

ecoMOD: Analyzing Energy Efficiency in Affordable Housing

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Abstract—The first home in the ecoMOD project, a design/build/evaluate initiative at the University of Virginia, is being monitored for energy and water consumption and interior and exterior air quality. Detailed data analysis is being conducted to determine whether the house is meeting its expected performance level.

I. INTRODUCTION

THE ecoMOD project began in 2004 as a multi-year design/build/evaluate initiative at the University of Virginia School of Architecture. Focused on affordability and efficient use of resources in the modular and manufactured housing industry, architecture students partnered with Piedmont Housing Alliance (PHA), a Charlottesville organization that promotes home ownership among low-income residents. Over the long term, the project will produce a minimum of four houses. To date, two have been completed (the second as a partnership for Habitat for Humanity in Mississippi) and the third is in the design phase. Each home will be equipped with a monitoring system to evaluate its performance and provide feedback to residents.

In the fall of 2005, the project scope broadened to include engineering, business, environmental science, planning, and economics students in the evaluation phase of the first ecoMOD house, called OUTin. The purpose of this phase in each iteration of the project is to publicize the benefits of green building as have been embodied in each specific home and to determine which building features give the greatest payback.

The engineers involved in the project developed and installed a monitoring system and began collecting data on energy consumption, interior and exterior temperature and humidity, carbon dioxide levels, and water flow. By spring of 2006, the monitoring system was recording data.

While preliminary data provided some insight into the effectiveness of ecoMOD's passive and active systems in reducing operating costs and improving environmental performance, more informative analyses could not be conducted until the house became occupied in February 2007.

A concrete, quantitative analysis of the environmental performance of OUTin fulfills two purposes. First, it would help identify the most efficient systems and design features for reducing energy and water consumption. Second, the analysis would facilitate the homeowners' efforts in these endeavors by increasing awareness of how daily activities affect the amount of utilities expended.

Evaluation of OUTin and other ecoMOD houses is crucial to the success of the project. Quantitative results are the most convincing tool for validating ecoMOD's claims to environmental consciousness and energy efficiency. Furthermore, there may be some elements of the house which are not performing as efficiently as expected, while others may be performing optimally. This data analysis allows both the architects and engineers to examine various systems and designs and decide whether their performance warrants continued use in the remaining houses.

II. PROJECT GOALS AND OBJECTIVES

The primary goal of this project is to deliver recommendations and conclusions on the performance of the design and systems of OUTin by analyzing data from the house. These recommendations should inform future ecoMOD designers as well as the current OUTin residents.

Analysis is facilitated by three major objectives. First, the team must design and install a comprehensive monitoring system which records various indicators of the house's performance. Next, the values collected from this monitoring system must be organized and stored in a location that is available to all students and faculty working on the evaluation phase of OUTin. Finally, a web-based data analysis tool will access the data and provide a mechanism for both graphical and numerical representation of the house's performance.

This data analysis lends credence to the efficiency of the ecoMOD designs and innovations, thus ensuring that the far-reaching benefits of the ecoMOD project are achieved. Through this project, the data analysis will help to provide education for University students, promote green building and affordable housing, and support the Charlottesville community in particular.

A. Academic Objectives

First, the continuation of the ecoMOD project carries incredible benefit for UVA students interested in the initiative. Provided that monetary support continues, the project will continue for the next few years and provide opportunities for students to learn through collaboration between professors and students from other disciplines. It also allows for students to benefit from an experience that closely simulates the project environment of a post-graduate job. Concrete analysis of the data will help ecoMOD to continue by proving that the systems in the first house are

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indeed efficient, and thus attracting more sponsors to support the ecoMOD efforts.

B. Environmental Objectives

The ecoMOD project also has the potential to serve as a landmark in green, sustainable building. Current concern with energy supply and home cost necessitates continued growth and innovation in this field. Residential and commercial buildings currently account for 65.2% of total electricity consumption in the United States [1]. In response, ecoMOD architects and engineers have employed various design techniques and EnergyStar rated appliances to reduce energy usage in the homes, consequently reducing the residential living costs.

