taylor Hall's single pane non-glazed exterior windows with double pane high efficiency alternatives yielded the second largest savings. Curiously, the adjustment of the heating and cooling activation temperatures resulted in increased combined annual energy costs. For a discussion of the causes of this unexpected result refer the detailed simulation results section for Taylor Hall.

Taylor Simulation: Detailed Graphical Analysis

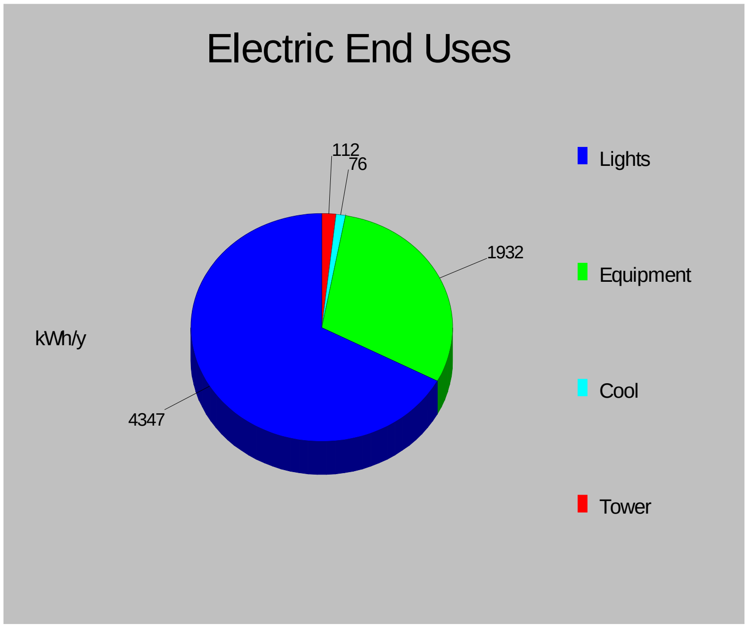
Electrical end usage breakdown for the Base Case and Alternative 1

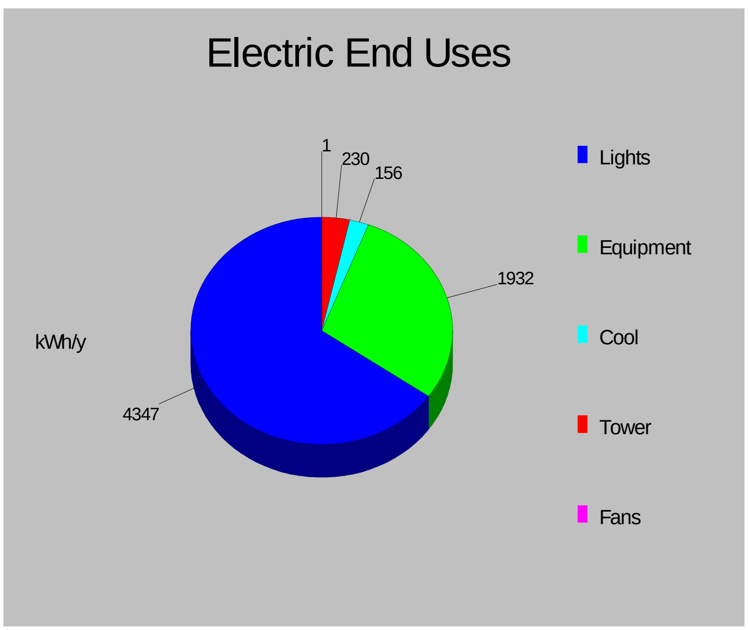




<u>Analysis:</u> In both the Base Case and the Alternative Case the largest component of the electricity demand in the Taylor Hall model is devoted to the powering of the motors for the intake and exhaust fans in the HVAC system. The composition of the electrical end usage breakdown changes little between the Base Case and Alternative Case 1. However, the magnitude of the electrical end uses for Alternative 1 is significantly lower than that for the base case. This corresponds to the 20% reductions in the lighting and equipment power densities between the two cases.

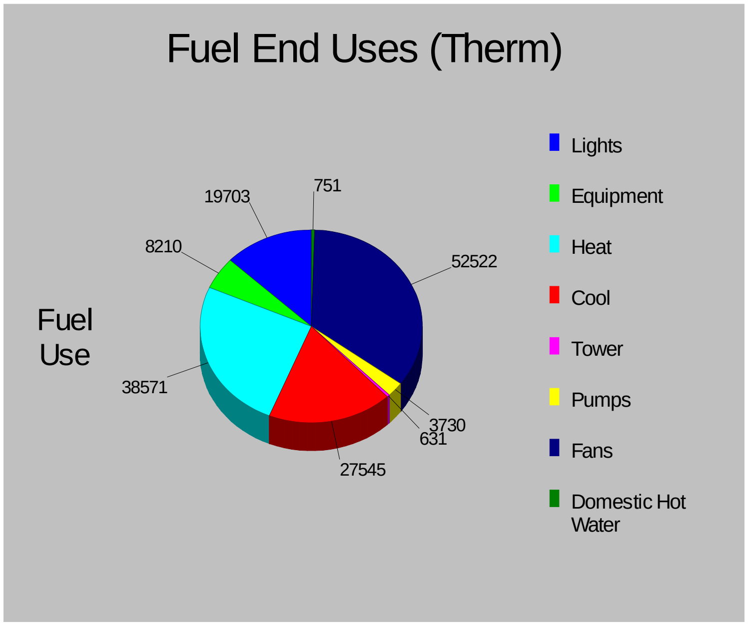
Electrical end usage breakdown for Alternative 2 and Alternative 3

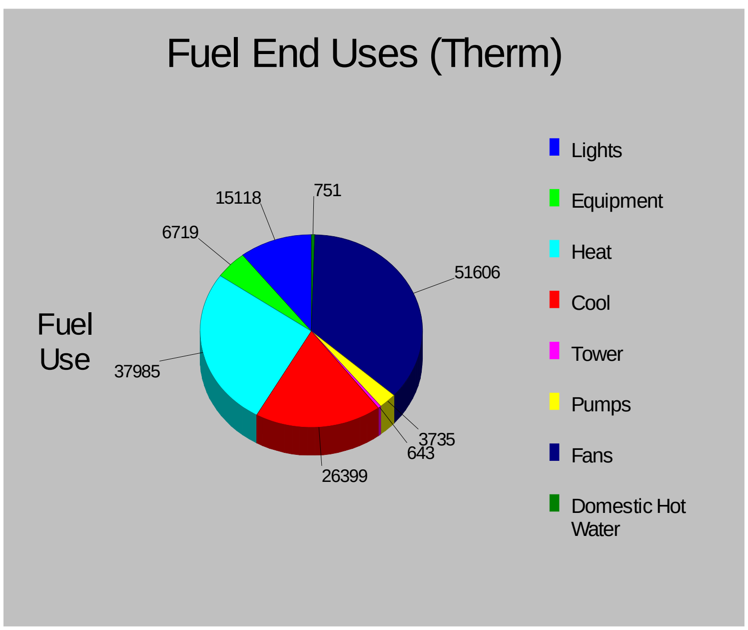




Analysis: There is a noticeable difference in the composition of the electrical end uses between the Base Case/Alternative 1 and Alternative 2/Alternative 3. This corresponds to the virtual elimination of need for intake and exhaust fans in the dual duct HVAC system as a consequence of the increased efficiency of the double paned windows that are present in the latter two model cases. With these two alternatives the single largest component of electrical energy consumption is devoted to lighting. Overall however, the differences between Alternative 2 and Alternative 3 are negligible, with the alteration in heating and cooling activation temperatures in Alternative 3 actually resulting in a slight increase in its simulated energy consumption.

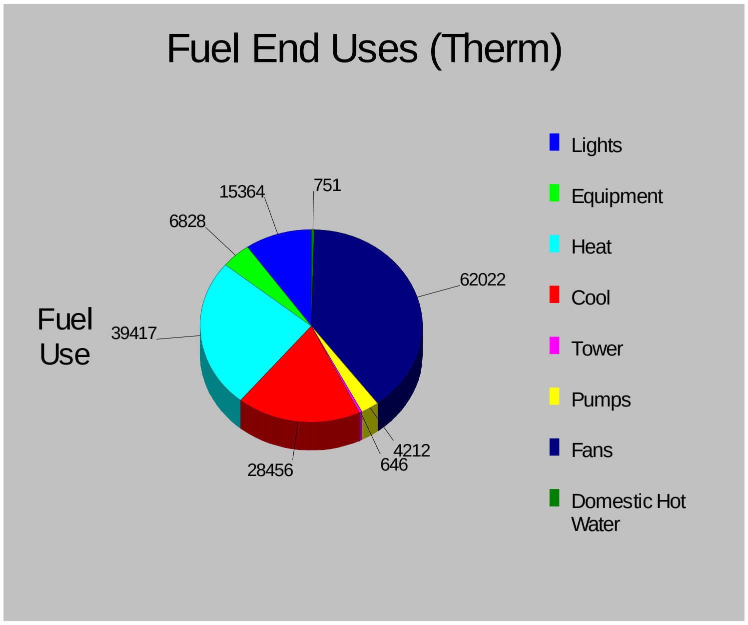
Fuel end uses in Therms for the Base Case and Alternative 1

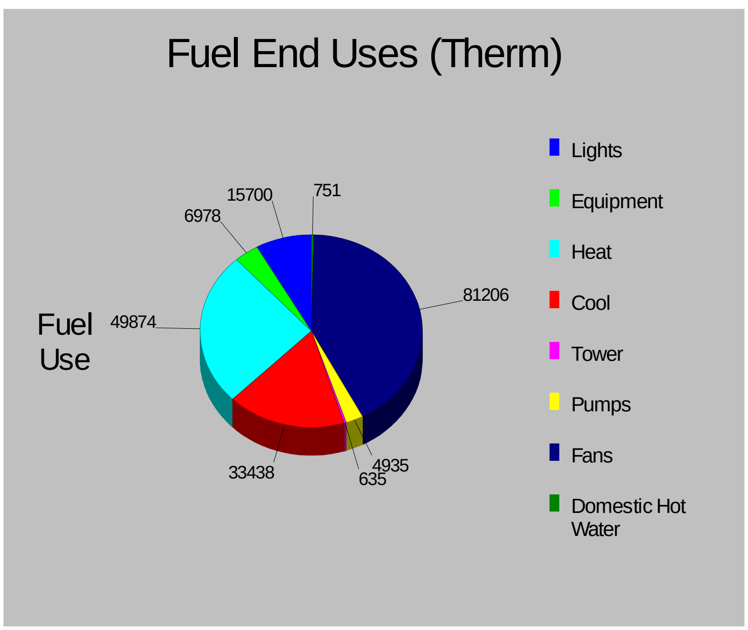




<u>Analysis:</u> The largest component of the end fuel consumption in the Base Case and Alternative 1 is devoted to generating the electricity to power the electric motors for the fans in the HVAC system. And indeed, this corroborates with the data regarding the end use electricity consumption for these two cases. The second and third most significant components of the end use fuel consumption for these two cases are associated with the buildings heating and cooling. Beyond these issues Alternative 1 boasts significantly less fuel consumption than the Base Case in the category examined in the simulation.

