

BUILDING AN ENERGY EFFICIENCY SUPPLY CURVE:
A CASE STUDY OF RUBENSTEIN HALL AT DUKE UNIVERSITY

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Duke University has a deep commitment to sustainability and a clear track record of constructing highly efficient buildings. The new North Carolina Building Energy Conservation Code requires that new construction be 30 percent more efficient than the ASHRAE 90.1-2007 standard. To determine the impact of meeting this new code, an energy model of Rubenstein Hall was constructed as if the building were being built new today. This model was used to assess the effect of energy efficiency projects on the building's overall energy use. Projects fell into four categories: heating ventilating and air conditioning, thermal performance, solar gain, and lighting.

The results of the analysis found that the entirety of the new NC Building Energy Conservation Code could be met through four projects, each with no upfront costs: reducing the minimum percentage of outside air to 15 percent (from 17-21 percent), altering the time at which thermostats return to set points from 5am to 7am, reducing the lighting power density to 0.9 watts per square foot (from 1.8 watts per square foot), and maximizing the window area at 30 percent of total wall area. These projects will result in a building that uses 43 percent less energy use than the ASHRAE 90.1-2007 standard, more than meeting the goals of the code.

The energy efficiency supply curve generated in this report can inform decision making during the design phase of new campus buildings, as well as guide efficiency upgrades in existing buildings. Overall, Duke should have no problem meeting the NC ECC. That being said, there are still operational and physical changes that can lead to reduced energy use, which should be pursued to the fullest extent.

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INTRODUCTION

Duke University (Duke) has a deep commitment to sustainability, evidenced by a pledge to achieve carbon neutrality by 2024. This dedication has encouraged aggressive, innovative projects across campus, including a “LEED+” building policy that sets high standards for new construction on campus. Duke has 22 buildings that have attained LEED certification, including the world’s first LEED Platinum dorm, the Duke SmartHouse (Duke University, 2011a).

Even with a clear ardor for highly efficient buildings, Duke will continue to face new challenges in the arena of sustainable construction. In particular, a new North Carolina Building Energy Conservation Code (NC ECC) will enforce more stringent energy targets for new construction. Given these new objectives, the Duke Facilities Management Department (FMD) will need to continue to build and operate buildings in an efficient and cost-effective manner. The goal of this paper is to build a supply curve for energy efficiency interventions that shows the cost and projected energy savings of potential energy efficiency projects that can be used in new campus buildings to meet the NC ECC.

BENEFITS

Energy efficiency is widely touted as a cogent first step towards increasing energy independence, reducing greenhouse gas emissions, and achieving a low carbon economy (ASHRAE *et al* 2011; Granade *et al* 2009). The benefits of energy efficiency can be divided into two categories: direct and indirect benefits.

The primary direct benefit of energy efficiency is reducing energy consumption, which in turn reduces building operating costs and associated greenhouse gas emissions (ASHRAE *et al* 2004; ASHRAE *et al* 2011; Granade *et al* 2009). Additionally, it can eliminate the need to build new power plants or allow older, less efficient plants to be shut down in favor of newer, more efficient plants. Finally, energy efficiency mitigates the effects of steadily rising energy prices and volatile natural resources prices (Granade *et al* 2009).

The indirect benefits of energy efficiency, while well known, are more difficult to quantify. In particular, energy efficiency can improve the overall working and living environment through enhanced indoor air quality, increased thermal comfort, and the prevalence of natural lighting (ASHRAE *et al* 2011). Poor indoor air quality can cause irritation of the nose and throat, asthma, and respiratory illnesses that can lead to reduced productivity and more sick leave (Granade *et al* 2009). Increasing indoor air quality alone has been shown to provide a five percent increase in productivity (Fisk 2000). Energy efficient buildings generally have more productive occupants who take

fewer sick days, which can have a significant impact on an organization's bottom line (Granade *et al* 2009).

BARRIERS

Despite the many known benefits of energy efficiency, investment is still below the economically efficient level (Granade *et al* 2009). The barriers to implementing energy efficiency projects have been extensively researched for the past several decades. Because of Duke's dedication to sustainability, clear understanding of the many benefits of energy efficiency, and years of experience building and operating highly efficient buildings, some of these barriers do not apply.

For example, some firms are reluctant to invest in a property because of uncertainty over how long they will be in that location. These firms fear that upon ownership transfer they will neither have received the "full duration of benefits" of the investment, nor be able to capture the remaining value of the benefits through increased sale price (Granade *et al* 2009). On the behavioral side, many firms lack knowledge about energy efficiency, habitually make decisions that are inefficient, or expect of short payback periods, which can lead to an expectation of a higher discount rate. Finally, some efficient products and services are either not readily available, or are bundled with premium features that make the efficiency measure unaffordable (Granade *et al* 2009).

However, there are still several barriers that Duke must overcome to realize the goal of super efficient buildings. First, there can be hidden costs that are difficult to monetize, such as the time and effort required to research and put into practice a new efficiency measures. Additionally, there is uncertainty about the level of savings that can be achieved, which makes the investment more risky. The energy efficiency interventions must be installed and operated properly, or the estimated level of savings may not be achieved. Finally, some energy efficiency upgrades can be quite costly, adding significantly to the upfront cost of construction (Granade *et al* 2009).

One way to overcome some of these barriers is a policy intervention. There are several options, including those that encourage energy efficiency through monetary incentives, as well as those that mandate energy efficiency. Incentive programs can range from grants for equipment, to tax rebates for installing various energy efficiency technologies, to funding utility programs that provide free equipment or energy audits. All of these programs reduce the costs associated with energy efficiency and encourage organizations to elect to participate. Mandated energy efficiency upgrades, on the other hand, set some target level of achievement with which all stakeholders must comply, regardless of the cost. This can foster a competitive market for energy efficiency products and services. North Carolina has both types of programs, including the NC ECC, which requires new buildings to be more efficient than the international standard.

NORTH CAROLINA ENERGY CONSERVATION CODE

The NC ECC was modeled after the International Energy Conservation Code (IECC), which sets minimum energy conservation conditions for new commercial and residential construction projects. North Carolina's amendments were intended to achieve 30 percent improved energy efficiency over the 2006 IECC and the current NC building code (NC ECC 2011, Robinson 2010). The code came into law on January 1, 2012 and took full effect in March 2012. It requires that new buildings comply with a slew of specific building techniques or use modeling to show increased energy efficiency. Thus, there is not only inherent flexibility, but also guidance available to achieve the aggressive efficiency targets.

The new code will help Duke overcome some of the barriers named above. In particular, the list of specific ways to meet the efficiency goals reduces the need for research on different technologies. At the same time, the ability to use modeling also provides some elasticity in meeting the requirements. Duke will thus be able to integrate its LEED+ policy requirements and considerable experience fashioning efficient buildings into its efforts to meet the NC ECC. This flexibility is especially important given the variety of building types that Duke builds, from classrooms and offices to dorms and laboratories. This is just the type of policy that can help Duke overcome some of its remaining barriers to implementing advanced energy efficiency.

RUBENSTEIN BUILDING

Duke's Rubenstein Hall (Rubenstein, Figure 1) was used to model the outcome of various energy efficiency interventions. The analysis examines what the change in energy use would be as if the building was going to be built today. Applying the analysis to new construction instead of existing buildings has several benefits. First, this is an analysis of how to meet the new Energy Conservation Code, which only applies to new construction. Additionally, it is easier to make changes to a building during the design phase than after it is already built. Many projects are less expensive when integrated in the building design process from the start, as opposed to retrofitting the building later.