Another benefit of decreasing the energy dependency of the United States is that it reduces adverse effects to the environment. In a day and age when global warming is a very serious threat, the green building initiative offers solutions to decrease harmful emissions to the environment. The ecoMOD project accomplishes this in various ways. First, the reduction of energy consumption will directly relate to the reduction of emissions from electricity plants such as those which use burning coal to create energy. Furthermore, the materials chosen for the construction of the OUTin house were carefully researched and selected in part because there is little off-gasing associated with them. Another important feature of the project is that it incorporates modularity into the construction phase. This allows for the homes to be built at one large manufacturing facility, which decreases energy consumption and therefore emissions, reduces cost, and allows for the reuse of waste.

C. Social Objectives

Charlottesville's population provides a fitting outlet for this work. Its wide gap in income levels demonstrates a need for affordable housing; 25.9% of residents lie below the poverty line [2]. The Piedmont Housing Alliance has a strong presence in neighborhoods just blocks from UVA, giving the ecoMOD project relevance to students and building a relationship between the Charlottesville and University communities.

The success of the ecoMOD project poses potential benefits not only for the University and Charlottesville communities but also the progression of the increasingly vital green building initiative. This research provides a means for determining whether the ecoMOD project has achieved its goals: to increase energy efficiency and livability while reducing residential costs.

III. PROCESS

A. Monitoring System

Last year, the engineering team agreed upon the final design of the monitoring system for the OUTin house. The monitoring system in the OUTin house observes different indicators that gauge the performance of the various systems in the house. In the design process, regions of the house were assessed as either stable or with higher variance for

readings of temperature, humidity, and air quality to ensure the data collected accurately represented the house's statistics.

In total, fourteen indoor and four outdoor temperature sensors were installed. Additionally, two indoor and another outdoor sensor were placed around the house to gauge humidity. Together using the temperature and humidity data, the data analysis team can examine air flow throughout the house and evaluate the HVAC system.

Similarly, water flow meters were installed to monitor the amount of water flow that came from the city water supply, the rainwater collection system, and the solar hot water heater. Water flow from the rainwater collection system is compared to the water flow from the city water supply to evaluate the water conservation features present in the house.

As for energy monitoring, a detailed system was put in place that enables the team to observe energy consumption by appliance. Fifteen sensors were placed on appliances, such as washer/dryer and stove. Finally, additional values are watched, such as carbon dioxide levels and outdoor wind speed. All these different observations provide the framework for the data analysis in this project.

The sensors used were chosen with considerable emphasis placed on cost. After sensor type was agreed upon, the engineering team also determined a traditional hard-wire approach to connect each sensor to the data collection module to be the best choice. This is primarily because it saved a considerable amount of money without increasing installation or maintenance difficulties.

B. Data Acquisition and Storage

Before performing any analysis of OUTin, the data collected from this monitoring system needed to be organized and stored in a manner that would allow a data analysis tool or a member of the engineering team to access it easily. Each sensor in the house is wired to a National Instruments field point module which organizes and time stamps the data. These values are then stored in tab-delineated files on a flash drive located at the house. Originally, the mechanism for retrieving the files required a team member to manually upload data from a flash drive at the house. However, this method for data acquisition is not a feasible long-term solution, and thus the team identified a method to remotely access the files.

Through a wireless connection, the University of Virginia server polls the field point module for new files every hour. These files are then added to the database which is currently stored on a laptop. Ideally, the database would be located on the U.Va. server with the ecoMOD website and resources; however, as server space is limited, the vast quantity of data exceeded the allotted storage amount. Thus, the laptop is constantly connected to the internet and can be remotely accessed by the data analysis tool.

C. Data Analysis Software

With the monitoring system in place and the acquisition and storage system functional, analysis can begin to reveal the performance of the house's systems and the effect of the

occupants' daily activities. While some of this analysis can be done by hand or using Microsoft Excel or other statistical programs, it is tedious and unrealistic given the quantity of data. For these reasons, the team chose to create the web-based analysis program.

The goals and requirements of this tool were set forth at the beginning of the 2006-2007 academic year. First, the data analysis program should be accessible to students working on the project, ecoMOD administrators, and OUTin residents. A web-based application would allow for remote access by these stakeholders, but must incorporate some level of security which protects the privacy of the residents by preventing unauthorized access of data. In order to cater to these audiences with varying levels of technical experience, the program must be easy to navigate and use. In terms of presenting the data, the tool must be able to convey trends both graphically and numerically. The user should have the option of specifying certain sensors and a certain time range and to then view a graph of these data or calculate a table of relevant statistics.

Figure 1 depicts the current version of the analysis tool.