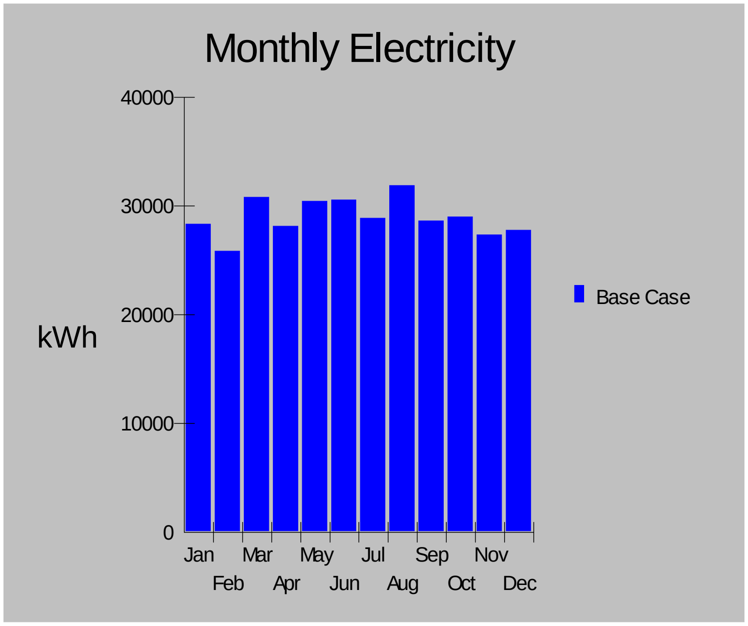
Fuel end uses in Therms for Alternative 2 and Alternative 3

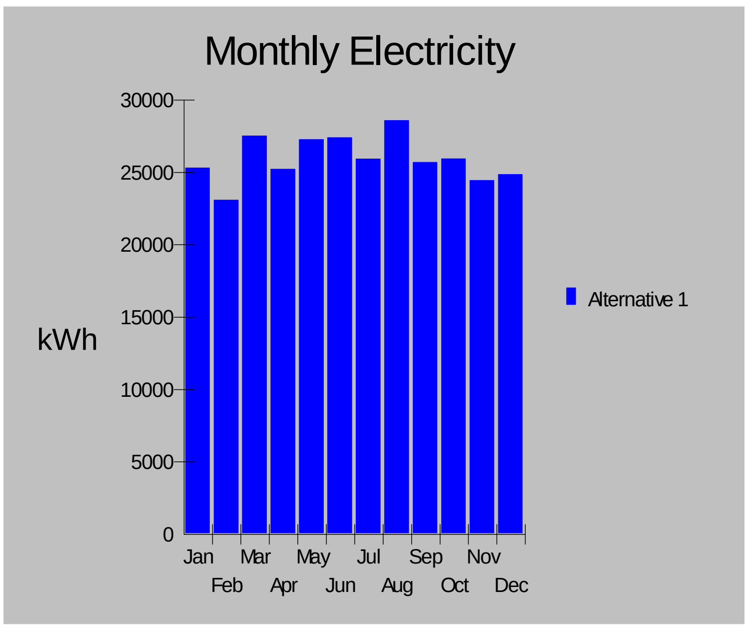




Analysis: The composition of the total end fuel consumption for Alternatives 2 and 3 is very similar to that for the Base Case and Alternative 1. The total volume of the fuel consumption for Alternatives 2 and 3 however is significantly lower than that for the Base Case and Alternative 1. Additionally, the end use fuel consumptions of the two cases presented above are virtually identical to one another save for the higher fuel consumption associated with powering the fans in Alternative 3. This correlates with the increased electricity requirements associated with fans in Alternative 3's HVAC system.

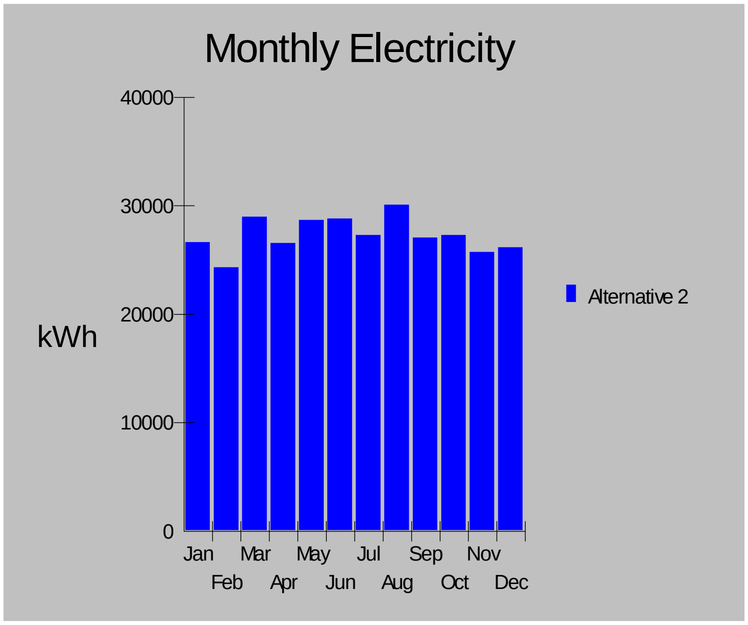
Monthly electricity demand for the Base Case and Alternative 1

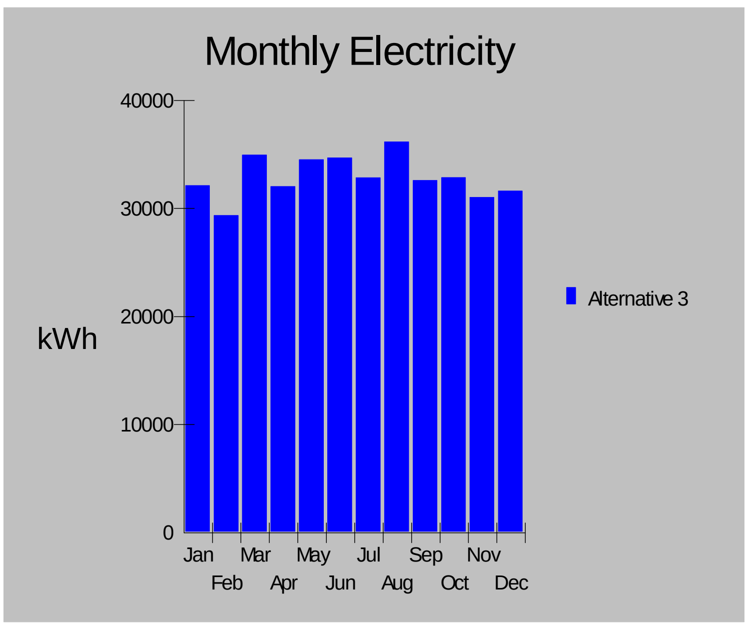




<u>Analysis</u>: The composition of the monthly electricity demand is roughly equivalent between the two model cases presented above. This should be expected because there were no significant changes in the usage schedules between the two cases (changes were only made in the usage intensity) and both models were subject to identical climactic conditions. Peak energy demand in both models occurred in August and this is likely corresponds to the demand of Taylor Hall air conditioning system during this period. Once again, it should be noted that the magnitude of the electricity demand for Alternative 1 is significantly lower than that of the Base Case.

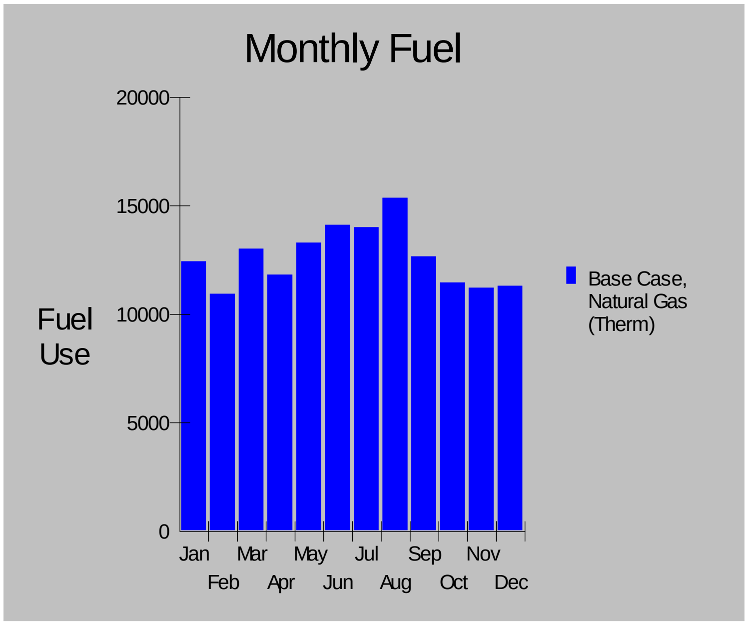
Monthly electricity demand for Alternatives 2 and Alternative 3

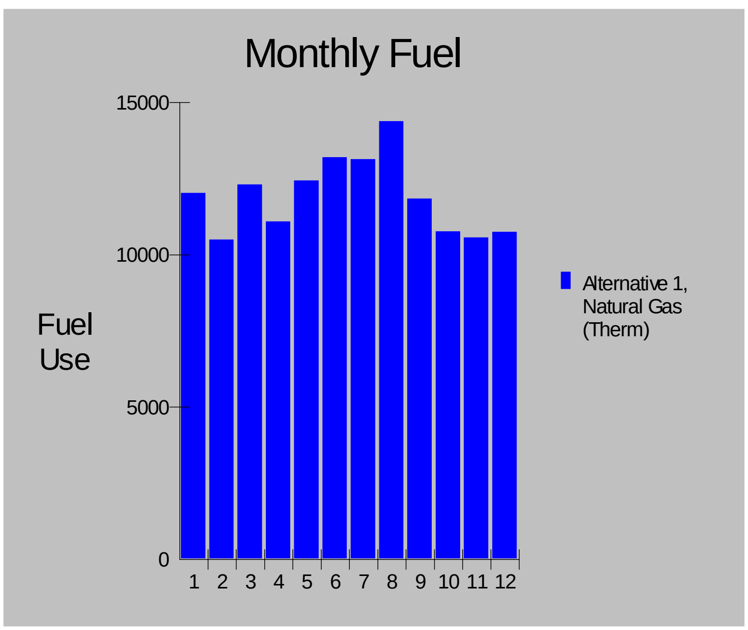




Analysis: The monthly electricity demand profiles for Alternatives 2 and 3 resemble both each other and the other model cases in their composition. Alternative 2 however exhibited significantly lower monthly energy demand than Alternative 3. This corresponds to the general trends that have been observed in the previous figures describing the additional electricity demand of the HVAC system in Alternative 3.

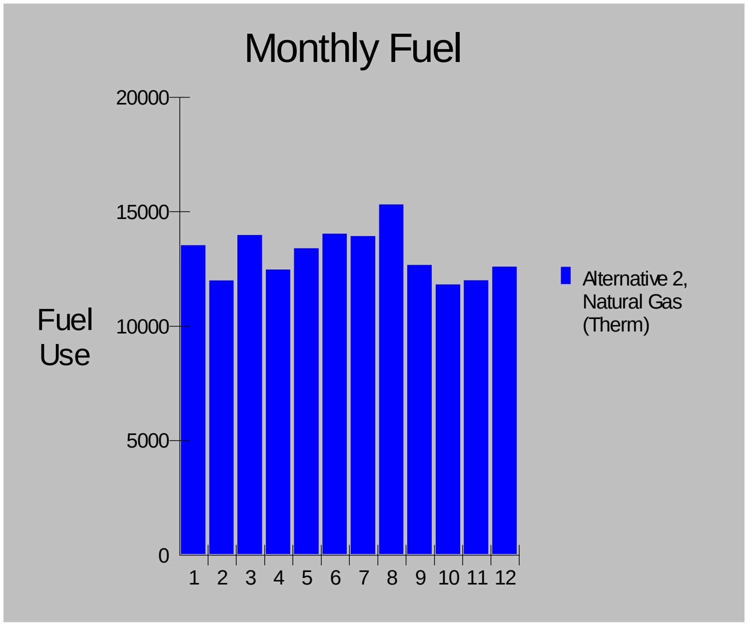
Monthly fuel costs for the Base Case and Alternative 1

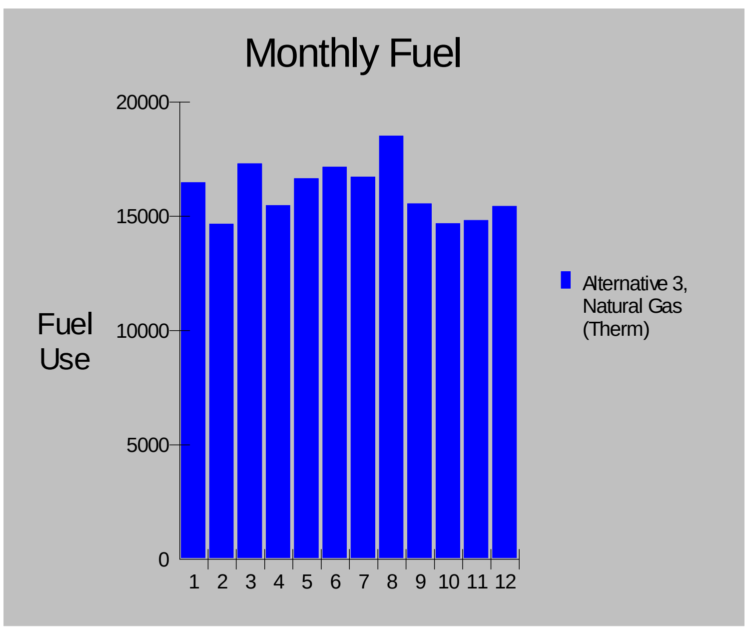




Analysis: The month associated with peak natural gas demand for both the Base Case and Alternative 1 was August. This corresponds with August being the month of peak electricity demand and the fact that natural gas is the principle fuel source for the central cogeneration plant. The overall composition of monthly fuel demand for the two cases is nearly identical, however the magnitude of the fuel demand exhibited by Alternative 1 is significantly lower.