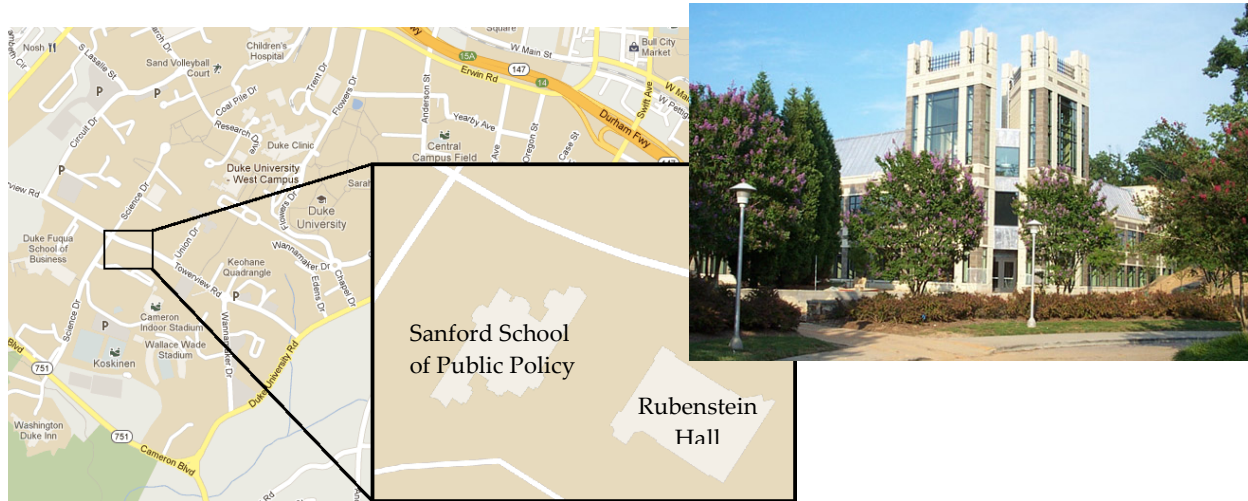


Figure 1. Location of Rubenstein Hall (Duke University 2011b, Duke University 2011c)

METHODS

To assess Duke's ability to meet the NC ECC, a building energy model was developed for Rubenstein. The model was used to determine the energy use of the building as it is built, the energy use of the building as if it had been built to ASHRAE 90.1-2004 standards, and the impact of a variety of energy efficiency interventions. This information was used to determine the associated cost savings based on reduced utility bills. The cost of each upgrade was estimated to determine the overall cost of meeting the requirements of the NC ECC.

TRACE700 MODEL

The model was constructed with Trane's Trace700 (Trace) software package. The as built architectural plans were the primary source of data for the construction of the model.¹ Schedules were obtained from FMD employees. Once a baseline model was constructed, it was duplicated and altered to assess individual energy efficiency interventions. Additionally, a version of the model was built to represent the ASHRAE 90.1-2004 standard.

The upgrades fall into four categories (Table 1).² For thermostat settings, maximum window area, and window orientation, two to three options were modeled and the least energy intensive option was selected for further analysis.

¹ Appendix A contains the key assumptions and inputs about systems, utilities, and schedules.

² Appendix B contains the assumptions and specifications of each upgrade.

Heating, Ventilating, and Air Conditioning (HVAC) upgrades deal with how the building is heated and cooled, as well as indoor air quality. Roughly 55.8% of building energy is used for HVAC, so it represents the largest potential for efficiency (US DOE 2003). The building envelope refers to the construction of walls, roofs, floors, and windows. This category is divided into two sub-categories, thermal performance and solar gain. Thermal performance refers to the conductivity of walls and windows. Controlling thermal losses in a building can make a considerable difference on how much energy is used for heating and cooling. Solar gain deals with the exposure of windows to the sun, which can also have a large impact on the energy used for HVAC. The final category is lighting design. Lighting is responsible for 11.5% of educational building energy use, and many commercial spaces are over lit, leaving considerable room for improvement (US DOE 2003).

Upgrade	Category
Reduced Outside Air	HVAC ³
Active Chilled Beams	HVAC
Thermostat Settings <ul style="list-style-type: none"> • Schedule Delay • Sliding Schedule 	HVAC
External Shading	Solar Gain
Maximum Window Area <ul style="list-style-type: none"> • Maximum of 40% • Maximum of 30% 	Solar Gain
Building Orientation	Solar Gain
Window Orientation ⁴ <ul style="list-style-type: none"> • Minimize E/W Windows – Height • Minimize E/W Windows – Width • Minimize E/W Window, Maximize N/S Windows 	Solar Gain
Lighting Power Density	Lighting
Increased Insulation	Thermal Performance
Argon-Filled Windows	Thermal Performance

Table 1. Energy efficiency projects and associated categories.

Many of the modeled projects were designed based on the Advanced Energy Design Guide for Small to Medium Office Buildings reports for both 30 percent and 50 percent energy savings (ASHRAE *et al* 2004; ASHRAE *et al* 2011). These reports will henceforth

³ HVAC – Heating, Ventilation, and Air Conditioning

⁴ Windows were modeled with the orientation upgrade: exterior walls facing cardinal directions

be referred to as the 30 percent EDG and the 50 percent EDG. Duke lies in climate zone four, which was used to determine the specifications of each recommendation.

PROJECT SPECIFICS

REDUCED OUTSIDE AIR

Providing outside air to a space can improve indoor air quality and make a building feel less stuffy. Air handling units are set with a minimum percentage of outdoor air to maintain good indoor air quality. However, outside air is typically further from the air temperature needed to meet the cooling and heating load of the space than the recirculating air already in the system. Thus, it takes more energy to cool or heat the return air once it has been mixed with the incoming outside air. Rubenstein was designed to require 17 to 21 percent minimum outdoor air. According to the 30 percent EDG, 15 percent minimum outdoor air will reduce the energy needed to heat and cool air while still maintaining acceptable indoor air quality levels (ASHRAE *et al* 2004).

ACTIVE CHILLED BEAMS

Chilled beams, a form of highly efficient space heating and cooling, are most efficient in spaces that are routinely occupied, such as offices. Classrooms and conference rooms are not as suitable to this technology. For this reason, the chilled beam systems were modeled just for the exterior offices on the first and second floors, with traditional HVAC units assigned to the rest of the conditioned spaces.

In active chilled beam systems, ventilation air from a central air-handling unit is supplied to either side of 2 vertical cooling coils (Figure 2). This creates a negative pressure area between the two coils, which induces airflow through the coils. The coils cool the warm air from the room; this cooled air mixes with the air being forced through the ventilation nozzles and is pushed out to the room. Thus, air is forced through the beams and out into the room much like cooled air is forced into the space in a traditional ventilation system. The design specifications for the system were drawn from the Trox Type DID632 chilled beam system with eight-foot beams, which is going to be installed in the forthcoming Environmental Hall project (Trox 2011).

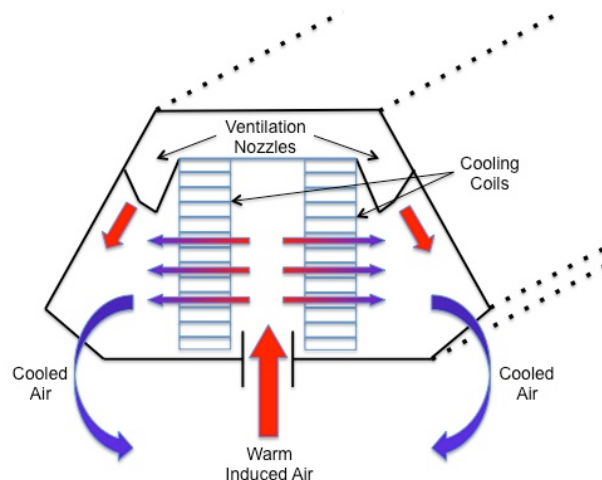


Figure 2. Active chilled beam schematic.
From Energy Design Resources
(<http://www.energydesignresources.com/resources/e-news/e-news-69-chilled-beams.aspx>).

THERMOSTAT SETTINGS

The building thermostats were designed to maintain winter temperatures of 70 degrees and summer temperatures of 76 degrees. At set times, the thermostats are allowed to drift several degrees above the cooling temperature and below the heating temperature so that the air handlers do not have to maintain those temperatures when the building is unoccupied. These times are typically 8pm to 5am. At 5am, the HVAC units come on to bring the building back to the thermostat set points. Two different thermostat schedules were modeled: a schedule delay and a sliding schedule.

A schedule delay allows the thermostats to stay at drift points until 7am. While there may be some building users present before 7am, the drift points can be manually overridden by these users. Alternatively, gradually changing the drift point over a period of several hours in order to bring the indoor air temperature back to the set point might use less energy. Thermostat drift points were changed to bring the temperature back to the set point at a speed of one or two degrees per hour, as seen in Figure 3.