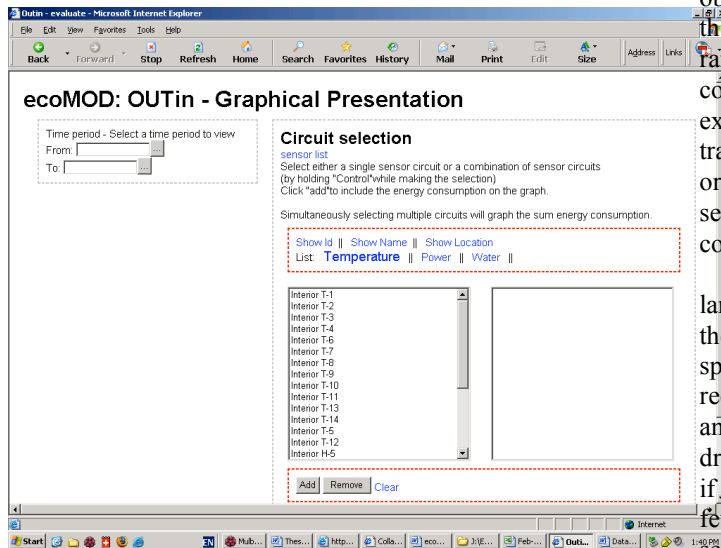


Figure 1. Screen shot of data analysis tool.

The program allows the user to enter a date range which can cover a single day, a range of days, weeks, or even months. The user then selects either an individual circuit or an aggregate of circuits to add to the text box on the right side of the screen. By selecting two or more circuits before clicking “Add”, the tool will calculate the sum of the sensors. For example, “Circuit 13 + Circuit 14” would give the sum energy consumption for the Air Handler and the Compressor, which together make up the heating, ventilation, and cooling (HVAC) system. If the user selects two or more temperature sensors or water flow meters then the tool will take the average rather than the sum.

Once a date range and selection of sensors has been specified, the user can choose to output either a set of graphs or a text file that can be imported into Excel for a more in-depth numerical analysis.

Given the progress which remains to be made on the graphing function of the tool, the exporting feature is crucial

as it allows the team to begin analyzing the data without having to wait for completion of the graphing tool. Thus, the data analysis thus far has been done primarily by exporting the files into Microsoft Excel to perform calculations and create graphs.

IV. ANALYSIS

A. Overview of Energy Consumption

Energy consumption is a major indicator of environmental consciousness in both residential and commercial housing. While it is not the only gauge of OUTin’s performance, the energy consumption of the various systems and appliances is vital to understanding which aspects of the design are strong and which need improvement. In order to perform any in-depth analysis involving energy data, it is first necessary to understand what is being measured and to verify the accuracy of those measurements.

By examining the available data of an occupied house (February 1-19, 2007), the team observed various trends and inconsistencies in the energy consumption. The most obvious peculiarity was the presence of negative values. For the circuit with the washer and dryer and the circuit with the range hood and dishwasher, some of the hourly energy consumption was negative. While the values were extremely small, this could be an indicator that the current transformers on these circuits are not properly calibrated. In order to remedy this, the most extreme negative value was set to zero by adding that value to every data entry in the column.

Another observation gleaned from the data is that while large energy spikes like those from the washer and dryer or the HVAC system are visible, it is impossible to see small spikes in energy. The power draw from each circuit is recorded and stored every three seconds, however the data analysis tool uses these values to find the average power draw over an hour, which is the energy used in that hour. So if a small appliance or lighting unit has a power spike for a few seconds and then returns to normal, it is impossible to see it in the data. Thus, the analysis tool should be revised to allow for time increments smaller than an hour.

However, even without smaller time increments, it is possible to learn from the total energy consumption of the house. Table 1 depicts the energy consumption from OUTin for the available date range, February 1-19. The chart, broken down by circuit, shows the distribution of energy in the house.

Circuit	Energy (kWh)	% of Total
Compressor	123	26%
Hot Water Heater	103	21%
1 st Floor L&R	66	14%
Air Handler	61	12%
2 nd Floor L&R	44	9%
Washer & Dryer	26	5%
1 st Floor L&R	21	4%
Refrigerator	15	3%
Water Sys. & Field Point	15	3%

1 st Floor L&R	5	1%
Kitchen & Microwave	4	1%
Stove	4	1%
Range Hood & Dish.	2	0%
2 nd Floor Bath	1	0%
Total	489	-

Table 1. Energy Consumption for February 1-19, 2007

As expected, the compressor and air handler, which comprise the HVAC system, use a significant portion of the energy over the first few weeks of February with 38% of the total energy consumption, or about 184 kWh. The HVAC system was followed closely by the hot water heater, which used 103 kWh or 21% of the total consumption.