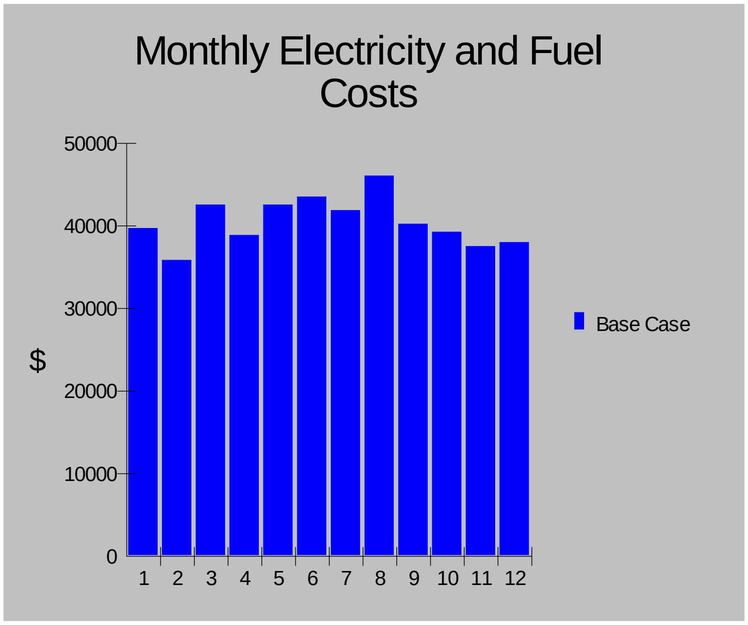
Monthly fuel costs for Alternative 2 and Alternative 3

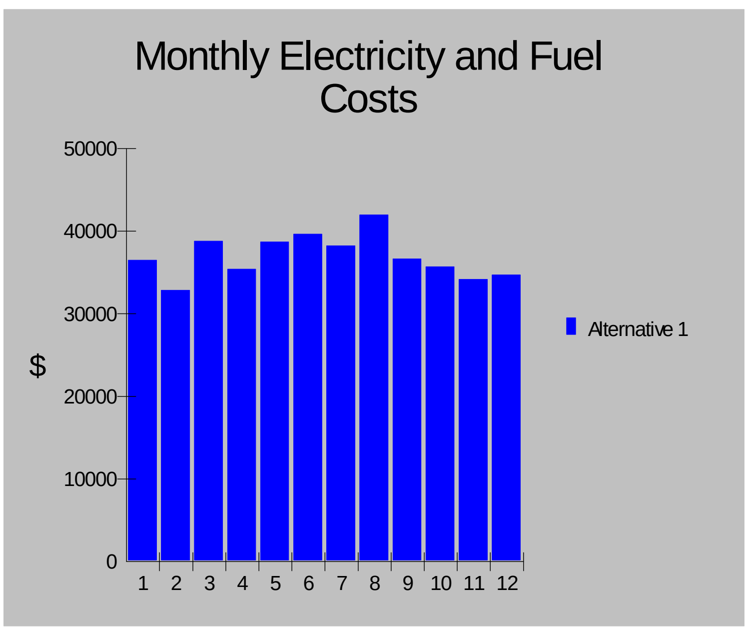




<ins>Analysis:</ins> Here, as with the monthly electricity demand breakdown, the composition of the monthly fuel consumption is highly conserved between all four model cases. And, corresponding to the trends observed in the electricity demand figures, Alternative 2 is experiencing the lowest fuel demand by virtue of the reduced need for electricity to power its duct fan motors.

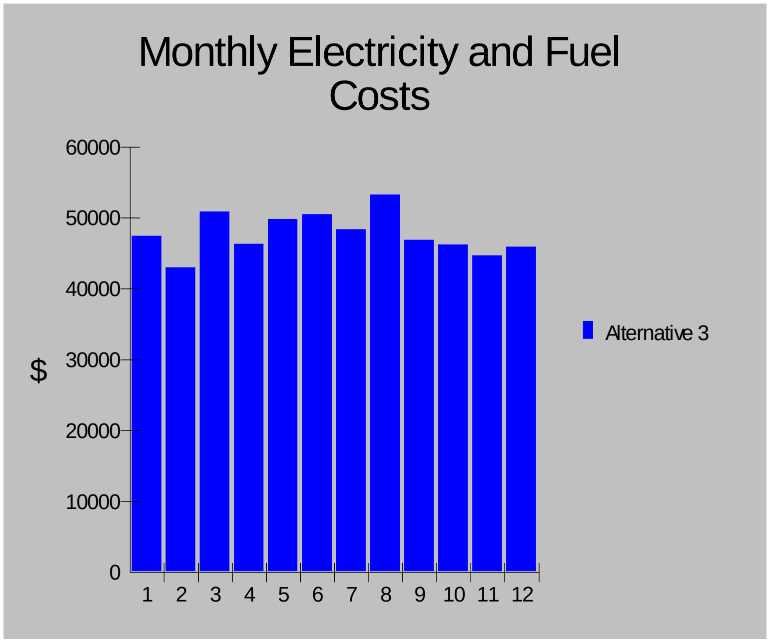
Monthly electricity and fuel costs for the Base Case and Alternative 1

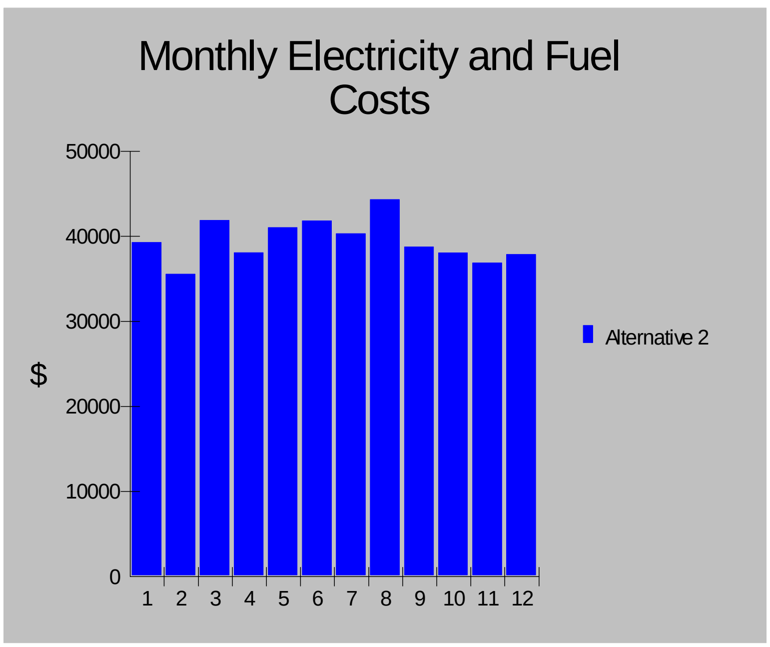




Analysis: The values presented in these graphs are projected averages over a 20 year period. The composition of the combined monthly energy costs over this period does not change between the four different model cases. The base case exhibits significantly high average monthly costs because of the previously discussed energy savings associated with the modifications included in Alternative 1.

Monthly electricity and fuel costs for Alternative 2 and Alternative 3





Analysis: The total combined energy costs for Alternatives 2 and 3 over this same 20 year evaluation period are roughly equivalent with Alternative 2 exhibiting slightly lower costs due to its slightly smaller energy consumption profile.

Potential Sources of Error

As I acknowledged in the introduction to the section on model design, I am neither an expert in commercial energy system design nor with the use of VisualDOE. Consequently, there could potentially be a number of significant factors that I may have overlooked or evaluated incorrectly during the modeling and simulation processes. However, I went to great lengths to ensure that all measurements, calculations, and approximations incorporated into the model were both as accurate and as reliable as possible. This process involved a great deal of oversight and error checking both by Jim Knight in facilities and Dr. Peter Stryker in the mechanical engineering department.

With that said, here are few issues with which I encountered some uncertainty and was forced to make educated approximations.

- The scheduling of variable use loads such as computer laboratories, building lighting, and other such building equipment which do not have regular usage schedules.
- The air exchange rates within the building. [These are largely a function of window opening and closing and the frequency of building entry and exit. These metrics are extremely difficult to calculate and thus I was forced to rely upon the estimates that were provided in association with the building usage classification]
- The precise nature of the building's exterior shading.
- The flow rate of the dual duct HVAC system.

VisualDOE Applications on Campus

Initially, only a single license for the VisualDOE software was purchased with funds that were generously provided by Dr. Peter Wilshusen and the BUEC. As I began to consult with professors in the civil engineering department about my work on this project, they expressed interest in purchasing the software for use in the classroom or as part of future senior design projects. Three weeks after returning from winter break, Dr. Peter Stryker arranged for me to give a presentation about my thesis work and the capabilities of VisualDOE for several interested students and professors.

As I walked them through the software's different features and discussed my experience with the modeling process it became clear that there were a number of ongoing projects that could benefit enormously from a software package like VisualDOE. Dr. Stryker discussed how he and a group of civil engineering students have been working with a local prefabricated home manufacturer to improve the efficiency of their designs. Civil engineering professor Stephen Buonopane and mechanical engineering professor Tom Rich both expressed interest in purchasing copies of the software for use in potential classroom laboratory exercises. And, finally, a mechanical engineering graduate student named Scott Parker mentioned that the software would inform his graduate thesis work involving the design of a new energy efficient dormitory on campus.

To date, it is my understanding that several individual licenses for VisualDOE have been purchased by the mechanical engineering department for use in their computer laboratories. The professors' decision to make this purchase was motivated in part by my agreement to prepare a comprehensive procedural document for working with VisualDOE, regardless of the outcome of my project.

Energy and Bucknell: Prospects for the Future

My experiences, first with the Solar Scholars program, and then later with my work on this thesis and with the campus sustainability assessment have given me cause to believe that Bucknell has a bright energy future. Each year a private research consortium called the Sustainable Endowments Institute publishes a report ranking the level of sustainability for a number of colleges across the nation (Sustainable Endowment Institute, 2008). In the 2008 College Sustainability Report Card Bucknell performed below average in six of the eight categories used for evaluation (Ibid.). And indeed, as a University, we actually received failing grades in the categories of Endowment Transparency and Shareholder Engagement. Significantly however, both with regards to the aims of this project and the future outlook of Bucknell's energy consumption profile, according to this report Bucknell's two best performing sectors were Food & Recycling and Climate Change & Energy (Ibid.).

In the category of Climate Change & Energy the institute's evaluation of our campus' performance read as follows:

> *In 1998 Bucknell's power plant was converted from a coal burning facility to a cogeneration power plant that captures and reuses waste heat for an overall efficiency of 75 to 80 percent. Beginning in 2002, Bucknell has purchased 1 million kilowatt-hours of wind energy per year. In August 2006, the Solar Scholars helped install a 2.5-killowatt solar array which serves as a power source for the Bucknell University Environmental Center. In April 2007, two more arrays were installed at the Bucknell Mods*.(Ibid.)

While the 1998 installation of the cogeneration plant received relatively little attention on campus it was an enormous leap forward in the effort to make Bucknell's campus more sustainable. Cogeneration technology is the most efficient and least polluting way to generate electricity from conventional fossil fuels and Bucknell's innovative use of the waste thermal energy from this process to heat campus facilities represents an impressive sustainability achievement.

As a founding member of the Solar Scholars Program and an active constituent in the BUEC I have borne witness to a rapid transformation in the attitude of the University's administration and its principle benefactors towards the possibility of installing renewable, carbon-free, energy production systems on Bucknell's campus. For me, the turning point came with the Board of Trustee's decision to approbate the release of funds to the student led Solar Scholars initiative; a program which culminated in the installation of three photovoltaic arrays possessing a total combined production capacity of 6 kilowatts.