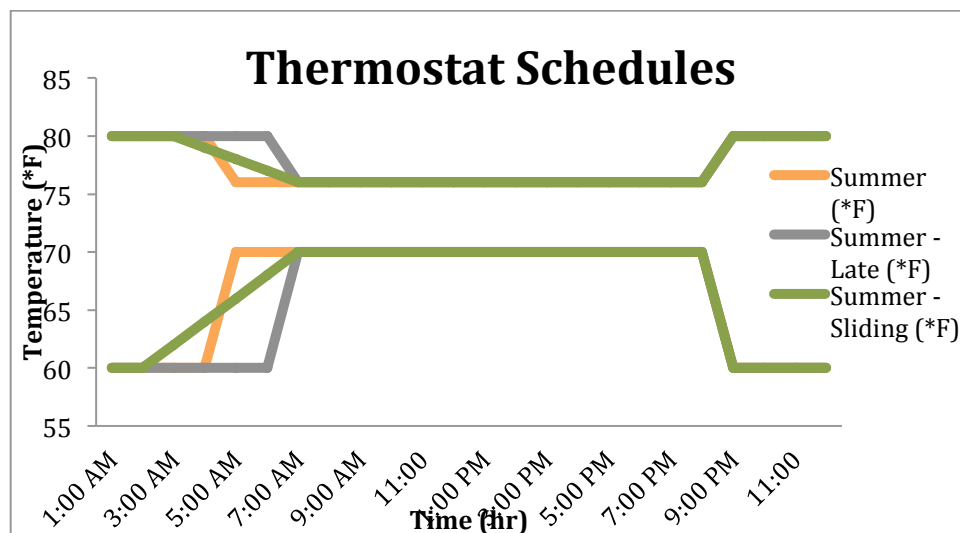


Figure 3. Thermostat schedules, actual and proposed.

EXTERNAL SHADING

External shades can reduce solar heat gain in the summer by up to 80 percent, as well as provide useful heating in the winter (Sustainable Energy Authority). Because the sun is higher in the sky during the summer months, overhangs shade windows from hot summer sun while allowing the winter sun to penetrate (Figure 4). The projection factor is a measure of the ratio between the height of the overhang above the window sill to the projection of the overhang. For climate zone four, a projection factor of 0.5 is recommended (ASHRAE *et al* 2004). The majority of the windows in Rubenstein are eight feet tall, so an overhang installed one foot above the top of the window (nine feet above the window sill) would need to project out 4.5 feet.

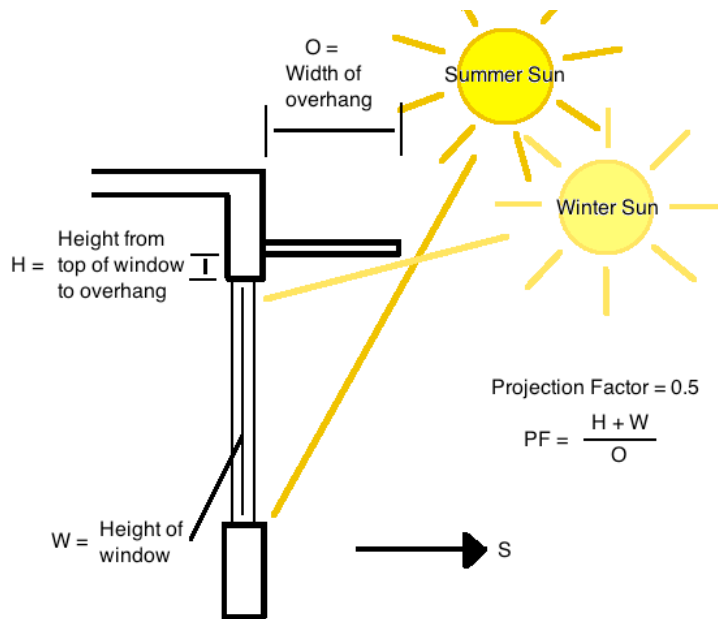


Figure 4. Illustration of external shading. Adapted from ASHRAE *et al* 2004.

MAXIMUM WINDOW AREA

The ratio of windows to exterior walls should be between 20 and 40 percent (ASHRAE *et al* 2004; ASHRAE *et al* 2011). However, most of the exterior offices have ratios of 49 percent. Limiting the windows to no more than 40 percent of the wall area reduces heat loss, because even the most efficient windows transfer heat more readily than a well-insulated wall. Two scenarios were modeled, one limiting windows to no more than 40 percent of the wall area, another limiting windows to no more than 30 percent of the wall area.

BUILDING ORIENTATION

In warm climates, shading can be added to north and south facades to reduce glare and solar gain. However, east and west facades are not as easy to shade. Therefore, the building should be oriented so that its longest exterior walls face north and south, and its shortest walls face east and west to take full advantage of the benefits of the ability to shade the sun (Figure 5). Rubenstein is oriented similarly to the “bad” orientation in Figure 5, with a corner facing north. This option rotates the building footprint 30 degrees counterclockwise so that the northeast wall becomes the north wall, the “okay” orientation in the figure. To achieve the “best” orientation, Rubenstein would have to be completely redesigned, which is outside the scope of this project.

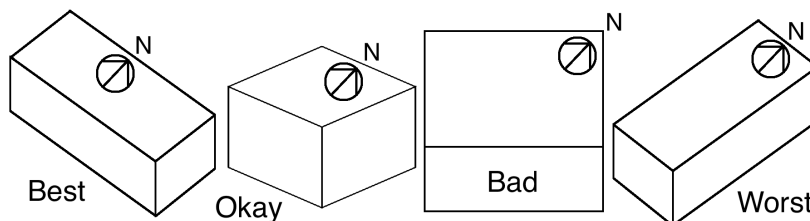


Figure 5. Building orientation for maximizing northern and southern exposures. Adapted from ASHRAE *et al* 2004.

WINDOW ORIENTATION

Provided that the building is oriented in either the “best” or “okay” direction (as in Figure 5), the windows should be minimized on the east and west walls and maximized on the north and south walls to take full advantage of the heating capacity of the winter sun and the ability to shade the summer sun. East and west walls are much more difficult to shade, and so should be used sparingly. With the same orientation as the previous upgrade (see Building Orientation), three scenarios were modeled: shorter windows on the east and west sides, narrower windows on the east and west sides, and a combination of smaller windows on the east and west sides with larger windows on the north and south sides (but still maximized at 40 percent of the wall area).

LIGHTING POWER DENSITY

Lighting is typically responsible for about 11.5% of educational building energy use (US DOE 2003). With careful design, the amount of lighting in a building can be reduced without sacrificing necessary lumens. Limiting the lighting load to 0.9 W per square foot could have a significant impact, since the current lighting load is an average of 1.8 W per square foot.

INCREASED INSULATION

To minimize thermal losses, the R-value of the walls, floors, and roofs should be maximized, to the extent possible. Additionally, U-values of windows should be minimized to limit thermal losses. Because traditional insulation is already used, R-7.5 rigid foam insulation should be added on top of the steel framing and cavity insulation to provide a continuous insulating barrier. This will reduce the impact of thermal breaks caused by the steel framing, which conducts heat. Similarly, R-7.5 rigid foam insulation should be installed on the slab-on-grade flooring in the basement. Finally, the attic should have R-38 batting and R-7.4 rigid foam for continuous insulation (ASHRAE *et al* 2004; ASHRAE *et al* 2011).

ARGON-FILLED WINDOWS

The windows in Rubenstein are designed to be double paned, with air in between the glass for thermal insulation and low emissivity coatings to reduce solar gains. Using argon in between the windowpanes has been shown to increase the thermal insulation by over 1.3 times compared to air (Butkus, Vladišauskas, Jakevičius 2004).

METRICS

The Trace model generated total energy use in Btu per square foot-year. Additionally, purchased steam and chilled water were measured in therms per year. Finally, electricity was measured in kWh per year. To compare energy use across the building, therms of steam and chilled water and kWh of electricity were converted to Btu.

Costs were estimated with the help of a building construction cost estimation consultant in terms of cost per square foot (Syler, 2012; Appendix B). This was multiplied by the square footage of Rubenstein to obtain the total estimated capital costs of the project. The utility costs (Appendix A) and the annual maintenance costs (estimated by FMD) were used to determine the annual operating costs. Because many projects have zero upfront cost, the “first year cost” was used to compare projects. First year cost is determined by subtracting the projected utility savings from the capital cost. For projects with no upfront cost, this leads to a negative first year cost, indicating that these projects have a net savings in the first year.