B. Actual vs. Predicted Energy Consumption

While the energy distribution gives an overall idea of how energy is being consumed in OUTin, more informative conclusions can be drawn by comparing it with the expected values. During the original evaluation phase of OUTin, before the house was occupied, an engineering team performed a series of modeling and simulation tests to determine how much energy the house should use. By inputting the exact design of the house, the materials and R-values of the walls and floors, and the conditions in Charlottesville, the team was able to predict the energy consumption for each month of the year.

	Predicted	Actual	% Less
HVAC	364	183	50%
Hot Water	186	103	45%
Total	657	490	25%

Table 2. Predicted vs. Actual Energy Consumption in kWh

Since we do not currently have the actual data for the entire month of February, but instead for just two-thirds, Table 2 finds the predicted values for just 20 days of the month and compares it to the actual values.

A comparison between these predicted values and the actual data yields an evaluation of the performance of the house's systems thus far. First, the predicted HVAC energy usage for 20 days in February is 364 kWh. Actual energy consumption for this time period was just 183 kWh, which is 50% less than the predicted value.

There are a few possible explanations for such an extreme difference. The residents could have been out of town during this time period, they could keep the house colder than most people, or this February may have been warmer than most. However, we know that the residents did not leave and by examining the indoor temperature data we can determine that they keep the thermostat set at around 73°F. Furthermore, from 1949-2005 the average low temperature for February was 28.9°F and the average high temperature was 48°F. February 2007 was actually colder than normal with an average low of 24.1°F and an average high of 41.7°F [3]. Thus, the system must be performing more efficiently than predicted.

The second major discrepancy between the predicted and actual values is the energy consumption for water heating. While the simulations predicted that hot water heating would consume 186 kWh for 20 days in February, the actual consumption was 45% less than that with just 103 kWh. Thus, while the hot water heater does use a large portion of the total energy consumption as discussed in the section above, it is still less than expected. This leads us to believe that the solar hot water heater is functional and is greatly reducing the workload of the conventional heater.

Finally, the total predicted energy consumption for 20 days of February is 657 kWh, compared to 490 kWh actually consumed. This 25% decrease from predicted to actual values again supports the higher than expected energy efficiency of OUTin. These results are very promising, and hopefully will continue throughout the monitoring period.

C. HVAC Energy vs. Temperature

Given that 38% of the total energy consumption is expended by the HVAC system, it is crucial to gain a better understanding of the heating, ventilation and cooling processes in the house and to identify a method for predicting their performance. During the time period being examined, the outdoor temperature never rose above the thermostat setting inside the house. Thus, the HVAC energy usage for this period can be contributed solely to heating and ventilation rather than cooling.

The most obvious predictor of heating energy is the outdoor temperature. If the thermostat setting remains constant, then the outdoor temperature should be the most accurate indicator of HVAC energy. Figure 2 graphs the behavior of outdoor temperature against the behavior of HVAC energy for February 14-19. As expected, when the outdoor temperature drops, the energy needed to heat the house increases.

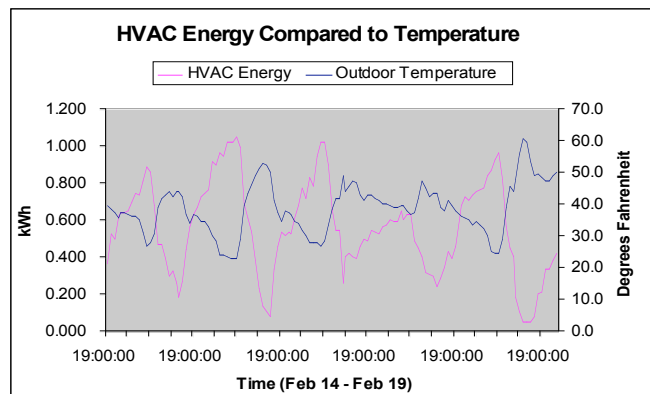


Figure 3. HVAC Energy vs. Outdoor Temperature

This relationship, however, is something that could have been expected, and the graph does little more than confirm those expectations. A more useful analysis would be one which allows us to predict the energy used to heat the house given the thermostat setting and the outdoor temperature. Figure 3 compares the energy consumption in an hour to the average difference between the indoor and outdoor temperature for that same hour. For example, if the

thermostat is set at 73°F and the average outdoor temperature for a given hour is 50°F, the temperature difference is 23°F.