Following the success of this program and others, the BUEC has grown immensely and its efforts to promote various environmental initiatives on campus have been positively received. A diverse group of interested students, faculty, and administration have coalesced behind the issues of energy and efficiency that are the subject of this thesis project. My optimism for Bucknell's energy future can be attributed to this group's demonstrated ability to achieve and sustain significant forward momentum in the effort to make Bucknell a more sustainable and environmentally conscious institution. An important tangible result of this effort has been the development of the ongoing Campus Wide Environmental Assessment and the hiring of Dina El-Mogazi as a dedicated campus sustainability coordinator.

Another major energy related development came at the culmination of Focus the Nation, where the BUEC sponsored Bucknell's participation in a nation wide teach in related to the issues of global climate change. In his keynote speech at the event's closing gathering, President Mitchell announced his decision to sign the Association of College and University Presidents [ACUP] President's Climate Commitment. This decision formally commits the University to a series of steps towards reducing carbon emissions through improved energy efficiency and the increased use of renewable energy technologies. One critical part of this commitment related to the work involved in this thesis is the requirement that the university consider LEED certification in the design and construction of all future buildings.

The continued use of VisualDOE at Bucknell may play a significant role in future plans to pursue LEED certification for new building construction. This is because the LEED certification process requires that the energy efficiency of the building be formally evaluated during the design phase. By incorporating the use of VisualDOE software into an undergraduate research program like an Honors Thesis or a Senior Design Project not only would the University be fostering a challenging real world educational experience but it would save a significant amount of money by forgoing the need to hire an outside consultant to perform this type of analysis.

Bibliography

Archibald, J. M., et al. Retrofitting of Commercial, Institutional, and Industrial Buildings for Energy Conservation. Ed. M. Meckler. First ed. New York: Van Nostrand Reinhold Company, 1984.

Architectural Energy Corporation (AEC). VisualDOE 4.0 User Manual. San Francisco, CA: Architectural Energy Corporation, 2004.

Brown, D. E., Fox, M., and Pelletier, M. R. Sustainable Architecture White Papers 3rd ed. New York: Earth Pledge Foundation, 2004.

Commission for Environmental Cooperation. Green Building in North America. Montreal, Quebec, Canada: Commission for Environmental Cooperation, 2008. <http://www.cec.org/files/PDF//GB_Report_EN.pdf>.

Creighton, S. H. Greening the Ivory Tower: Improving the Environmental Track Record of Universities, Colleges, and Other Institutions. First ed. Cambridge, Massachusetts: MIT Press, 1998.

DeCarolis, Joseph F., Robert L. Goble, and Christoph Hohenemser. Searching for Energy Efficiency on Campus Clark University's 30-Year Quest. Vol. 42., 2000.

Department of Energy. "DOE-2." United States Department of Energy. 2007. <http://gundog.lbl.gov/dirsoft/d2whatis.html>.

Energy Information Administration (EIA). "1.1 Buildings Sector Energy Consumption." Buildings Energy Data Book. Washington D.C., USA: Energy Information Administration, 2007 <http://buildingsdatabook.eren.doe.gov/docs/1.1.3.pdf>.

EIA ii. "Cushing, OK WTI Spot Price FOB (Dollars Per Barrel)." Energy Information Administration. 2007. Petroleum Navigator. <http://tonto.eia.doe.gov/dnav/pet/hist/rwtcA.htm>.

EIA iii. "Baisic Petroleum Statistics." Energy Information Administration. 2006. Energy Baisics 101. <http://www.eia.doe.gov/basics/quickoil.html>.

EIA iv. "Buildings End use Energy Consumption Graphic." Buildings Data Book. Washington D.C., USA: Energy Information Administration, 20073/1/2008 <http://buildingsdatabook.eren.doe.gov/images/charts/2007/2005_BuildingsEnd-Use.gif>.

EIA v. "International Total Primary Energy Consumption and Energy Intensity." Energy Information Administration. 2006. International Energy Statistics. <http://www.eia.doe.gov/emeu/international/energyconsumption.html>.

EIA vi. "Table A1. World Total Energy Consumption by Region, Reference Case, 1990-2030." International Energy Outlook 2006. Washington D.C., USA: Energy Information Administration, 2006. 83.

Environmental Protection Agency. "About ENERGY STAR." Environmental Protection Agency. 2008. <http://www.energystar.gov/index.cfm?c=about.ab_index>.

Fussman, C. "The Energizer." Discover Magazine 2/20/2006 2006 <http://discovermagazine.com/2006/feb/energizer/>.

Halber, D. "Students Help MITEI 'Walk the Talk' on Energy." MIT Tech Talk September 26, 2007 2007, sec. Energy: 8. 10/2/2007 <http://web.mit.edu/newsoffice/2007/techtalk52-3.pdf>.

Knight, J. Bucknell's Cogeneration Powerplant. Powerpoint Presentation ed. Lewisburg, PA:, 2008.

McDonough, W., and M. Braungart. Cradle to Cradle. 1st ed. New York: North Point Press, 2002.

McGlone, M. Commodity Perspective: S & P GSCI. January ed. Standard and Poor Index Services Group, 2008. <http://www2.standardandpoors.com/spf/pdf/index/200801_GSCI.pdf>.

MIT News Office. "Students Help MITEI Walk the Talk on Energy." MIT Press. 2007. <http://web.mit.edu/newsoffice/2007/energy-map-tt0926.html>.

National Highway Transportation Safety Administration (NHSTA). "CAFE Overview - Frequently Asked Questions." National Highway Traffic Saftey Administration. 2008.

National Highway Traffic Saftey Administration.
<http://www.nhtsa.dot.gov/cars/rules/cafe/overview.htm>.

Osborne, P. L. Tropical Ecosystems and Ecological Concepts. 1st ed. Cambridge, UK: Cambridge University Press, 2000.

Patrick, S. R., D. R. Patrick, and S. W. Fardo. Energy Conservation Guidebook. First ed. Lilburn, GA: The Fairmont Press, Inc., 1993.

Reddy, T. A., I. Maor, and C. Panjapornpon. "Calibrating Detailed Building Energy Simulation Programs with Measured Data - Part 1: General Methodology (RP-1051)." Hvac&R Research 13.2 (2007): 221-41.

Roberson, J. A., et al. After Hours Power Status of Office Equipment and Energy use of Miscellaneous Plug-Load Equipment. Vol. LBNL-53729. Berkeley, CA: Ernesto Orlando Lawrence Berkeley National Laboratory, 2004.

Schipper, L., et al. Energy Efficiency and Human Activity: Past Trends, Future Prospects. First ed. Cambridge, UK: Cambridge University Press, 1992.

Smith, P. F. Sustainability at the Cutting Edge. Second ed. New York: Architectural Press, 2007.

Steadman, P., et al. Energy, Environment and Building. Ed. P. Steadman. London: Cambridge University Press, 1975.

Stein, R. Architecture and Energy. First ed. Garden City, New York: The Anchor Press, 1977.

Sustainable Endowment Institute. College Sustainability Report Card. 2008th ed. Sustainable Endowment Institute, 2008.

Tavares, P. F. D. F., and A. M. D. G. Martins. "Energy Efficient Building Design using Sensitivity Analysis - A Case Study." Energy and Buildings 39.1 (2007): 23-31.

United Nations Department of Economic and Social Affairs, Population Division. World Urbanization Prospects; the 2005 Revision. New York, N.Y.: United Nations, 2005.

United States Green Building Council. "LEED Rating Systems." United States Green Building Council. 2008. <http://www.usgbc.org/DisplayPage.aspx?CMSPageID=222>.

World Resources Institute (WRI). "Energy Consumption: total energy consumption per capita." World Resources Institute. 2006. International Energy Agency. Energy and Resources. <http://earthtrends.wri.org/searchable_db/results.php?years=2003-2003&variable_ID=351&theme=6&cID=190&ccID>.

Zhang, Y. P., et al. "Application of Latent Heat Thermal Energy Storage in Buildings: State-of-the-Art and Outlook." Building and Environment 42.6 (2007): 2197-209.

Detailed Simulation Description: Taylor Hall

VisualDOE 4.1 - Architectural Summary

April 7, 2008

Project Information

Name: Taylor Hall
Address: Taylor Hall, Bucknell University, Lewisburg, PA, 17837
Description: Stephen W. Taylor Hall, named in honor of the author of the university's charter, was erected in 1849 as the first building on College Hill. In 1994, Taylor Hall was renovated for use by the management department, the Office of International and Off-Campus Studies, and Bucknell Press offices.
Analysis done by: Eric Fournier @ Bucknell University
Project File: c:\documents and settings\eric fournier\desktop\thesis models\taylor hall.gph
Case Name: Base Case
Case Description: Base Case
Gross Area: 22,027 ft²
Conditioned Area: 22,027 ft²
Window-Wall-Ratio: 8.5%
Skylight-Roof-Ratio: 0.0%
Number of Blocks: 4
Note: This report includes floor multipliers

Occupancies Summary

Name	Area (ft²)	Avg. LPD (W/ft²)	Avg. EPD (W/ft²)
Educational occupancies above 12th grade	22,027	1.2	0.5
Building Totals & Averages	22,027	1.2	0.5

Constructions Summary

Name	Net Area (ft²)	U-Factor (Btu/h-ft²-°F)	HC (Btu/ft²-°F)	Absorptance	Type	Category	Layers
12" Brick wall uninsulated	11,017	0.41	5.33	0.7	Walls	Light	1
Simulated Slab	17,923	0.03	45.6	0.0	Slabs	Light	3
Partition	15,143	0.39	1.04	0.3	Partitions	Light	3
Simulated Below-Grade Wall	3,465	0.24	20.0	0.1	Below-Grade Walls	Light	1
R-7 Mass	94,567	0.13	9.33	0.7	Floors	Light	3

Fenestrations Summary

Name	Ucog (Btu/h-ft²-°F)	SHGC	Tvis	North (ft²)	East (ft²)	South (ft²)	West (ft²)	Total (ft²)	No.
3 x 5.5 single clear	1.087	0.610	0.534	677	264	710	297	1,947	118
Entry door 6 x 4 single clear	1.087	0.610	0.534	0	24	48	0	72	3
Building Totals & Averages	1.087	0.610	0.534	677	288	758	297	2,019	121

VisualDOE 4.1 - Systems Summary

April 7, 2008

Project Information

Name: Taylor Hall
Address: Taylor Hall, Bucknell University, Lewisburg, PA, 17837
Description: Stephen W. Taylor Hall, named in honor of the author of the university's charter, was erected in 1849 as the first building on College Hill. In 1994, Taylor Hall was renovated for use by the management department, the Office of International and Off-Campus Studies, and Bucknell Press offices.
Analysis done by: Eric Fournier @ Bucknell University
Project File: c:\documents and settings\eric fournier\desktop\thesis models\taylor hall.gph
Case Name: Base Case
Case Description: Base Case
Number of Systems: 4

Systems Summary

Name	Type	Conditioned Area (ft²)	Supply Air (CFM)	Min. OA Ratio	Cooling Cap (kBtu/h)	Heating Cap (kBtu/h)	Cooling Peak (kBtu/h)	Heating Peak (kBtu/h)	Cooling Energy (MBtu)	Heating Energy (MBtu)
System_10152	DDS	5921	4213	0.281	175.7	273.3	191.1	309.5	179.4	410.1
System_10153	DDS	5328	7924	0.146	303.5	492.4	352.8	478.8	320.9	758.1
System_10154	DDS	5357	7862	0.149	301.7	488.5	350.3	473.5	321.5	750.1
System_10155	DDS	5421	7799	0.151	300.5	484.6	347.4	460.7	322.6	744.4

Systems Summary per Conditioned Area

Name	Type	Conditioned Area (ft²)	Supply Air (CFM/ft²)	Min. OA Ratio	Cooling Cap (Btu/h/ft²)	Heating Cap (Btu/h/ft²)	Cooling Peak (Btu/h/ft²)	Heating Peak (Btu/h/ft²)	Cooling Energy (kBtu/ft²)	Heating Energy (kBtu/ft²)
System_10152	DDS	5921	0.711	0.281	30	46	32	52	30.3	69.3
System_10153	DDS	5328	1.487	0.146	57	92	66	90	60.2	142.3
System_10154	DDS	5357	1.468	0.149	56	91	65	88	60	140
System_10155	DDS	5421	1.439	0.151	55	89	64	85	59.5	137.3