The cost of an energy efficiency project can be expressed as the cost in dollars per unit of energy saved. In this case the first year cost was used to determine the cost per unit of energy saved. Projects were ranked based on this cost to help determine which projects to pursue.

Finally, greenhouse gas emissions were calculated for each model based on the various utilities consumed. The conversion factor for electricity, steam, and chilled water were based on the output and efficiencies of the plant generating the utility. For electricity, the Tennessee Valley subregion (of which Durham, NC is a part), the estimated carbon emissions for electricity are 0.00077 tons per kilowatt-hour (eGRID 2010).

RESULTS & DISCUSSION

MODEL CALIBRATION & ASHRAE COMPARISON

First, the baseline model was compared to the actual utility consumption of Rubenstein from fiscal year 2011 (June 2010 through May 2011). Adjustments were made to schedules and settings until the baseline utility consumption was sufficiently similar to the actual usage of the building (Figure 6a-b). The modeled utility consumption was within 20 to 30 percent of the actual usage. This discrepancy is greater than was initially desired. However, there is only one year of data available for Rubenstein because significant changes were made to the thermostat and HVAC schedules in 2010, leading to a large reduction in overall energy use. The model uses weather data based on a ten-year average for outdoor air temperature. It is expected that an average of several years of data from Rubenstein would match more closely with the modeled utilities. Because the model utilities follow similar patterns to the actual utilities, the 20 to 30 percent difference is acceptable for this application.

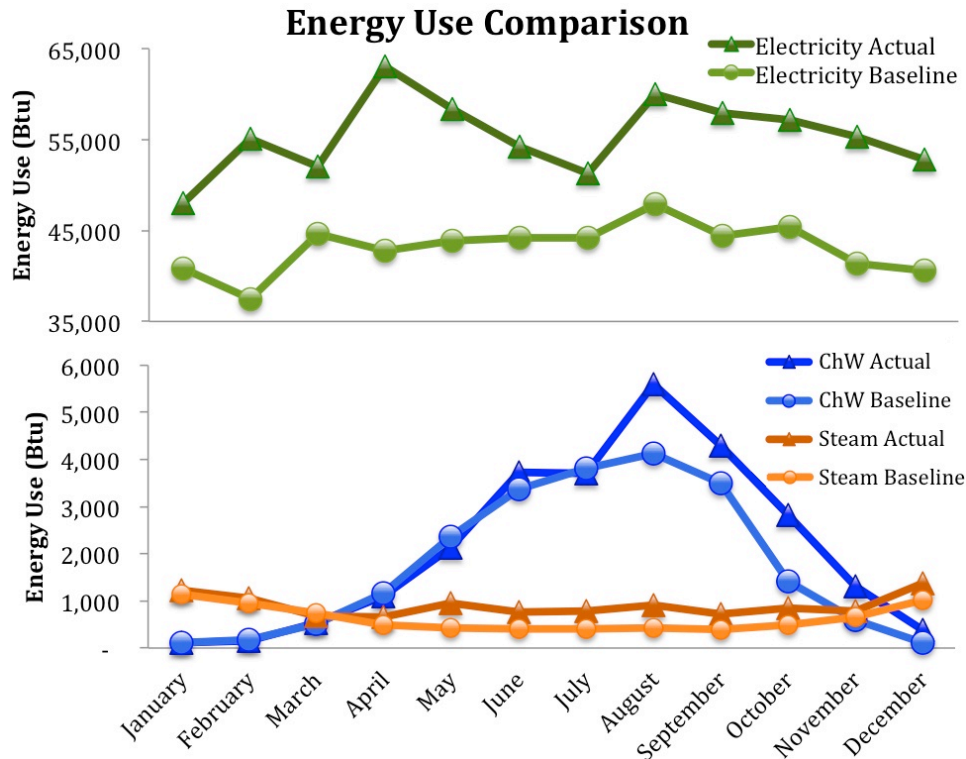


Figure 6. (a) Upper: Electricity usage from Rubenstein versus the model. (b) Lower: Chilled water and steam usage from Rubenstein versus the model.

To establish the magnitude of energy reduction required, the ASHRAE model was compared to the baseline model (Figure 7). As shown, the Baseline model already uses less energy than the ASHRAE model. In fact, the Baseline consumes 16 percent less energy than the ASHRAE model. The actual consumption of the building is 10 percent less than the ASHRAE model. While this is commendable, a new building would have to implement additional efficiency projects in order to meet the NC ECC.

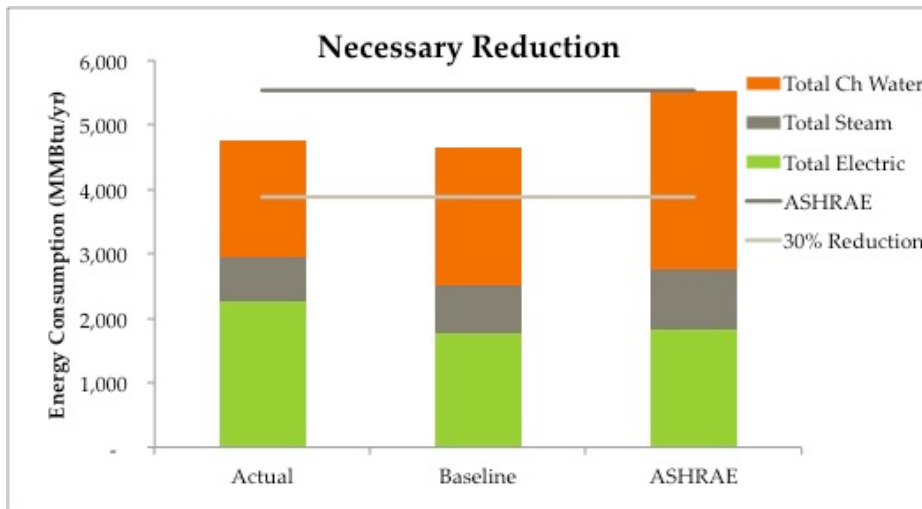


Figure 7. Baseline model versus ASHRAE model.

PROJECT COMPARISONS

The total energy consumption of each project is broken out by end-use type (Figure 8).

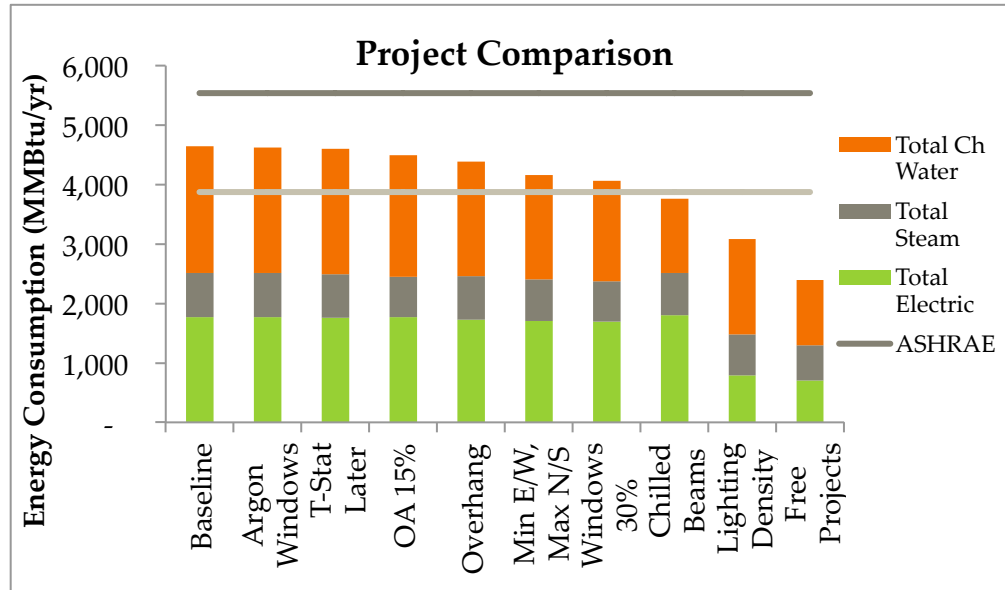


Figure 8. Project energy use comparison for chilled water, steam, and electricity.

