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Energy Consumption Trends for AC Systems in a Typical House

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Dr. Shehadi is an Assistant Professor of Mechanical Engineering Technology (MET) at Purdue University. His academic experiences have focused on learning and discovery in areas related to HVAC, indoor air quality, human thermal comfort, and energy conservation. While working with industry, he oversaw maintenance and management programs for various facilities including industrial plants, high rise residential and commercial buildings, energy audits and condition surveys for various mechanical and electrical and systems. He has conducted several projects to reduce carbon dioxide and other building emission impacts by evaluating and improving the energy practices through the integration of sustainable systems with existing systems. His current research focuses on engaging and educating students in sustainable and green buildings' design and energy conservation. He is currently investigating various ways to reduce energy consumption in office buildings.

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Abstract

Part of Purdue University MET (Mechanical Engineering Technology) program is to educate its students on energy conservation in general and for buildings in specific. In this study, which was part of a project in HVAC & Refrigeration class (MET 42100), the team decided to investigate energy consumption trends for a typical house/apartment under actual outdoor conditions and following different indoor temperature schedules and scenarios. The indoor base temperature was set to 72° F. Different schedules were created sometimes increasing the temperature during day or night time, shutting off the system when the outdoor temperature was cool and adequate, opening balcony doors or windows while keeping the system on, etc. Daily energy consumed for each case was collected using the electrical company's database who collects and stores all data using smart meters for the investigated apartment.

It was seen that increasing the indoor set temperature by 1-5° F for couple hours in the afternoon or at night can save up to $80 per month or even more if combined cases were adopted. The results presented in this study depend on the circumstances of the house where the data was collected and it may not replicate the same/exact results if applied to other apartments/houses.

The project helps the students meet the course learning outcomes in addition to ABET learning outcomes for MET programs. Students gained analytical and experimental skills, applied science and technology to engineering theories and applications, worked in a team, and developed their communication skills such as oral and written skills.

Keywords: energy conservation, thermostat temperature effects, human thermal comfort, actual measurements, home smart meters.

Introduction

Commercial and residential buildings are the largest contributors toward the total energy consumption in the world [1]. Energy consumption in buildings significantly increases on a yearly basis due to increased human comfort needs and services [2]. Residential and commercial buildings comprise 40% of the US primary energy of which 75% is electrical. Half this amount of energy consumed is by the ventilation and air-conditioning systems of the building [3].

According to a publication in 2009 by Energy Star company, the average annual energy consumption in US household is more than $2,200, with nearly half of it being spent on heating and cooling systems and demands [4].

The equipment demand for heating, ventilation and air-conditioning has increased in the USA from $11 billion in 2004 to $19 billion in 2014 [5]. Several energy audit reports for buildings indicated that occupancy sensors can significantly reduce energy consumption if they can adjust the cooling and heating loading supplied according to the desired load. However, this would necessitate an efficient air-conditioning supply and control system in order to efficiently reduce energy consumption in buildings.

In many buildings, especially residential ones, the indoor set-point temperature is dominated by the the occupants' behavior and needs. Yan et al. [6] showed a significant relation between energy consumption and occupants' presence and behavior using simulation tools. Another study predicted human behavior inside buildings based on other environmental conditions such as outdoor temperatures, indoor temperature and humidity, lighting density, and other variables [7]. These prediction simulations and tools help estimate the metabolic behavior of the occupants and thus help decide the optimum indoor temperatures.

Table 1 shows recommended set temperatures during the different day and night times in summer and winter to achieve the most optimum energy consumption and reduce the electrical bill related to cooling and heating.

Table 1. Recommended day and night set-point Temperatures to achieve optimized energy consumptions [4]

Setting	Time	Setpoint Temperature	
		Heat	Cool
Wake	6 a.m.	70°F (21°C)	78°F (26°C)
Day	8 a.m.	62°F (17°C)	85°F (29°C)
Evening	6 p.m.	70°F (21°C)	78°F (26°C)
Sleep	10 p.m.	62°F (17°C)	82°F (28°C)