Economizer

Type	Temperature
Compressor Lockout	Yes
Drybulb Temperature Limit	72 °F
Lower Temperature Limit	0 °F

Heating

Max Supply Temperature	105 °F
Control	Constant
Heating Cap (kBtu/hr)	AutoSized
Autosized Ratio	1.2
Autosized Capacity	273.26
Heat Source	Hot Water from Plant

Preheat

Preheat Temperature	45°F
Preheat Source	Hot-Water

Humidifier

Minimum Relative Humidity Setpoint	40%
Humidification Source	Hot-Water

Supply Fan

Spec Method	Enter Pressure/Efficiency
On-Hours Control	Constant Volume
Off-Hours Control	Stay Off
Static Pressure (in. water)	4
Mechanical Efficiency	0.55
Motor Efficiency	0.85
Drive Efficiency	0.95
Air Flow (cfm)	AutoSized
AutoSized Air Flow	4213

Return Fan

Power (bhp/cfm)	0.000685
Motor Efficiency	0.85
Delta-T	3 °F

Cooling

Min Supply Temperature	55 °F
Control	Constant
Total Capacity (kBtu/h)	Autosized
Sensible Capacity (kBtu/h)	Autosized
Autosized Ratio	1
Total Capacity	175.67
Dehumidification	n.a.
Coil Bypass Factor	0.19
Desuperheater	n.a.
Evaporative Condenser	No
Water Cooled Condenser	No

VisualDOE 4.1 - Plant Summary April 7, 2008

Project Information
Name: Taylor Hall
Address: Taylor Hall, Bucknell University, Lewisburg, PA, 17837
Description: Stephen W. Taylor Hall, named in honor of the author of the university's charter, was erected in 1849 as the first building on College Hill. In 1994, Taylor Hall was renovated for use by the management department, the Office of International and Off-Campus Studies, and Bucknell Press offices.
Analysis done by: Eric Fournier @ Bucknell University
Project File: c:\documents and settings\eric fournier\desktop\thesis models\taylor hall.gph
Case Name: Base Case
Case Description: Base Case

Chilled Water Temperature 42 °F

Chilled Water Pumps

Type	Fixed-Speed
Head (ft)	30
Motor Efficiency	0.9
Impeller Efficiency	0.8

Hot Water Pump

Type	Fixed-Speed
Head (ft)	30
Motor Efficiency	0.85
Impeller Efficiency	0.7

Cooling Tower (Central Plant)

Type	Open
Efficiency (bhp/tons)	0.013
Approach Temperature	8 °F
Design Wetbulb Temperature	78 °F
Design Range	10 °F
Cooling Cap (tons) AutoSized	259.0823
Waterside Economizer	No
Number of Cells	1
Cell Control	Minimum Needed
Temperature Control	Fixed
Setpoint Temperature	85 °F
Throttling Temperature	10 °F
Minimum Water Temperature	66 °F
Capacity Control	One-Speed Fan

Chiller Type #1: Screw

Condenser Type	Water-cooled
Chiller Autosized	Yes
Hot Gas ByPass	No
Min. Operating Point	0.1
Rated Efficiency	0.8 (kW/ton)
Rated CHWS	44 °F
Rated Condition CWS	85 °F
Evap. Flow	3 (gpm/ton)
Evap. Pressure Drop	5 (ft)
Evap. Imp. Eff.	0.77
Evap. Motor Eff.	0.9
Cond. Flow	3 (gpm/ton)
Cond. Pressure Drop	5 (ft)
Cond. Imp. Eff.	0.77
Cond. Motor Eff.	0.9
Number Installed	1
AutoSized	.0 (tons)

VisualDOE 4.1 - Plant Summary April 7, 2008

Absorption Chiller Type #1:

Chiller Autosized	Yes
Min. Operating Point	0.1
Heat Input Ratio	0.8
Electrical Usage	0 (W/(Btu/hr))
Rated CHWS	44 °F
Rated Condition CWS	85 °F
Evap. Flow	3 (gpm/ton)
Evap. Pressure Drop	5 (ft)
Evap. Imp. Eff.	0.77
Evap. Motor Eff.	0.9
Cond. Flow	3 (gpm/ton)
Cond. Pressure Drop	5 (ft)
Cond. Imp. Eff.	0.77
Cond. Motor Eff.	0.9
Number Installed	1
AutoSized	.0 (tons)

Fuel Boiler Type #1: Fuel Hot Water w/ Atmospheric Burner

Boiler Autosized	Yes
Number Installed	1
Boiler Efficiency	0.8
Min. Operating Point	0.5
Max. Operating Point	1
AutoSized	2.657 MBtu/h

Electric Generator

Type	Gas Turbine
Generator Autosized	Yes
Min. Operating Point	0.3
Max. Operating Point	1.1
Operating Point	1
Generator Efficiency	0.19
Exhaust Heat Rec. Eff.	0.55
Heat Rec. Primary Demand	None
Heat Rec. Secondary Demand	None
Number Installed	1
AutoSized	174.38 (kW)

Detailed Simulation Results: Taylor Hall

VisualDOE 4.1 - Results

April 7, 2008

Project Information
Name: Taylor Hall
Address: Taylor Hall, Bucknell University, Lewisburg, PA, 17837
Description: Stephen W. Taylor Hall, named in honor of the author of the university's charter, was erected in 1849 as the first building on College Hill. In 1994, Taylor Hall was renovated for use by the management department, the Office of International and Off-Campus Studies, and Bucknell Press offices.
Analysis done by: Eric Fournier @ Bucknell University
Weather File: williapa
Project File: c:\documents and settings\eric fournier\desktop\thesis models\taylor hall.gph
Calculation Engine: DOE-2.1E-119

Electrical Use Summary

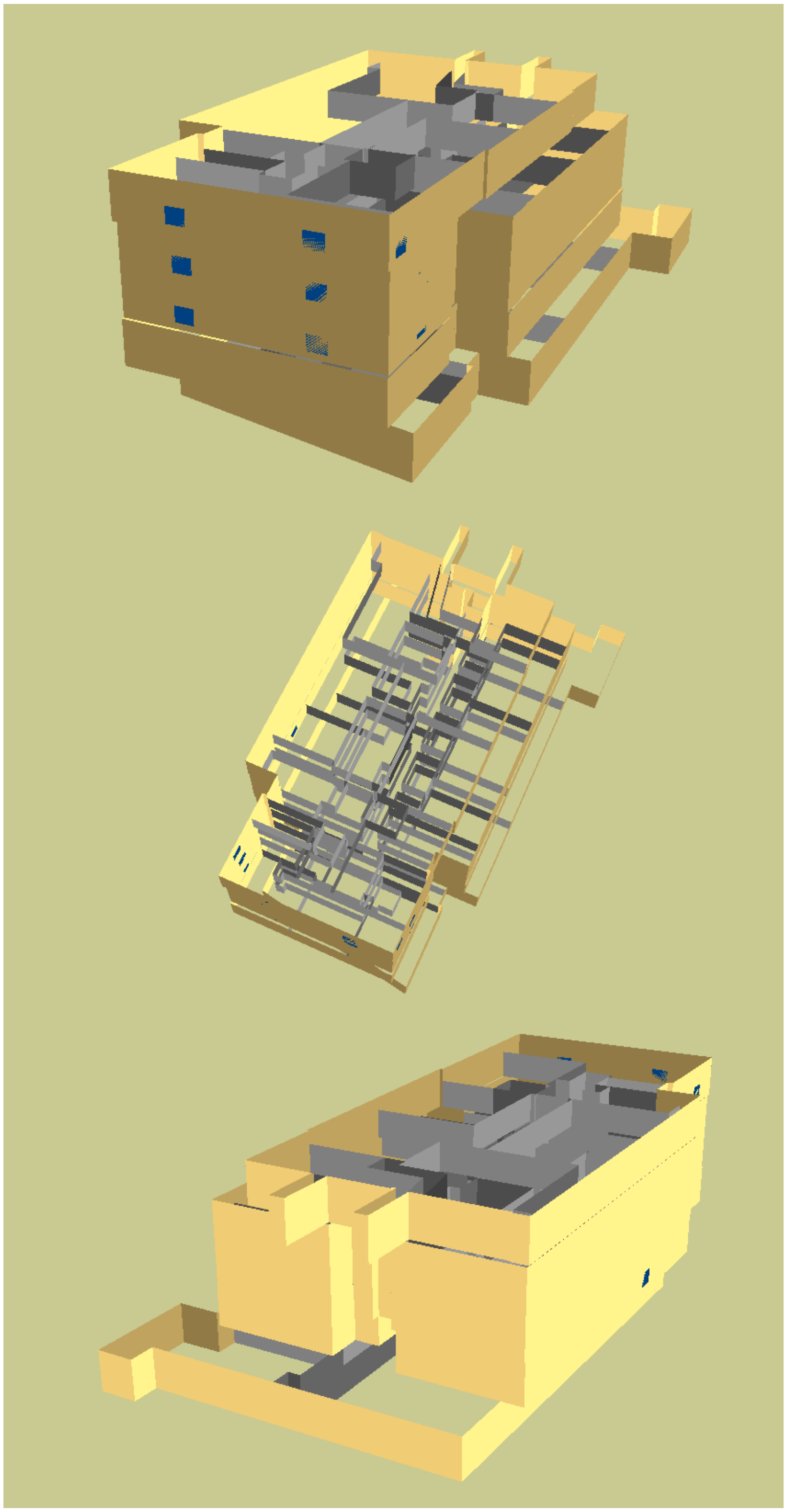
Alternative	Lights	Equipment	Cooling	Tower/Heat Reject.	Pumps/Aux.	Fans	Total
Electrical End-use Totals (kWh)							
Base Case	6,383	2,660	71	114	1,094	19,041	29,363

Alternative	Lights	Equipment	Cooling	Tower/Heat Reject.	Pumps/Aux.	Fans	Total
Electrical End-use Totals (kWh)							
Alternative 1	4,748	2,110	41	62	938	16,651	24,550

Alternative	Lights	Equipment	Cooling	Tower/Heat Reject.	Total
Electrical End-use Totals (kWh)					
Alternative 2	4,347	1,932	76	112	6,467

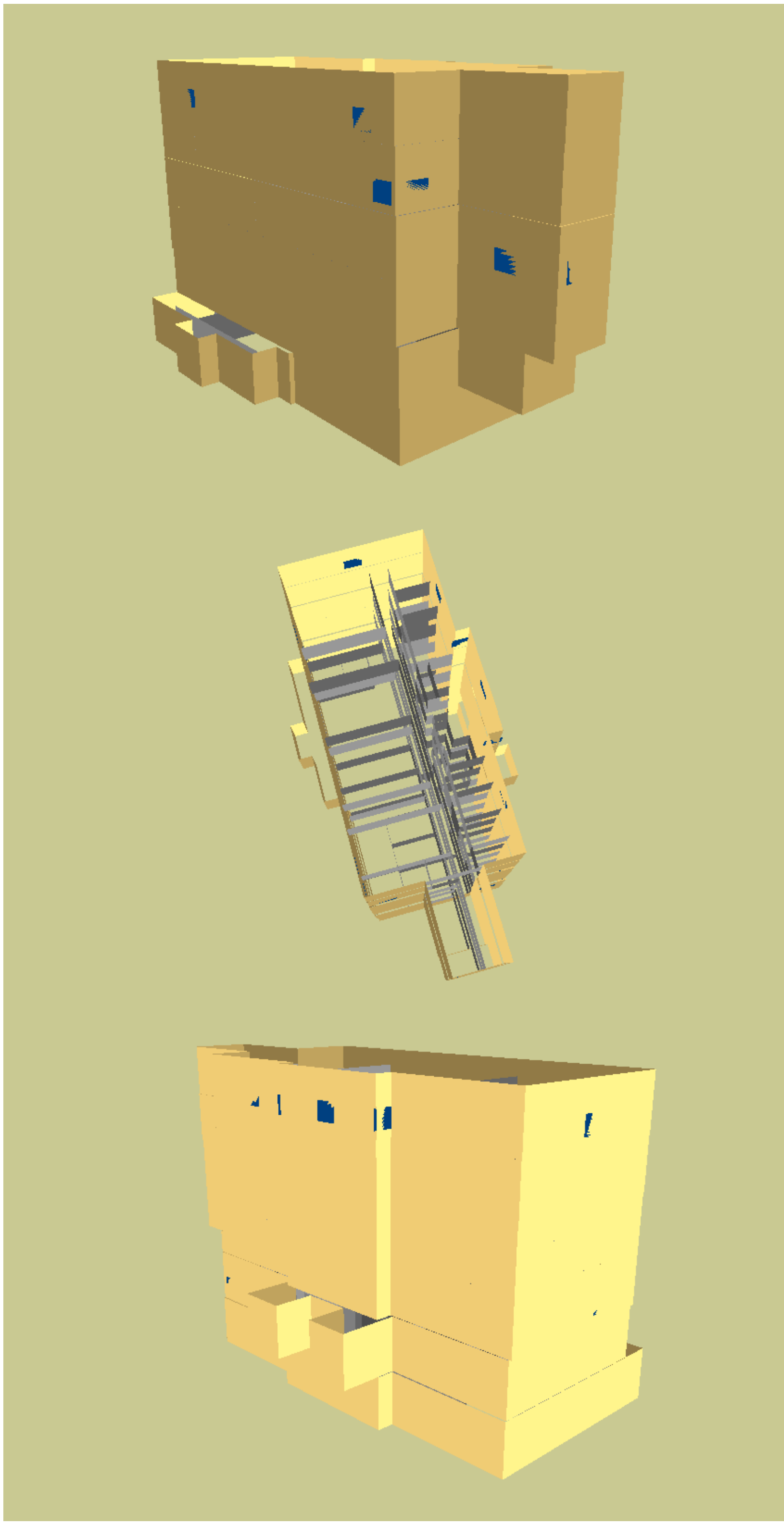
Alternative	Lights	Equipment	Cooling	Tower/Heat Reject.	Fans	Total
Electrical End-use Totals (kWh)						
Alternative 3	4,347	1,932	156	230	1	6,666