Of the energy efficiency interventions mentioned above, two of them use more energy than the Baseline: building orientation and increased R-values. For the three groups of projects mentioned earlier (Table 1), only the project with the greatest energy reduction was selected. With thermostat settings, the late start schedule used less energy than the sliding schedule. For window orientation, minimizing east- and west-facing windows while maximizing north- and south-facing windows used the least energy of the three options. Finally, for the window area project, 30 percent window area used less energy than 40 percent window area. Actual reductions are presented in Table 2.

<i>Upgrade</i>	<i>Category</i>	<i>Energy Saved (Btu/yr)</i>	<i>CO₂ Saved (MT/yr)</i>	<i>Cost Savings (\$/yr)</i>	<i>Capital Cost (\$)</i>	<i>1st Year Cost (\$)</i>	<i>Simple Payback (yrs)</i>
Chilled Beams	HVAC	839.98	1.91	\$11,333.32	\$25.00	\$719,416.68	63
Argon Windows	Thermal Performance	18.71	(0.31)	\$252.58	\$0.65	\$18,746.92	74
Direction	Solar Gain	(10.03)	429.19	\$0.00	\$0.00	\$0.00	Never
Lighting Density	Lighting	1,476.99	205.23	\$25,968.18	\$0.00	\$(25,968.18)	Instant
OA 15%	HVAC	146.03	5.73	\$2,225.37	\$0.00	\$(2,225.37)	Instant
Overhang	Solar Gain	241.21	10.15	\$3,553.46	\$16.36	\$474,649.34	134
R-Vales	Thermal Performance	(168.72)	429.19	\$0.00	\$3.65	\$106,689.50	Never
T-Stat Later	HVAC	42.30	2.73	\$668.23	\$0.00	\$(668.23)	Instant
Windows 30%	Solar Gain	550.08	23.56	\$8,154.58	\$0.00	\$(8,154.58)	Instant
Windows 40%	Solar Gain	346.05	429.19	\$418.88	\$0.00	\$(418.88)	Instant
Chilled Beams	HVAC	839.98	1.91	\$11,333.32	\$25.00	\$719,416.68	63
Total Savings ⁵		3,661.35	1,536.57	\$52,574.60	\$42.01	\$1,175,378	22

Table 2. Energy, carbon emissions, and cost reductions; upfront costs of projects.

HVAC

Setting the minimum outside air requirement to 15 percent instead of 17 to 21 percent will yield a three percent reduction in overall energy use compared to the baseline model and save \$2,225 per year. Setting the thermostat schedule to start later will reduce energy use by about one percent, yielding \$668 in annual savings. These two projects are cost-free, so the payback is immediate. Finally, the active chilled beam system will result in 19 percent less energy use over the baseline and 32 percent over the ASHRAE model, which is sufficient to meet the entire NC ECC in itself. A chilled beam system such as this one will cost roughly \$25 per square foot (\$730,750 total), but only creates about \$11,333 in utility bill savings annually, which is a simple payback period of about 64 years.

⁵ Includes all window projects. A new building would include only one of the three window projects.

SOLAR GAIN

The Direction project, which is changing the orientation of the building, increased the building's energy consumption. However, maximizing north- and south-facing windows while minimizing east- and west-facing windows, which is based on the Direction intervention, has a projected energy reduction of 10 percent over the baseline. This will create \$6,803 in annual energy savings. In most cases, ensuring that the building orientation is primarily north-south will have no cost impact on the project, provided this is a goal from the outset of the project. Alternatively, leaving the building in its current orientation, limiting window area to 30 percent will allow an energy reduction of about 13 percent compared to the baseline and \$8,155 in energy savings annually. This project essentially has no net upfront cost because windows cost more than walls, so the savings will be realized immediately. Installing overhangs on windows (current orientation) will save an estimated six percent of energy use over the baseline and \$3,553 in energy savings annually. The estimated capital cost of installing overhangs on the southeast and southwest windows is \$478,203, with a payback period of over 100 years, this project will not pay itself back in the lifetime of the building.

THERMAL PERFORMANCE

Increased insulation in the walls, floor, and roof did not lead to an energy reduction. This is very curious, as increasing the R-value of the walls, roof, and floor of a building have been shown to produce considerable energy savings across many building types and climate zones. The Trace software support team said that it is possible for increased R-values to increase the impact of internal loads. However, through consultations with FMD, this does not seem likely. FMD plans to continue investigating R-values as a potential energy efficiency project. Argon-filled windows will only lead to a 0.4 percent reduction in energy use over the baseline and only \$253 in energy savings per year. At a capital cost of \$19,000, this project will not pay itself back in the lifetime of the building.

LIGHTING

Reducing the lighting density to 0.9 watts per square foot for the entire building will lead to a 33 percent reduction in energy use compared to the baseline, and 44 percent compared to the ASHRAE model, which is enough to meet the NC ECC alone. This project will save an estimated \$25,968 per year in energy costs. Installing fewer fixtures or fewer bulbs within the same fixture will be sufficient for the lighting reduction. Thus, this project has zero upfront cost and will provide immediate benefit. It is notable that this option is also the most subject to building occupant behavior, and thus is likely the least reliable estimate.

SUPPLY CURVE

A supply curve for energy efficiency was built from the above project data. For each project, the first year cost was calculated and used to rank projects from lowest to highest cost. From there, the cumulative energy savings were calculated. The resulting graph (Figure 9) illustrates how much energy each project will save by the width of the bar and how much the project will cost in the first year by the height of the bar. The upper figure (Figure 9a) illustrates projects with a net positive cost during the first year. These projects have high capital costs that even when offset by energy savings in the first year they still have a positive cost. The lower figure (Figure 9b) illustrates projects with a net negative cost during the first year. These projects have no upfront capital costs and also save money during the first year of operation.

This will provide a valuable tool for FMD. First of all, it shows very clearly the “low-hanging fruit” that save money in the first year. Additionally, designers can decide what price they are willing to pay per unit of energy saved, draw a horizontal line at that price, and see which projects meet that criteria. Alternatively, designers can determine what level of energy reduction they want to achieve, draw a vertical line at that level, and easily see what projects are needed to meet the goal and how much it will cost. Finally, this tool is easily explained to lay audiences, and conveys the most crucial information in one figure.