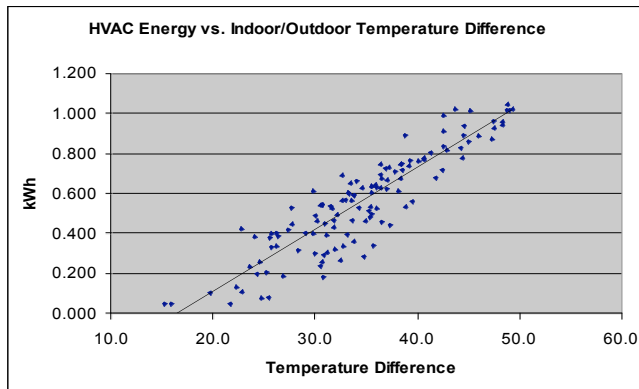


Figure 4. HVAC Energy vs. Outdoor Temperature

As seen in Figure 4, the relationship between heating energy and temperature difference is strongly linear with an R-squared value of 0.8. By calculating a best-fit line to approximate this relationship, the equation for this line can be used to predict the energy required to heat the house.

D. Redundancy of Sensors

One goal of the analysis is to make recommendations for the monitoring of the remaining ecoMOD houses. As OUTin was the first iteration in this process, the number and location of the sensors were based on few concrete specifications. Thus, by determining how strongly correlated the temperature, humidity, and CO₂ sensors are, we can identify specific sensors which were unnecessary. With these conclusions, the monitoring team for future ecoMOD evaluations can make a more informed decision concerning sensor quantity and location.

The correlation results for the indoor temperature sensors reveal extremely high correlations (0.7 and above) between most sensors. For example, T-6, which is located on the first floor near the bathroom, is highly correlated with eight other temperature sensors. While some of these may simply be chance, most of them are correlated because they are nearby or in a similar placement on the second floor.

There are, however, some negative correlations. T-1, T-2, and T-9 are negatively correlated to many of the other sensors, meaning that if the temperature changes in one of these locations, it doesn't necessarily correspond with a temperature change in the rest of the house. By examining the locations of these sensors, this temperature behavior can be explained. T-1 is located directly beside the largest window of the house, which takes in a significant portion of sunlight and T-2 is positioned in that same room. T-9 is fixed near the ceiling of the upstairs bathroom, directly next to the shower. Given the heat generated by an occupant bathing, it makes sense that this sensor would not correlate with the others.

The remaining sensors all demonstrate high correlation and suggest that fewer sensors are needed in the next monitoring iteration for ecoMOD. For outdoor temperature, all of the sensors are at least moderately correlated, and three

of the four of them are strongly correlated. The two indoor humidity sensors are highly correlated, and so are the two carbon dioxide sensors. Given this information, the future monitoring team should be able to save money and time by reducing the quantity of sensors in the house.

V. DISCUSSION

The ability to analyze data based on residential patterns offers significant opportunities to communicate the benefits of the technologies incorporated into the OUTin house. Monitoring will continue for the first year that the residents occupy the house in order to reflect seasonal trends.

The data from this analysis will be used in three ways. First, the architects and engineers continuing work on this project will use the data collected to evaluate their design decisions and optimize the technologies integrated into future iterations of the project. Comparing data from the monitoring system with predicted values will make this possible.

Second, the data will be used to publicize the ecoMOD project to interested parties. Samples of data will be available on the ecoMOD website; access to all data will be limited, as showing all information would reveal residents' living habits and potentially compromise their privacy and security.

Third, the data will be used to help alter residents' behavior. Ideally, learning about energy consumption trends will help the residents optimize their resource use.

In addition to providing information about the efficiency of the home, the analysis indicates that the monitoring system can be considerably improved. Already, students are working on a wireless system that will provide the potential for mass distribution. The information gathered about redundancy will assist in streamlining future versions of the system.

Recent examination has called into question the validity of the data. Missing time intervals may have compromised the completeness of the information; the next steps of the project will be to understand which data is most accurate and how the team can prevent power outages and other problems from affecting data transfer from now on. Because this is an ongoing process, such steps will only improve the future experience.

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