3-D Model Visualizations



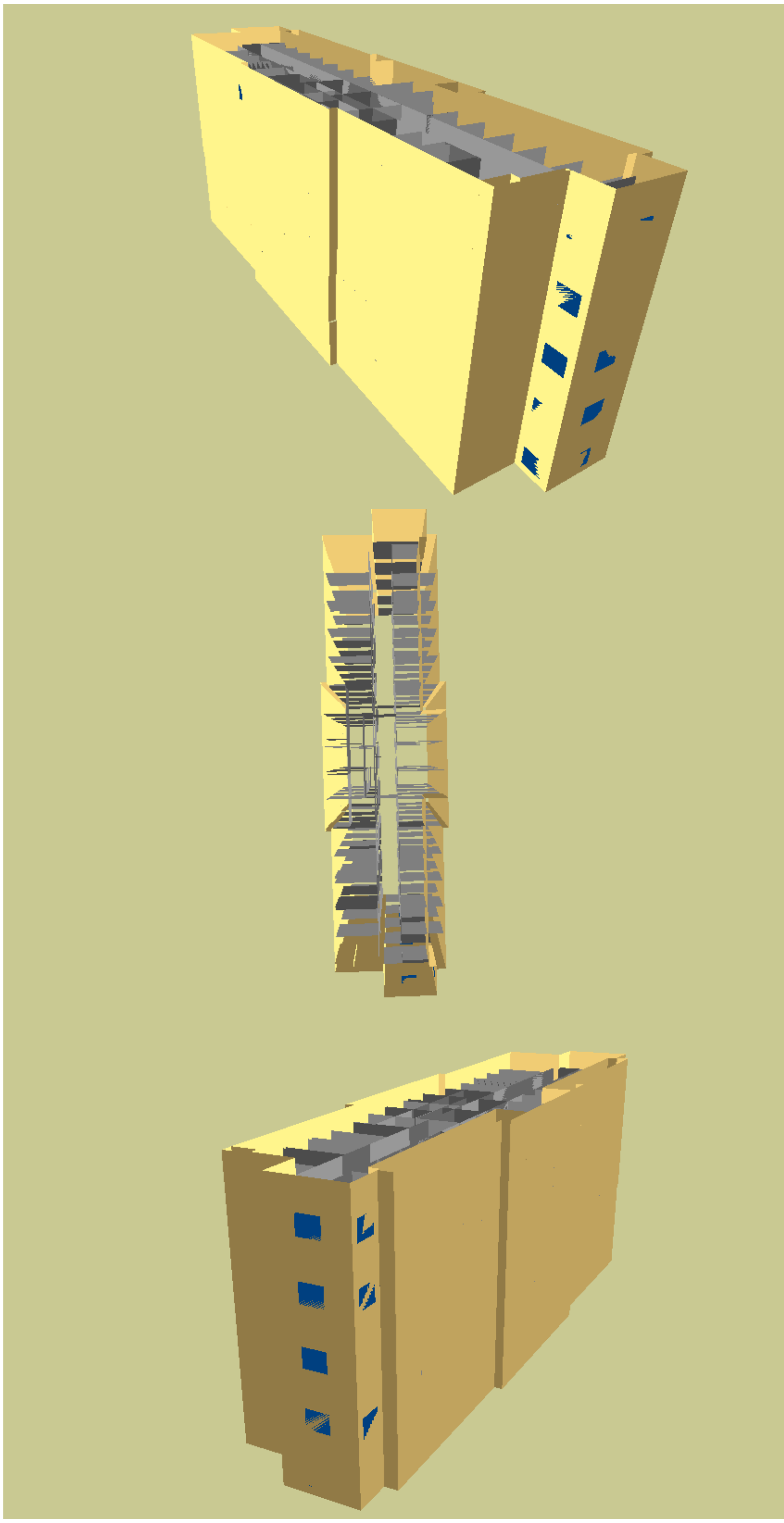
<u>Facility:</u> The Biology Building

<u>Model Status:</u>
Blocks: Complete
Façades: Incomplete
Rooms: Empty
Systems: Empty



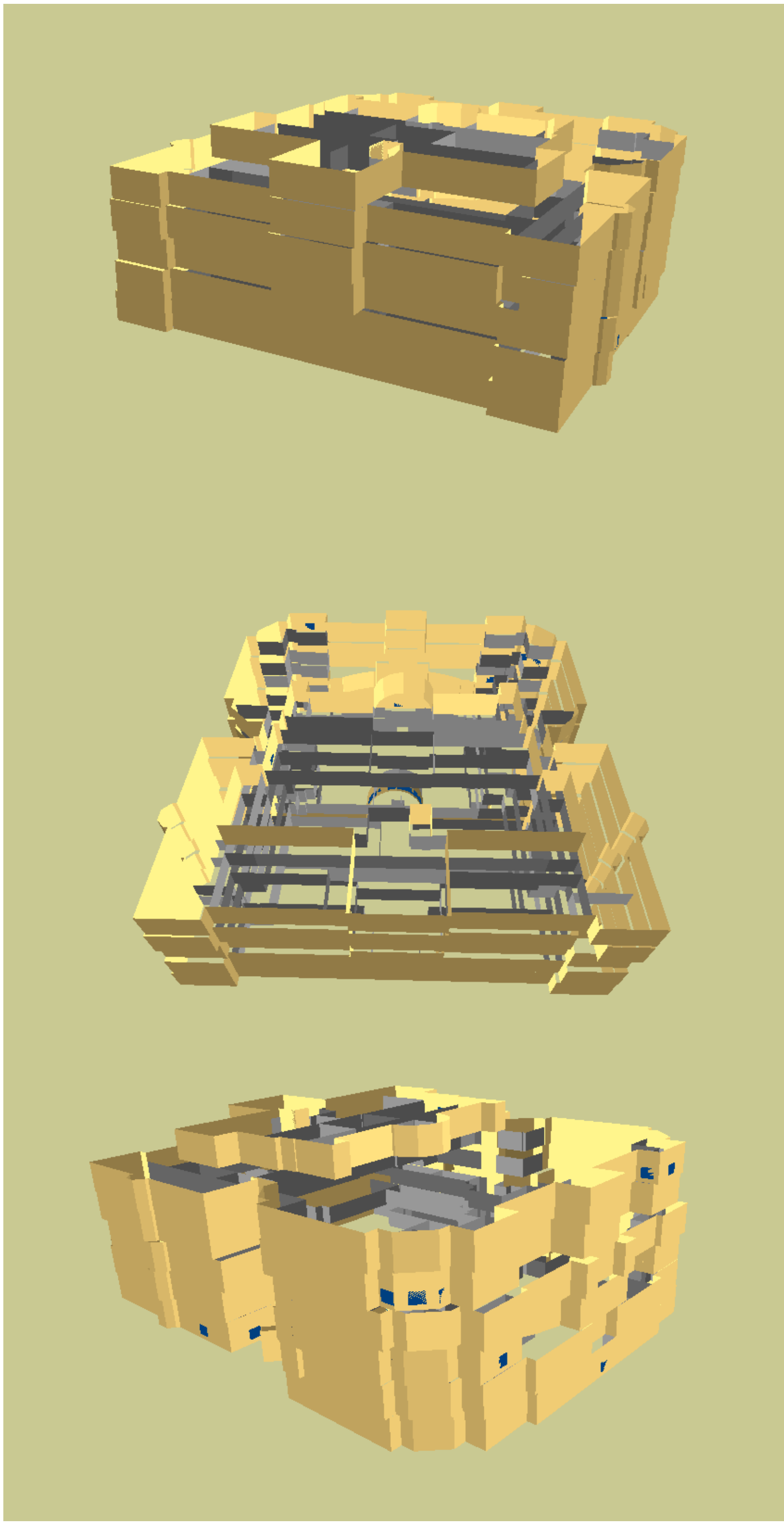
Facility: Breakiron Engineering

Model Status:
Blocks: Complete
Façades: Incomplete
Rooms: Empty
Systems: Empty



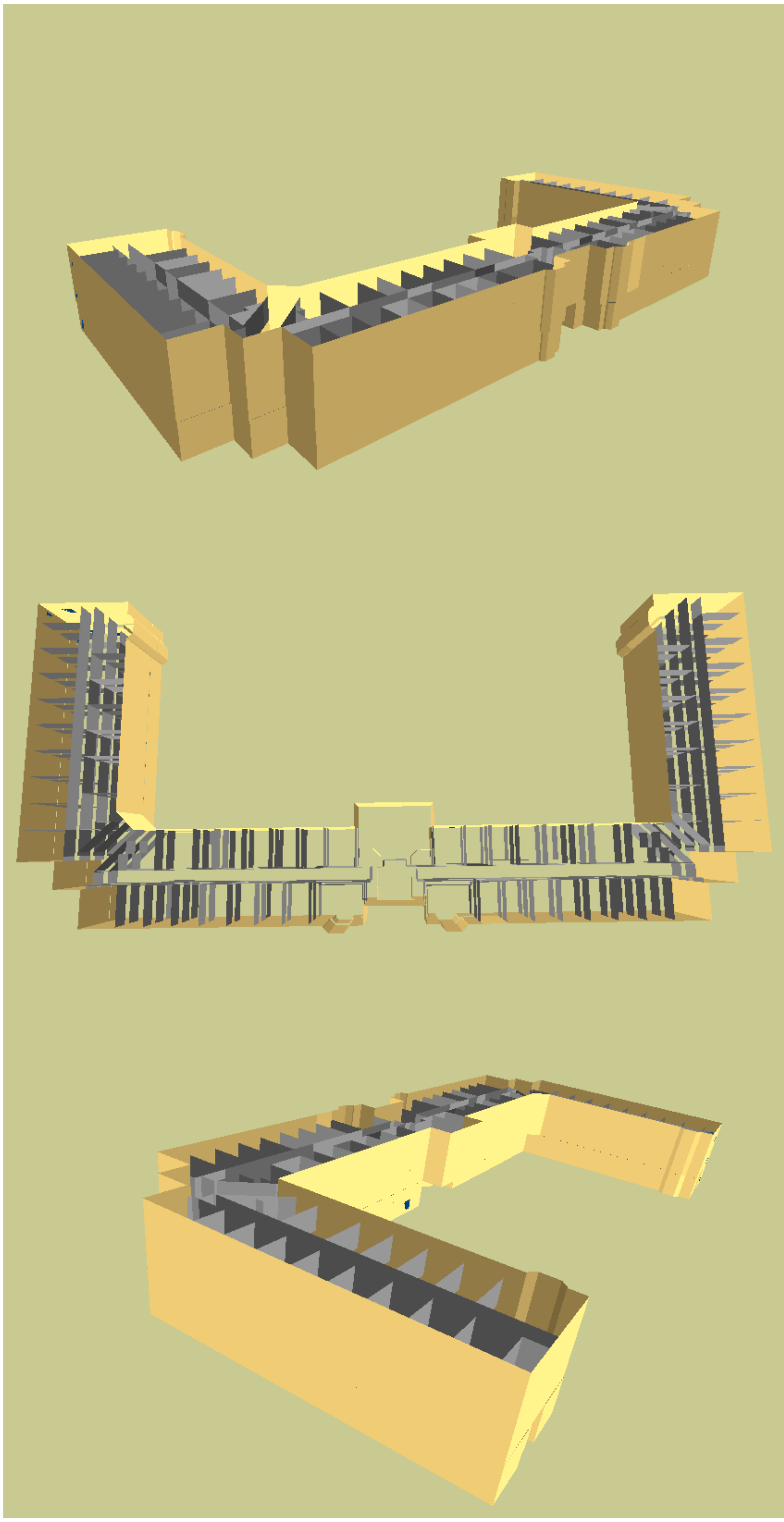
<u>Facility:</u> Kress Hall

<u>Model Status:</u>
Blocks: Complete
Façades: Incomplete
Rooms: Empty
Systems: Empty