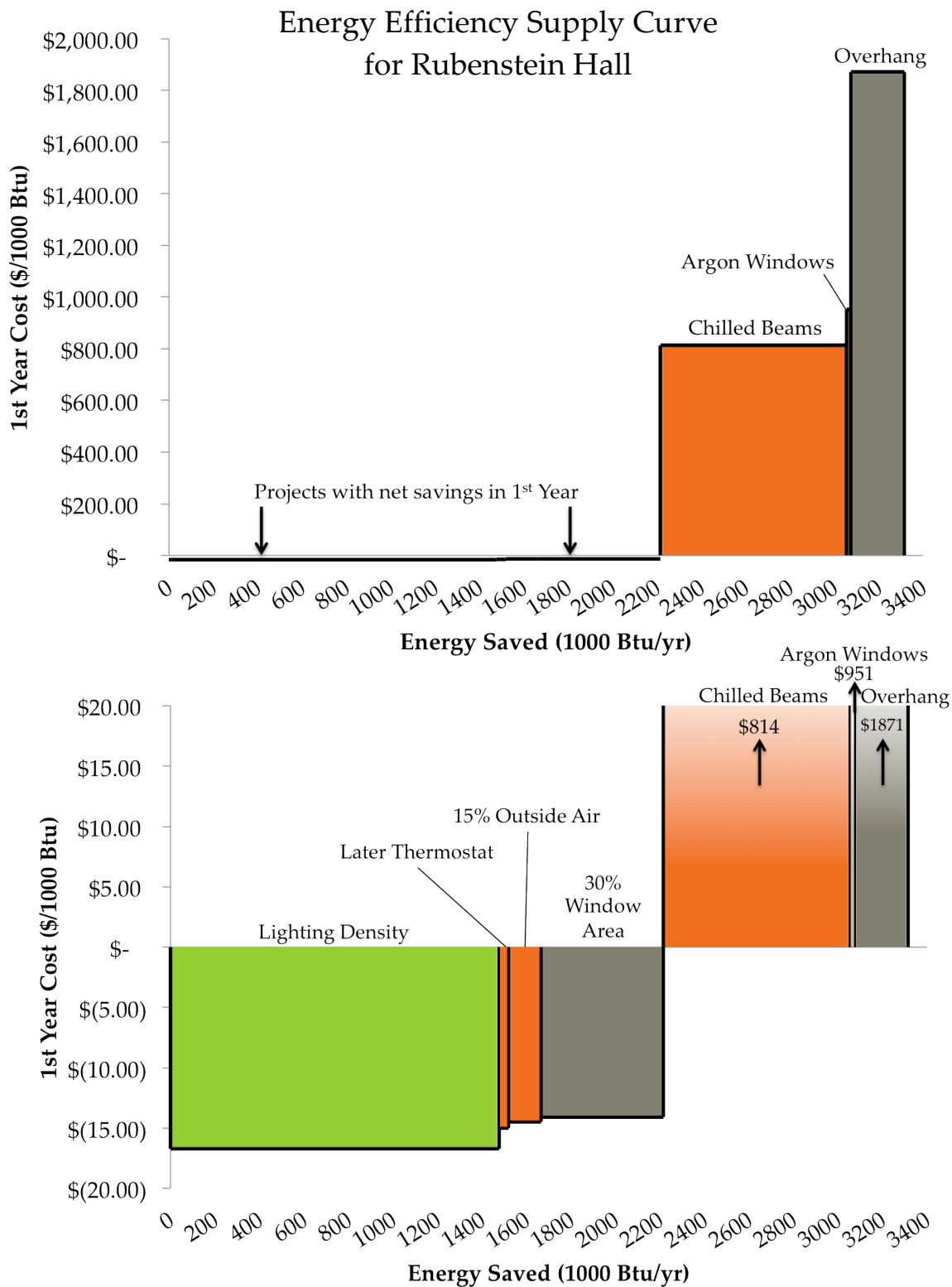


Figure 9. Energy efficiency supply curve showing potential energy and monetary savings. Upper (a): Projects with net positive first year cost. Lower (b): Projects with net negative first year cost.

Given Duke’s goal of climate neutrality by 2024, greenhouse gas emissions are also important to new building design. Duke will continue to grow and erect new buildings, which will make the greenhouse gas emissions goal more difficult to achieve. Thus, buildings should be designed to produce the least amount of greenhouse gas emissions as possible. This analysis shows that while some of the projects will provide greenhouse gas emissions reductions compared to the baseline, many of them are quite small (Figure 10). One reason for this is that most of the projects provide the most significant reductions in steam and chilled water, which are less carbon-intensive than electricity.

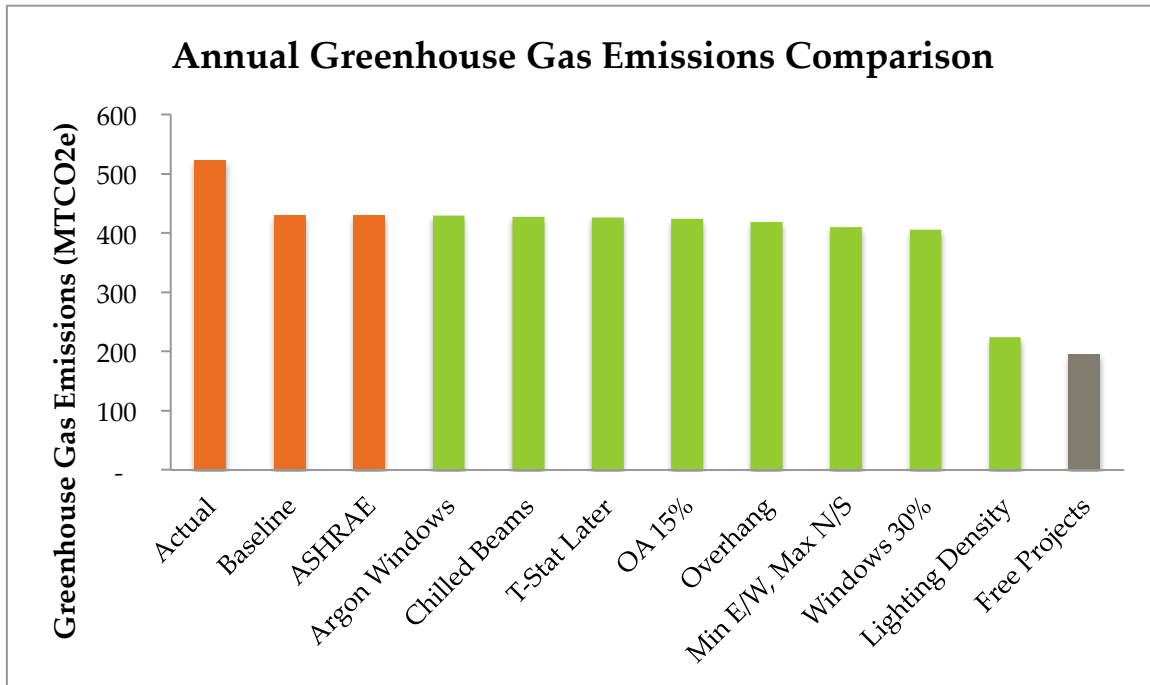


Figure 10. Total greenhouse gas emissions reductions expected from each project.

As evidence of this, the average greenhouse gas emissions reduction per million Btu of energy reduced is 0.05 metric tons of carbon dioxide equivalent per million Btu, but the same metric for the lighting density project is 0.14 metric tons of carbon dioxide equivalent per million Btu. Thus, the lighting density project provides the greatest reduction in greenhouse gas emissions. The benefits of these projects really lie in the energy and associated cost savings, not in greenhouse gas emissions.

RECOMMENDATIONS

There are a number of efficiency projects that make solid business sense to implement and will help Duke achieve the NC ECC. The projects with no upfront costs are recommended for new buildings to garner additional energy savings (Table 3). Because two projects involving windows would produce energy savings, the one with greater potential savings – limiting windows to 30 percent of the wall area – was selected and

included in the following analysis. However, reductions would still be realized if the other project – minimizing east and west facing windows while maximizing north and south facing windows – was implemented. The four recommended projects would reduce the operational costs of the building without adding any costs to construction. In total, these projects are expected to save 2,275 Btu of energy, \$37,016 annually.

Upgrade	Category	Energy Savings (Btu/yr)	Carbon Savings (MT/yr)	Economic Savings (\$/yr)	Capital Cost (\$)	Simple Payback (yrs)
Lighting Density	Lighting	1,476.99	205.23	\$25,968.18	\$0.00	Instant
30% Windows	Solar Gain	550.08	23.56	\$8,154.58	\$0.00	Instant
OA 15%	HVAC	146.03	5.73	\$2,225.37	\$0.00	Instant
T-Stat Later	HVAC	42.30	2.73	\$668.23	\$0.00	Instant
Total Savings		2,257.70	237.25	\$37,016.36	\$0.00	Instant

Table 3. Recommended project details.

For window area, there are three project options, all of which will accrue energy savings: 30 percent window area, 40 percent window area, and minimizing east and west window area while maximizing north and south window area (at a maximum of 40 percent) when the building is oriented in the cardinal directions. The 30 percent window area project saves the most energy and allows the building to be oriented in any direction, and thus was chosen for the general recommendation. However, either of the other two projects may be more appropriate depending on the building design goals. For example, more glass may be desirable to achieve a particular aesthetic. Because all three projects have no upfront cost, the decision can be made building-by-building.

In addition to the recommendations for new construction, a few of the projects investigated can be easily implemented in existing buildings. It is recommended that FMD implement the projects in Table 4. These projects are recommended for Rubenstein, but should also be considered for other campus buildings. These projects would have some associated labor costs for their implementation, but these would be quite small. The three recommended retrofit projects would save 1,665 Btu of energy and \$28,862 annually. These types of savings will add up quickly if applied broadly across campus.