The effect of thermostat setting on energy savings in houses and its related effects on human comfort was examined by the CCHT (Canadian Center for Housing Technology). The study considered identical two story houses under different temperature settings: 1) reference case at 72°F (22°C) without any change in the set temperature in winter or summer, 2) a) In summer, two different set temperatures were considered 75°F (23.8°C) during day time and 72°F (22°C) during night and the second one simply set the house at 75°F (24°C) during all times; b) during winter time, three different set temperature were adopted: i) 64°F (18°C) during night time only, ii) 64°F (18°C) during the whole 24 hours, and iii) 61°F (16°C) during the whole 24 hours. Temperatures for the thermostat, room air temperature, window surface temperature and the wall temperatures were collected. Winter savings from the three different strategies were significant, whereas summer savings were significantly different for the two adopted settings. During summer testing, the 75°F (23.8°C) setting for 24 hours resulted in 23% seasonal savings and an average of 17% savings during the hottest day whereas the other set point, 72°F (22°C) during daytime, resulted in 11% seasonal savings and 14% savings during the same hottest day. For winter testing, the seasonal savings were 6.5%, 10%, and 13% whereas the coldest day savings were 11%, 17%, and 21% for the three set points described above, respectively [8].

This project was done as a course project by three MET students in the HVAC and Refrigeration course (MET 42100). The team members were interested in looking into the electric bills for typical three bedroom houses and apartments and wanted to make an impact on the environment by recommending changes to the indoor temperature schedules for different outdoor temperatures in summer. The team collected real time energy consumption rates in a typical three-bedroom house. A smart meter installed in an apartment was used to collect the hourly and daily energy consumption during the month of August while adjusting the indoor set point temperature to an adequate level.

Methodology

A typical house/apartment for one of the team's member was selected as the unit to be investigated. The house had a total gross area of 1400 ft^2 and consisted of three bedrooms, kitchen, living room and two bathrooms. The mechanical room containing the furnace and the AC unit and the laundry units were all located within the house. The team recorded the energy consumed in the house during summer time from August 7th till Sep 3rd when five people were residing at the house. The analysis of the results showed that 85% of the electric bill was due to the cooling needs and thus the team used the overall energy consumption by the house as an indication to energy consumed by the air-conditioning unit. It was recognized that the electric bill was approximately 10-15% to that when the AC system was on.

The team used different indoor temperature schedules as shown in Table 2. The kilo-watt hour (kWh) of energy consumed was collected through Duke Energy's website since it had the capability to provide hourly and daily consumption through smart meter system installed in the house. Electric bill tariffs and rates were obtained as used by Duke Energy billing and the total monthly bill was calculated for the daily consumed kWh. The collected days were categorized based on the outdoor temperatures.

Table 2. Indoor temperature schedule for different days investigated along with daily incurred kWh and monthly bill (cells were color coded for ease visual distinction of temperature set values)

Outdoor Temperature (F)	72				73			74		
Monthly Bill	$ 143.1	$ 97.4	$ 169.4	$ 152.8	$ 125.6	$ 175.0	$ 95.8	$ 188.6	$ 127.9	$ 181.0
Daily kWh	40.08	25.12	48.69	43.26	34.36	50.53	24.59	54.98	35.11	52.49
Day in August	15	21	25	30	16	17	31	9	11	18
1:00 AM	72	72	72	72	72	72	72	72	72	72
2:00 AM	72	72	72	72	72	72	72	72	72	72
3:00 AM	72	72	72	72	72	72	72	72	72	72
4:00 AM	72	72	72	Door opened	72	72	72	72	72	72
5:00 AM	72	72	72	Door opened	72	72	72	72	72	72
6:00 AM	72	72	72	Door opened	72	72	72	72	72	72
7:00 AM	72	72	72	Door opened	72	72	72	72	72	72
8:00 AM	72	72	72	Door opened	72	72	72	72	72	72
9:00 AM	72	72	72	72	72	72	72	72	72	72
10:00 AM	72	72	72	72	72	72	72	72	72	72
11:00 AM	72	72	72	72	72	72	72	72	72	72
12:00 PM	72	72	78	72	72	72	72	72	72	72
1:00 PM	72	72	78	72	72	72	72	72	72	72
2:00 PM	72	72	70	72	72	72	72	72	72	72
3:00 PM	72	72	70	72	72	72	system off	72	72	72
4:00 PM	72	72	70	72	72	72	system off	72	72	72
5:00 PM	72	72	72	72	72	72	system off	72	75	72
6:00 PM	72	72	72	72	72	72	system off	72	75	72
7:00 PM	72	78-Off	72	72	78	72	system off	71	75	72
8:00 PM	72	78-Off	72	72	78	72	system off	71	72	72
9:00 PM	72	78-Off	72	72	78	72	system off	71	72	72
10:00 PM	72	78-Off	72	72	71	72	system off	71	72	72
11:00 PM	72	78-Off	72	72	72	72	system off	71	72	72
12:00 AM	72	78-Off	72	72	72	72	system off	71	72	72