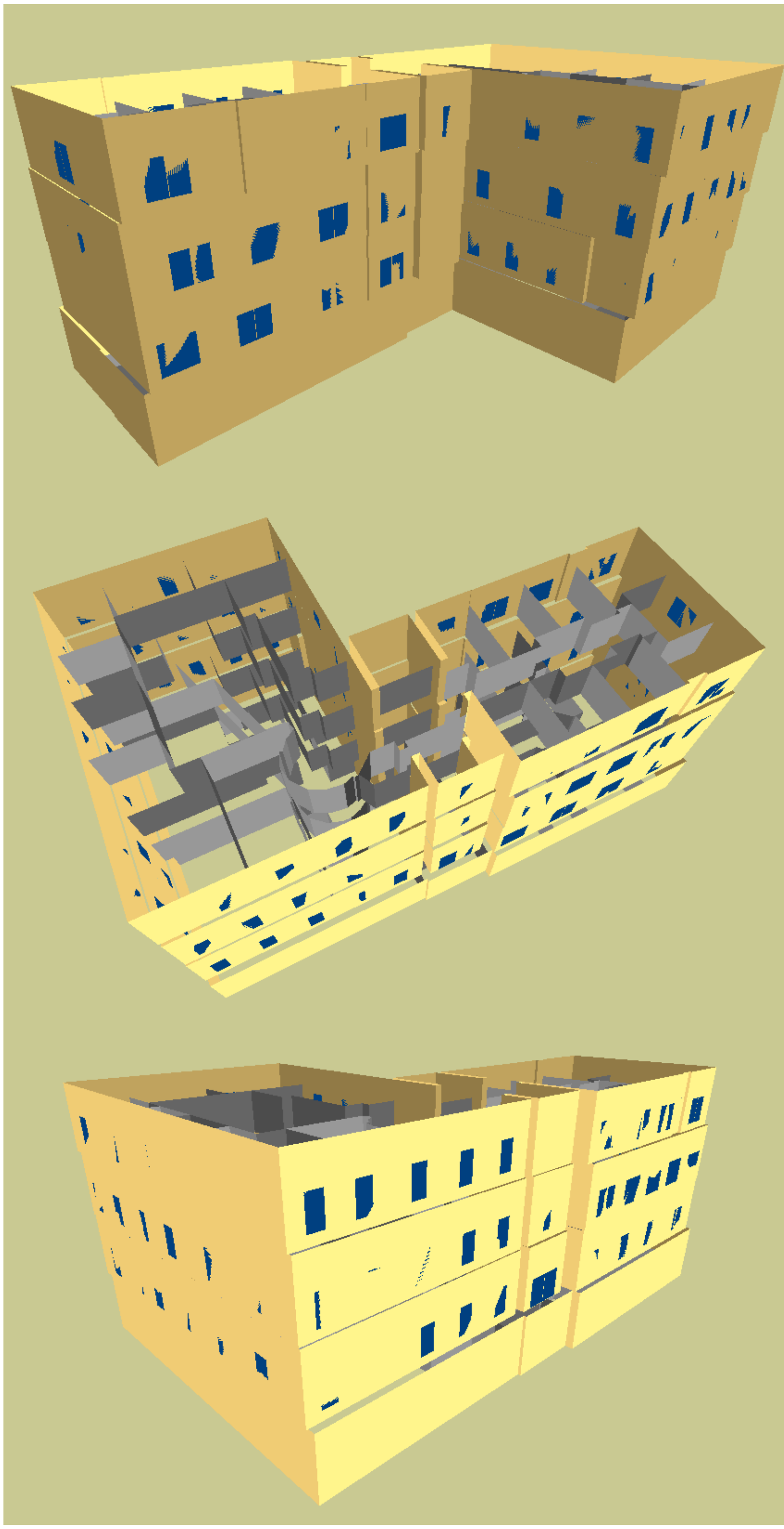
<u>Facility:</u> Bertrand Library

<u>Model Status:</u>
Blocks: Complete
Façades: Empty
Rooms: Empty
Systems: Empty



Facility: Smith Hall

Model Status:
Blocks: Complete
Façades: Empty
Rooms: Empty
Systems: Empty



Facility: Taylor Hall

Model Status:
Blocks: Complete
Façades: Complete
Rooms: Complete
Systems: Complete

VisualDOE Supplemental Procedure

VisualDOE Project Workflow Diagrams

The Modeling Process

Describe the Project

Input basic information about the physical attributes of the project site and provide a brief description of the building being modeled.

↓

Edit Blocks

In VisualDOE blocks correspond to unique floor plans within the building. Using the block editor the user can choose from a library of block templates or create your own custom block. The custom block editor provides a simplified CAD environment or allows the user to upload a pre-prepared CAD file created in another software package.

Check Model Definitions ↓

Edit Rooms

Each block is composed of a number of rooms which represent continuous thermal zones. The room editor allows the user to customize the occupational density and lighting characteristics of every room in the block.

Check Model Definitions ↓

Edit Facades

The façade editor allows the user to define the precise characteristics of the design elements and construction materials used up the buildings envelope. The façade editor allows the user to create custom materials to add to the existing library.

Check Model Definitions ↓

Specify Systems and Zone Characteristics

The performance characteristics of the building's heating and cooling systems are then specified using the systems/zoning editors. The option exists to include information about a central plant to which a building might be coupled.

Performing Simulations

<u>Define the Base Case</u>

The base case is the standard against which alternatives are to be compared. In front end analysis the base case should correspond to the most basic structural design option. In back end analyses the base case should correspond to the existing building as it has been constructed.

↓

<u>Define Alternative Cases</u>

Any number of alternative cases can be created. Alternative cases can either be developed by modifying a copy of the base case or they can be built iteratively upon one another. Alternative cases are used to test the performance of different design features and load management scenarios.

↓

<u>Choose Report Types</u>

There are a large number of reports to choose from that can be generated from the simulation results. Each focuses on different specific characteristics of the building's energy performance.

Check BDL File ↓

<u>Run Simulations</u>

Simulations can be performed for each case individually or all of the cases at once. A separate data file is created when a simulation is run and can be stored and accessed by computers that do not have VisualDOE installed.

↓

<u>Analyze Simulation Results</u>

Using the different graphs and tables available in the simulation results section determine which combination of design features and load management regimes optimizes the building's energy performance.

VisualDOE – Informational Requirements

The following is a breakdown of the informational requirements for the successful completion of each stage of the modeling process. With the exception of the initial project description, each stage must be successfully completed before the user is able to continue on to the following stage. .

Project Description

- Physical characteristics of the project site: climate zone (associated with a weather file for the closest available location) azimuth, altitude

- Utility rates: gas and electricity

- Number of utility meters: gas and electricity

- Construction date (or the date of the most recent major renovation)

- Holiday set

- For front end analysis: discount rate and project life cycle

Block Editing

- Block design: If the user has chosen to generate their block designs using drawing file that were created with an external CAD software those drawing files must be formatted to ANSC II text with a .DXF file extension. Additionally, the blocks must be composed of closed contiguous polygons. Any gaps between the polygons or overlapping regions will result in an error message and a failure to import the file into VisualDOE. If the user is able to successfully import their external drawing file into Visual DOE they must take care to ensure that the correct scale conversion is being used such that the dimensions of their drawing the software are accurate to those of the building in the real world.

- For each unique floor plan in the building a unique block must be created. If a single floor plan is the same for a number of different floors in the building, that number must be specified when editing the corresponding block.

- Floor height

- Plenum height
- Construction materials for the following: roof, ceiling, floor, internal floors, and partitions

Room Editing

- LPD (Lighting Power Density) W/ft^2
- EPD (Equipment Power Density) W/ft^2
- Light to space ratio in each room
- Occupation density in persons/ ft^2 for each room
- Zone type: weather the room is air conditioned or non air conditioned
- Occupancy type: there are various saved templates to choose from including hotel, office, educational facility, etc.
- Infiltration: a measure of air exchange in the room given in air-changes/hr
- Process loads: Process loads contribute to zone heat/cooling loads but do not go to meters. A custom load editor is available which allows the used to input the type (process, gas, or electric) scheduling, and Btu/h consumption rate of loads for each room in a block.

Façade Editing

- Openings: the type and size of all windows must be known; this includes information about the number of panes, the thickness of each pane, the window's efficiency rating, and the type of glazing, if any, that has been applied. Additionally, the specific location of each window on the building's façade must be known.
- External wall construction material including insulation rating and wall thickness

Systems Editing

- System assignments must be made on either the room, block, or building level.
- HVAC system design: a custom system editor is available which allows the user to choose from a number of potential design components. The type of system, operating schedules, system era, and method of air return must be specified.
- Central plant design: a central plant editor allows the user to specify the components of a central plant that is coupled to the buildings heating/cooling systems. The user is required to input information about the number and type of water chillers, boilers, and generators in the central

plant. Additionally, the user can customize the load ranges and scheduling for the heating and cooling systems.

- Water heating system design: information about the method of heating (gas, electric, or heat pump), the schedule for heated water delivery, peak consumption values, delivery temperature, and tank loss rate can all be input in the custom water heating system editor.

Zone Editing

- Zone assignments are made on the same level as that chosen for systems editing
- Thermostat type: proportion, reverse action, or two position
- Throttling range in degrees Fahrenheit
- Minimum flow ratio
- The presence of exhaust fans or baseboards
- For custom zone editing: total flow, flow area, and air-change/hr for supply air and outside air.

Procedural Comments and Experiential Insight for Individual Modeling Stages

AEC includes a detailed discussion of the modeling procedure in a set of formal tutorials that come bundled with the software package. The following procedural comments/recommendations are meant to act as a supplement to the official VisualDOE tutorial. In these remarks I hope to convey some of the more valuable and time saving solutions that I discovered to problems that I encountered during the modeling process. As a general caveat, I must admit that this advice is based upon learned knowledge and is coming from someone without formal training in the software package or academic background in the art and science of energy efficiency modeling. With that said, I do believe that it will be helpful for someone with a background similar to mine who, at first blush, may find the user interface and modeling process of VisualDOE to be overly complex or counterintuitive.

After the completion of every stage in the modeling process it is imperative that the energy analyst perform an error check to ensure that they have entered the appropriate information properly. This checking of model definitions can be done by following the drop down menu in the main view frame titled “Simulation” to the subheading “Check Model Definition.” Frequent checks of the model definitions ensure that whatever work is done during the next modeling phase will be built upon a valid foundation. As an instructive example, say that you have completed the block editing process and want to on to the specification of building facades. If you do this without first checking for errors in the model definitions, while editing the facades you might receive and error prompt that prevents you from either being able to continue with your work or save that which has already been completed during the session. If the source of this error is a fault in the block design you must return to the block editor to fix it. By re-editing the block however you automatically lose all of the work that had been invested in the specification of the facades on the faulty block. As this example clearly illustrates, because of VisualDOE's iterative modeling process, there is a strong incentive to minimize unnecessary effort through simple periodic error checking.

The error messages that you will inevitably encounter can be a bit cryptic to those not fluent in energy modeling terminology. As such, do not hesitate to consult the VisualDOE support staff over the phone or via email. They are highly educated professionals who offer helpful advice and, more often than not, will request a copy of your project file to find the most appropriate solution to your problem.