Upgrade	Category	Energy Savings (Btu/yr)	Carbon Savings (MT/yr)	Economic Savings (\$/yr)	Capital Cost (\$)	Simple Payback (yrs)
Lighting Density	Lighting	1,476.99	205.23	\$25,968.18	\$0.00	Instant
OA 15%	HVAC	146.03	5.73	\$2,225.37	\$0.00	Instant
T-Stat Later	HVAC	42.30	2.73	\$668.23	\$0.00	Instant
Total Savings		1,665.32	213.69	\$28,861.78	\$0.00	Instant

Table 4. Recommended retrofit project details.

CONCLUSION

There is great potential for increasing the energy efficiency of new buildings on campus using both the new NC ECC and Duke’s LEED+ policy as a guide. There are also considerable low- and no-cost upgrades available to existing buildings. Using Trace to model different scenarios is a more accurate way to calculate potential savings than off-the-cuff estimates based on system size or other engineering characteristics. The Trace model can show interactions between systems and the effect of scheduling.

That being said, it is difficult for FMD to set aside the time of existing employees to model existing buildings in search of efficiency projects. Undergraduate students have been deemed unsuitable for the task, as they do not have sufficient training in building science or facilities management. However, there are many Master of Environmental Management students in the Nicholas School who would be interested in this type of work. Learning Trace and modeling a campus building would make a great summer internship and masters project and provide highly useful information for FMD. This type of collaboration is highly encouraged by the Nicholas School and has the potential to be valuable to both students and FMD.⁶

This project has used basic energy modeling with the Trace software. Several variables were not directly considered and could be incorporated into future research. For example, while an inflation rate was used for fuel prices, these prices were expected to remain otherwise stable. Incorporating a fuel price projection curve into the analysis would provide a more accurate picture of future operating costs. Additionally, performance degradation was not integrated into the model. Future models could consider the impact of regular maintenance on the life of system as well as the ultimate need to replace equipment.

⁶ For more specific recommendations, please see Appendix C.

Finally, an optimization would be ideal for choosing the sequence of energy efficiency interventions. True optimization would use an algorithm to determine the least cost path to energy efficiency by maximizing energy use reduction while minimizing cost. This process is far more involved than the model presented here, but would be a valuable asset to Duke, in particular the FMD staff.

In conclusion, the energy efficiency supply curve generated in this report can inform decision making during the design phase of new campus buildings, as well as guide efficiency upgrades in existing buildings. Overall, Duke should have no problem meeting the NC ECC. That being said, there are still operational and physical changes that can lead to reduced energy use, which should be pursued to the fullest extent.

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APPENDIX A

SCHEDULES

Thermostat Schedules

Cooling	Start Time	End Time	Temperature (*F)
Weekdays	Midnight	5am	80
	5am	8pm	76
	8pm	Midnight	80
Saturday	Midnight	7am	80
	7am	5pm	76
	5pm	Midnight	80
Sunday	Midnight	9am	80
	9am	5pm	76
	5pm	Midnight	80

Heating	Start Time	End Time	Temperature (*F)
Weekdays	Midnight	5am	60
	5am	8pm	70
	8pm	Midnight	60
Saturday	Midnight	7am	60
	7am	5pm	70
	5pm	Midnight	60
Sunday	Midnight	9am	60
	9am	5pm	70
	5pm	Midnight	60

Lighting Schedules

Corridors	Start Time	End Time	Percent Usage
Year Round	Midnight	Midnight	100%

Mechanical Rooms	Start Time	End Time	Percent Usage
Weekday	Midnight	7am	0%
	7am	4pm	25%
	4pm	Midnight	0%
Weekend	Midnight	Midnight	0%

Classrooms	Start Time	End Time	Percent Usage
Academic Year - Weekday	Midnight	5am	0%
	5am	8am	30%
	8am	8pm	100%
	8pm	Midnight	0%
Academic Year - Weekend	Midnight	9am	0%
	9am	5pm	50%
	5pm	Midnight	0%
Summer - Weekday	Midnight	8am	0%
	8am	5pm	75%
	5pm	Midnight	0%
Summer - Weekend	Midnight	9am	0%
	9am	5pm	50%
	5pm	Midnight	0%

Offices	Start Time	End Time	Percent Usage
Weekday	Midnight	8am	0%
	8am	5pm	100%
	5pm	8pm	30%
	8pm	Midnight	0%
Weekend	Midnight	9am	0%
	9am	5pm	10%
	5pm	Midnight	0%

Appliances

Coffee Maker	Start Time	End Time	Percent Usage
Weekday	Midnight	7am	0%
	7am	7pm	75%
	7pm	Midnight	0%
Weekend	Midnight	Midnight	0%

Dishwasher	Start Time	End Time	Percent Usage
Weekday	Midnight	5pm	0%
	5pm	6pm	25%
	6pm	Midnight	0%

Elevator	Start Time	End Time	Percent Usage
Elevator	Midnight	7am	0%
	7am	7pm	20%
	7pm	Midnight	0%

	Start Time	End Time	Percent Usage
Microwave	Midnight	7am	0%
	7am	8am	50%
	8am	Noon	10%
	Noon	1pm	50%
	1pm	7pm	10%
	7pm	Midnight	0%

	Start Time	End Time	Percent Usage
Photocopier	Midnight	7am	0%
	7am	5pm	20%
	5pm	10pm	10%
	10pm	Midnight	0%

	Start Time	End Time	Percent Usage
Plasma Screen TV	Midnight	7am	10%
	7am	5pm	100%
	5pm	10pm	75%
	10pm	Midnight	10%

	Start Time	End Time	Percent Usage
Projector	Midnight	6am	0%
	6am	8am	50%
	8am	Noon	100%
	Noon	1pm	30%
	1pm	5pm	100%
	5pm	6pm	50%
	6pm	Midnight	0%

Refrigerator	Start Time	End Time	Percent Usage
	Midnight	7am	30%
	7am	7pm	50%
	7pm	Midnight	30%

Vending Machine	Start Time	End Time	Percent Usage
	Midnight	Midnight	100%

PLANT INPUTS

Chiller Plant			
Capacity	Fuel	Cost, \$/ton hour	GHG Emissions, MTCO ₂ e/ton hour
	Electricity	\$10.75	

Steam Plant			
Capacity	Fuel	Cost, \$/lb	GHG Emissions, MTCO ₂ e/lb
	Natural Gas	\$165.00	

APPENDIX B

INTERVENTION SPECIFICATIONS

ASHRAE	
Lighting Density	1.2 W/sq ft
Main heating & cooling supply	To be calculated
Ventilation	
Apply ASHRAE Std 62.1-2004/2007?	Yes
Type	Default Std62
Clg Ez	Ceiling clg supply, ceiling return
Htg Ez	Ceiling supply > trm + 15°F
System Ventilation Flag	ASHRAE Std 62.1-2004/2007 w/ Vent Reset
Construction	
Roof U-Factor	0.0455
Wall U-Factor	0.0500
Floor U-Factor	0.5871

Active Chilled Beams	
Cooling Design Setpoint (*F)	52
Heating Design Setpoint (*F)	52.5
Direct dehumidification, max room RH	65%

Auxiliary Cooling Coil	
Capacity	110 Btuh/cfm primary airflow
Control	Activate after primary system
Type	Active Chilled Beams
Fan	None
Auxiliary Heating Coil	
Capacity	100% of Design Capacity
Control	Activate after primary system
Type	Active Chilled Beams
Main Coils	
Main cooling & heating coil capacity	100% of design minus Aux Capacity
Preheat & humidification coils capacity	100% of Design Capacity
Fans	
Primary	BI Centrifugal variable speed motor
Primary Static Pressure	3 in. wg
Return	BI Centrifugal variable speed motor
Return Static Pressure	2 in. wg
Cost (per sq ft)	\$25.00

Argon Windows	
Original Selection	6mm Dbl Low-E Glass (e2= 0.1), Clr 13mm Air
Alternative Selection	6mm Dbl Low-E Glass (e2= 0.1), Clr 13mm Argon
Cost (per sq ft)	\$0.67

Direction	
Original Selection	Global rotate 30 degrees
Alternative Selection	Global rotate 0 degrees
Cost (per sq ft)	\$0

Lighting Power Density	
Original Selection	As built
Alternative Selection	0.9 W/sq ft
Cost (per sq ft)	\$0