Building Description

- When conducting back-end energy analyses (that is, analyses on buildings that have already been constructed) for buildings that have either been constructed or renovated within the last twenty years it is likely that documentation of the building's site characteristics will be available either in paper or electronic form. The architecture and civil engineering professions have developed a coding system for the documentation of building design which corresponds to the type of information displayed on each drawing. The following is a short list of architectural drawings that contain pertinent information to the modeling process in VisualDOE.

  A Drawings – These drawings contain information about each individual floor plan and building elevations. These are useful in both the development of custom blocks in VisualDOE and designing custom facades.
  C Drawings – C drawings depict the overall site plan and utilities layout for the entire project. These drawings will usually contain the necessary information about building azimuth, elevation, etc. that is necessary during the building description phase.
  M Drawings – These drawings contain very detailed information about the HVAC systems on both a building wide and individual floor plan scale. M drawings should also be used in conjunction with A Drawings to specifying the thermal zones contained in each floor plan.

- For front end building energy analyses (analyses conducted prior to building construction) the availability of information will likely depend on the design phase of the project in question. If the architectural firm involved has already developed a suite of design alternatives with their own corresponding drawings than these drawings can be used according to the process discussed above. If the building design has not yet reached this phase it may be necessary for the energy analyst to visit the proposed project site and take the necessary measurements themselves using basic surveying techniques.

- The climate to which the building is exposed will have a significant impact on the demands placed upon that building's HVAC systems. Consequently, it is absolutely essential that climate data from the most similar location available be obtained an incorporated into the model as a DOE-2 weather data file with a .bin extension. A comprehensive list of available weather data files from a number of different sources can be obtained by following the links from the following website: <http://doe2.com/index_Wth.html> The data registry from which the weather files used in this project were obtained can be found via this link: <http://doe2.com/Download/Weather/TMY2/>

- Each building has its own specific usage schedule and the precise nature of that schedule can heavily influence simulation outputs. For back-end analyses I found that the simplest way to develop the most accurate usage schedule is to consult the building's maintenance staff, calendar in hand, and go through with them, month by month, exactly how the building is being used. Alternatively, for front end analyses, there are a number of standard templates provided by VisualDOE that can function as a proxy if the exact usage scheduling is not known.

- For back end analyses gas and utility rates can be found simply by looking at the most recent utility bills for the building being modeled. Likewise, for front end analyses it may be valuable to create a suite of simulations that consider different possible scenarios with regards to rate changes for both gas and electricity. By doing this you will be able to hedge against some of the significant uncertainty inherent to energy utilities markets.

Block Editing

- In both front and back end analyses, block editing will likely be one of the most difficult and time intensive process in the entire modeling process. This is because, particularly in the case of custom block design, it demands an enormous amount hands-on drafting work. The construction diagrams included in A Drawings show the interior and exterior walls of the floor plans as they were or are meant to be built. Because VisualDOE is only concerned with contiguous thermal zones, in virtually all cases, blocks will not simply be replicates of the building's floor plans. Rather, the energy analyst must use HVAC system schematics in concert with the actual floor plan to create a block design which is both scale-accurate and representative of the thermal zones within the building.
  The most effective way that I found to do this was to use a print out of the HVAC schematic while working on manipulating the floor plans within the CAD program.
  When using AutoCAD the most effective way I found to accomplish this task was by creating a dedicated layer for the block design. Using this layer, I would manually draw the block design using the floor plan as a guide and conforming to the information contained in the HVAC plan. The drawing tool that was most effective for this job was the segmented line

editor. To ensure that the shapes which were being drawn had the required closed polygon form factor you must right click on a closed shape and check the option "Close." After the block design is completed I would turn off all of the other layers in the drawing so that only the block layer was visible. Then I would copy and paste this layer into a new file making sure during the pasting process to keep the original base points. Depending on the scale of the CAD drawing it may be necessary to alter its size before importing into VisualDOE to ensure scale accuracy. To do this simply select the entire block design, right click, select "Scale" and input the appropriate scale factor.

- A block design that is created using a third party CAD software must be saved in the ".mdx" format to be compatible with VisualDOE. This can easily be done by selecting it from the options in the "File Type" drop down menu while saving the building design.

- It is likely that a situation will arise where one of the polygons making up your block design will not be accepted by VisualDOE. This can happen for a number of reasons and requires error checking within the external drafting software used to create the block design. Some possible reasons for the rejection of a polygon include:

    - Two overlapping polygons in the block design. (This is not always obvious and may require significant magnification of the polygon vertices to see a minute line intersection)

    - Holes between polygons in the block design (Once again, this may be a situation that requires significant magnification before it is evident)
    - Open polygons (Polygons that have not been closed or which are not completed)

    - Overlapping sides (When using the freeform drawing tool in AutoCAD for instance it is possible to loose track of your starting point when drawing a polygon and draw an overlapping side)

- After a block design has been successfully imported, it can easily be used to represent more than one floor if it is conserved in the building's design. This is done simply in the block editing feature by indicating a value in the "Number of Floors" field.

- The precise nature and performance of the building's external and internal construction materials are determined using the drop down menus available within the block editing tab. If the options available in the materials and constructions library do not adequately represent the nature of the materials or construction that were used in your building VisualDOE allows for custom editing of these parameters. As a caveat, the editing process requires significant technical knowledge about the material's performance characteristics. To access these editors simply click on the "Organizers" tab at the top of the main view screen and select which editor you want to work with.

Room Editing

- The input fields in the room editor can seem confusing and overly difficult to estimate at first but you should not overemphasize the importance of things like occupancy density and infiltration rate. It can be virtually impossible to measure these things in the building that you are modeling so you must rely upon the accuracy of the default values that are associated with the different building occupancy classifications. The two most important metrics in this field are Lighting Power Density (LPD) and Equipment Power Density (EPD).

- With back end analyses the actual LPD for each room can be determined by adding together the wattages of all the lighting fixtures in a room and then dividing that figure by the room's square footage.

- Likewise, for back end determinations of a room's EPD a summation of the power requirements for all the equipment being used in the room can be divided by the room's square footage.

- VisualDOE takes a very sophisticated approach to the issues of building shading and daylight control. The specific editors for these features can be found within the room editor tab. If the building contains a daylight control system, special care must be taken with the placement of the sensors within individual rooms.

- Indicating the precise nature of exterior building shading is accomplished with the shading editor which can be found as an option within the "Edit" tab at the top of the main view screen. Determining the proper orientation of external shading is critically important for buildings that are built in close proximity to one another and thus may be experiencing increased insolation as a result of the reflected light from surrounding buildings.

- In addition to the standard type loads which are represented by the EPD and LPD metrics, a room may contain significant process loads (loads that do not go to utilities meters but contribute to a rooms heating and cooling loads). Process loads correspond to the heat that is released into the ambient environment as a result of the operation of standard loads. Significant process loads, like computer servers, large laboratory equipment, or heavy duty manufacturing equipment can significantly impact the amount of energy needed to maintain a constant temperature in a given thermal zone. Determination of process loads can be difficult however. I found that the Department of Energy has published several documents indicating the average process loads associated with various types of equipment. These documents can be extremely helpful in determining the approximate impacts of various types of equipment.

Façade Editing

- The façade editing process is principally concerned with the location and materials used in building openings such as windows and doors. The amount of work involved with the façade editing process depends heavily upon the number and variability of building openings. For simple façade designs a default window bay can be developed within VisualDOE and used repeatedly. As a word of caution for back end analyses, it is important to select a glazing option which most closely corresponds to that which exists on the windows installed on the building. This is because the thermal properties of a building's windows can drastically affect its heating and cooling loads.

- The properties of individual building surfaces can be edited using the "Custom Façade Editor." This editor allows the energy analyst to specify different window materials and locations on individual facades. Also, it allows for the determination of specific construction materials. If the available libraries of window types and glazings do not accurately depict the windows present on the building being modeled, the façade editor provides for the creation of a custom window profile. In much the same way as with the construction and materials editors however, a significant amount of technical knowledge about the windows performance characteristics are required for this process.

Systems Editing

- The systems editor in VisualDOE is perhaps one of the software's most powerful features. VisualDOE allows the user to custom design and schedule complex HVAC and water heating systems. It also provides for the inclusion of a separate external physical plant for the delivery of electricity, chilled water, and steam to the building being modeled. The detailed nature of the systems editor does not come without its problems however. Navigating through its scheduling process and accurately designing the different systems can be a daunting task for someone not familiar with commercial utilities system design and maintenance. For this project, I was fortunate to have a professional facilities plant manager, in the form of Jim Knight, to assist me with my work on this phase of the modeling process.

- The first stage of the system editing process involves a decision as to whether or not each building, block, or zone will be specified with its own system. For back end analyses it may be necessary to select the "Custom" radio button to accurately depict the building being modeled.

- In the HVAC system editor, the energy analyst is presented with a number of different option regarding system layouts and optional components. It should be noted that if a "packaged system type" is selected this necessarily obviates the inclusion of a central physical plant as it is assumed that all utilities requirements will be satisfied by the building's internal systems.

- If a central plant must be included in the model it is important to make as accurate determinations as possible of the scheduling and priority of the various individual components (such as boilers, water chillers, etc.). This feature can have a significant impact on the performance of the central physical plant during the simulation process.

Zone Editing

- Zone editing is the final stage of the modeling process and it involves the detailed specification of the air exchange parameters associated with the building's individual zones. Here once again, as with the issues of occupancy densities and process loads, it can be extremely difficult to obtain accurate values while conducting a back end analyses. A consequence of this reality is that you may be forced to rely upon the program to size the supply air flow characteristics.

- The zone editor also includes several ancillary heating and cooling options such as baseboards, exhaust fans, and zone reheating systems. Each one of these can be specified for individual zones simply by checking the appropriate boxes and filling in values for the required fields that appear.

Procedural Comments and Experiential Insight for the Simulation Process

Once the zone editing process has been completed and a final check of the building definitions has been performed the user is then ready to begin the process of designing a simulation for their model building. In back end analyses, the model which has been created should closely mimic the performance characteristics of the existing buildings. In addition to this "Base Case" VisualDOE allows for the simultaneous evaluation of several "Alternative Cases" which possess different design features and/or load management schedules that the Base Case.

Editing Alternative Cases can be accomplished by selecting the "Alternatives" tab located at the top of the main view screen. By selecting the "Define Alternatives" subheading under the "Alternatives" tab the user is able to create any number of Alternative Cases which can be based either upon the original Base Case or be constructed iteratively off of existing Alternative Cases.

The following are several general caveats for first developing Alternative Cases and then performing successful simulations within VisualDOE.

- When creating alternatives be sure to title and label them properly. It is relatively easy to become confused as to what changes have been made in the specification of different Alternative Case features. As such, I found that it is helpful to list all of the changes that have been made between each Alternative Case and the Case on which it was based. Doing this facilitates the analysis and comparison of several different model cases.

- Extensive modification of an Alternative Case can be performed relatively quickly by selecting the “Advanced Edit…” option under the “Alternatives” tab in the main view screen. This tool allows you to rapidly interchange different model features that would otherwise have to be edited individually in the traditional modeling process.

- When modifying alternative cases, be sure that the case in which you are working is actually the correct one. This determination can be made by selecting the “Alternatives” tab in the main view screen and checking that the proper Case has a small check mark next to it. This indicates the case that is currently active.

- After all Alternative Cases have been defined you may attempt to set up and run a simulation by selecting the “Simulation” tab in the main view screen and choosing the “Setup and Run…” subheading. Each individual case can be simulated separately or all together as a group. Simulations generally do not take a significant period of time (3-10 minutes each depending on the size and complexity of the model and the number of cases being simulated).

- If the simulation is terminated and you receive an error message for a specific alternative, return to the “Simulation” tab in the main view screen and click on the subheading “View DOE2 Files.” From here, you must access the BDL building files and manually search for error messages presented in the code. If you find an error that you do not understand you should copy it in an email to the VisualDOE online support team and include a copy of the project file.

- Once the BDL file is free of errors the simulation should continue normally. At this point you will be able to obtain graphical and tabulated results for the simulations that you have run. The tables provided can be exported to either the .txt or .pdf file extension. Likewise, the graphical information can be copied to the clipboard and then manually pasted into a word processing document.