Min E/W, Max N/S	
Original Selection	As built
Alternative Selection	E/W windows: 30% of wall area
	N/S windows: 40% of wall area
Cost (per sq ft)	\$0

Narrow E/W	
Original Selection	As built
Alternative Selection	Decrease window width by average of 10%
Cost (per sq ft)	\$0

15% Outside Air	Air handler	Min % Outside Air
Original Selection	AHU1	
	AHU2	
	AHU3	
	AHU4	
	AHU5	
	AHU6	
Alternative Selection	All Units	15%
Cost (per sq ft)	\$0	

Overhang		
Original Selection	None	
Alternative Selection	Ratio	0.5
	Height above sill	9 ft
	Projection	4.5 ft
	Width beyond sides	0.5 ft each side
Cost (per sq ft)	\$16	

R-Vales	Construction	Insulation
Original Selection	Walls	R-13
	Roof	R-20
	Floor	2" Insulation
Alternative Selection	Walls	R-13 + R-7.5 ci
	Roof	R-38 + R-7.5 ci
	Floor	4" Insulation + R-7.5 ci
Cost (per sq ft)		

Short E/W	
Original Selection	As built, most windows 8' height
Alternative Selection	Reduce window height to 7'
Cost (per sq ft)	\$0

T-Stat Later				
Original Selection	Cooling	Start Time	End Time	Temperature (*F)
	Weekdays	Midnight	5am	80
		5am	8pm	76
		8pm	Midnight	80
	Saturday	Midnight	7am	80
		7am	5pm	76
		5pm	Midnight	80
	Sunday	Midnight	9am	80
		9am	5pm	76
		5pm	Midnight	80
	Heating			
	Weekdays	Midnight	5am	60
		5am	8pm	70
		8pm	Midnight	60
	Saturday	Midnight	7am	60
		7am	5pm	70
		5pm	Midnight	60
	Sunday	Midnight	9am	60
		9am	5pm	70
		5pm	Midnight	60
	Alternative Selection	Cooling	Start Time	End Time
Weekdays		Midnight	7am	80
		7am	8pm	76
		8pm	Midnight	80
Saturday		Midnight	9am	80
		9am	5pm	76
		5pm	Midnight	80
Sunday		Midnight	9am	80
		9am	5pm	76
		5pm	Midnight	80
Heating				
Weekdays		Midnight	7am	60
		7am	8pm	70
		8pm	Midnight	60
Saturday		Midnight	9am	60
		9am	5pm	70
		5pm	Midnight	60
Sunday		Midnight	9am	60
		9am	5pm	70
		5pm	Midnight	60
Cost (per sq ft)		\$0		

T-Stat Sliding				
Original Selection	Cooling	Start Time	End Time	Temperature (*F)
	Weekdays	Midnight	5am	80
		5am	8pm	76
		8pm	Midnight	80
	Saturday	Midnight	7am	80
		7am	5pm	76
		5pm	Midnight	80
	Sunday	Midnight	9am	80
		9am	5pm	76
		5pm	Midnight	80
	Heating			
	Weekdays	Midnight	5am	60
		5am	8pm	70
		8pm	Midnight	60
	Saturday	Midnight	7am	60
		7am	5pm	70
		5pm	Midnight	60
	Sunday	Midnight	9am	60
		9am	5pm	70
		5pm	Midnight	60
Alternative Selection	Cooling	Start Time	End Time	Temperature (*F)
	Weekdays	Midnight	4am	80
		4am	5am	79
		5am	6am	78
		6am	7am	77
		7am	8pm	76
		8pm	Midnight	80
	Weekends	Midnight	6am	80
		6am	7am	79
		7am	8am	78
		8am	9am	77
		9am	5pm	76
		5pm	Midnight	80
	Heating			
	Weekdays	Midnight	3am	60
		3am	4am	62
		4am	5am	64
		5am	6am	66
		6am	7am	68
		7am	8pm	70
8pm		Midnight	60	
Weekends		Midnight	5am	60
	5am	6am	62	
	6am	7am	64	
	7am	8am	66	
	8am	9am	68	
	9am	5pm	70	
5pm	Midnight	60		
Cost (per sq ft)				\$0

Windows 30%	
Original Selection	As built, office windows = 8' x 8'
Alternative Selection	Office windows = 5.6' x 7', all windows 30% of wall area or less
Cost (per sq ft)	\$0

Windows 40%	
Original Selection	As built, office windows = 8' x 8'
Alternative Selection	Office windows = 6.5' x 8', all windows 40% of wall area or less
Cost (per sq ft)	\$0

APPENDIX C

This project uncovered significant potential energy and monetary savings in just one existing campus building, and a LEED Certified building at that. There could be countless potential projects in the remaining existing buildings that would require minimal investment by FMD to achieve. The type of modeling completed for this project provides a more detailed look at the energy use profile of a building than just looking at the historical energy usage alone. I strongly recommend modeling other existing buildings to determine what projects might be suitable to reduce energy use and cost.

In general, FMD employees do not have time to build models from scratch and test scenarios. However, there are a number of students at the Nicholas School, particularly in the Energy and Environment concentration, who are very interested in buildings and energy efficiency. Using MEMs to complete the work would not only benefit FMD and Duke greatly, but also provide relevant work experience for the students. Nevertheless, three key concerns have kept FMD from reaching out to the Nicholas School in the past. In general, students lack:

1. Sufficient course work in building science,
2. Experience and understanding of facilities management,
3. Familiarity with the Trace700 software.

A combination of courses, a facilities seminar, and software training, would effectively overcome these barriers and allow a team of MEMs to help FMD investigate building energy efficiency projects.

RECOMMENDED COURSE WORK

The following courses will prepare students for building energy modeling and evaluating energy efficiency projects. Courses marked with an asterisk (*) are required for Energy and Environment students. Students who express an interest in the project should be encouraged to take Aaron Lubeck's classes to get a more detailed look at building systems and energy efficiency in existing buildings.

Course Number	Title	Professor	Semester
ENVIRON 716L*	Modeling for Energy Systems	Dalia Patino Echeverri	Fall
ENVIRON 330*	Energy and the Environment	Lincoln Pratson	Fall
ENVIRON 301.21	Building Science	Aaron Lubeck	Spring
ENVIRON 301.22	Green Building	Aaron Lubeck	Spring
ENVIRON 298.23*	Energy Technology	Franklin Cocks, Josiah Knight	Spring

FACILITIES SEMINAR

Facilities managers at colleges and universities often pride themselves on being nearly invisible to the students, faculty, and staff at their universities. The goal is for the entire campus to operate as smoothly as possible. At Duke, FMD employees are very good at their jobs, so most students have no idea what it takes to keep Duke up and running. As a result, very few students will be prepared to complete the type of building analysis being suggested here. While the Energy and the Environment course mentioned above does talk about and often visit the chiller and steam plants on campus, students are still underprepared to work with facilities.

A one or two day seminar on facilities at Duke would bring students up to speed quickly and efficiently. If they have completed the recommended course work, it will not take much to bring them up to speed. This seminar should be put on by a variety of facilities employees, and would ideally involve tours of the steam and chiller plants, as well as an in-depth tour of at least one campus building. The goal is to introduce students to the operations and maintenance that the campus requires, as well as the systems that Duke has in place to manage such a large campus. Additionally, students will have an opportunity to meet a variety of FMD employees who they can reach out to throughout the project.

SOFTWARE TRAINING

The final barrier, lack of familiarity with the software, is easily overcome by a software training, which is offered by Trane. I attended a two-day software training seminar with several other FMD employees, which prepared me well to use the software. Bringing in an outside trainer has an associated cost, so determining how to fund the training would be a crucial step in the process of setting up an MP. Of note, the software will only run on a PC, so students will need to have access to one personally. Trace700 is installed on one computer in the "fishbowl" lab in the LSRC, and could be installed on the others in that lab (about 6 computers) to give students access.

In addition to software training, students will likely also need to be trained to read and interpret architectural plans. Much of the building parameters needed to build the model are contained within the building plans. Ideally, this training would be in conjunction with the software training. The cost of printing a set of architectural plans for each student to work off of is an additional cost of the project.

These three elements would effectively address all of FMD's concerns with allowing MEMs to complete building analysis for their MPs. Based on my experience with this MP, I think that a mutually beneficial relationship is possible between the Nicholas School and FMD.