Outdoor Temperature (F)	75					76			77	
Monthly Bill	$ 131.3	$ 152.9	$ 159.8	$ 159.9	$ 108.3	$ 197.2	$ 219.3	$ 204.6	$ 184.5	$ 222.4
Daily kWh	36.21	43.29	45.548	45.6	28.71	57.8	65.04	60.22	53.63	66.04
Day in August	7	8	12	20	1-Sep	13	14	19	10	29
1:00 AM	73	73	72	72	80	72	72	72	72	72
2:00 AM	73	73	72	72	74	72	72	72	72	72
3:00 AM	73	73	72	72	74	72	72	72	72	72
4:00 AM	73	73	72	72	74	72	72	72	72	72
5:00 AM	73	73	72	72	74	72	72	72	72	72
6:00 AM	73	73	72	72	74	72	72	72	72	72
7:00 AM	73	73	72	72	74	72	72	72	72	72
8:00 AM	73	73	72	72	74	72	72	72	72	72
9:00 AM	73	73	72	72	74	72	72	72	72	72
10:00 AM	73	73	72	72	75	72	72	72	72	72
11:00 AM	73	73	72	72	75	72	72	72	72	72
12:00 PM	73	73	72	72	75	72	71	72	72	72
1:00 PM	73	73	72	72	75	72	71	72	72	72
2:00 PM	73	73	72	72	75	72	71	72	72	72
3:00 PM	73	78	72	72	75	72	71	72	72	72
4:00 PM	73	78	72	72	75	72	71	72	72	72
5:00 PM	73	78	72	72	75	72	71	72	73	72
6:00 PM	73	78	72	72	75	72	71	72	73	72
7:00 PM	73	73	75	72	75	72	71	71	78	72
8:00 PM	73	73	75	72	75	72	71	71	78	72
9:00 PM	73	73	75	72	76	72	71	71	72	72
10:00 PM	73	73	75	72	76	72	72	72	72	72
11:00 PM	73	73	72	72	76	72	72	72	72	72
12:00 AM	73	73	72	72	76	72	72	72	72	72

Outdoor Temperature (F)	79		81		
Monthly Bill	$ 128.0	$ 202.8	$ 200.9	$ 288.8	$ 223.4
Daily kWh	35.13	59.63	58.99	87.78	66.36
Day in August	2-Sep	3-Sep	26	27	28
1:00 AM	76	76	72	72	72
2:00 AM	76	76	72	72	72
3:00 AM	76	76	72	72	72
4:00 AM	76	76	72	72	72
5:00 AM	76	76	72	72	72
6:00 AM	76	76	72	72	72
7:00 AM	76	76	72	72	72
8:00 AM	76	76	72	72	72
9:00 AM	76	74	72	72	72
10:00 AM	74	74	72	72	72
11:00 AM	74	74	72	72	72
12:00 PM	75	74	72	72	72
1:00 PM	75	74	72	72	72
2:00 PM	75	74	72	72	72
3:00 PM	76	74	72	72	72
4:00 PM	76	74	72	72	72
5:00 PM	76	74	72	72	72
6:00 PM	76	74	72	72	72
7:00 PM	78	74	72	72	72
8:00 PM	78	74	72	72	72
9:00 PM	78	72	72	72	72
10:00 PM	78	72	72	72	72
11:00 PM	78	72	72	72	72
12:00 AM	78	72	72	72	72

The project was evaluated based on 1) Final report, 2) presentation, 3) biweekly progress reports, and (4) team work evaluation. Team evaluation was done by cross self-evaluation for each team where each member evaluated himself and the other team members. The evaluation forms were confidential to ensure assessment transparency. In addition to self-evaluation, the instructor conducted individual oral assessments with each team member to ensure that he/she did participate towards the project.

Results

The daily energy consumption is shown in Figure 1b along with average set point indoor temperature and average outdoor temperature for each day during the testing period shown in Figure 1a.

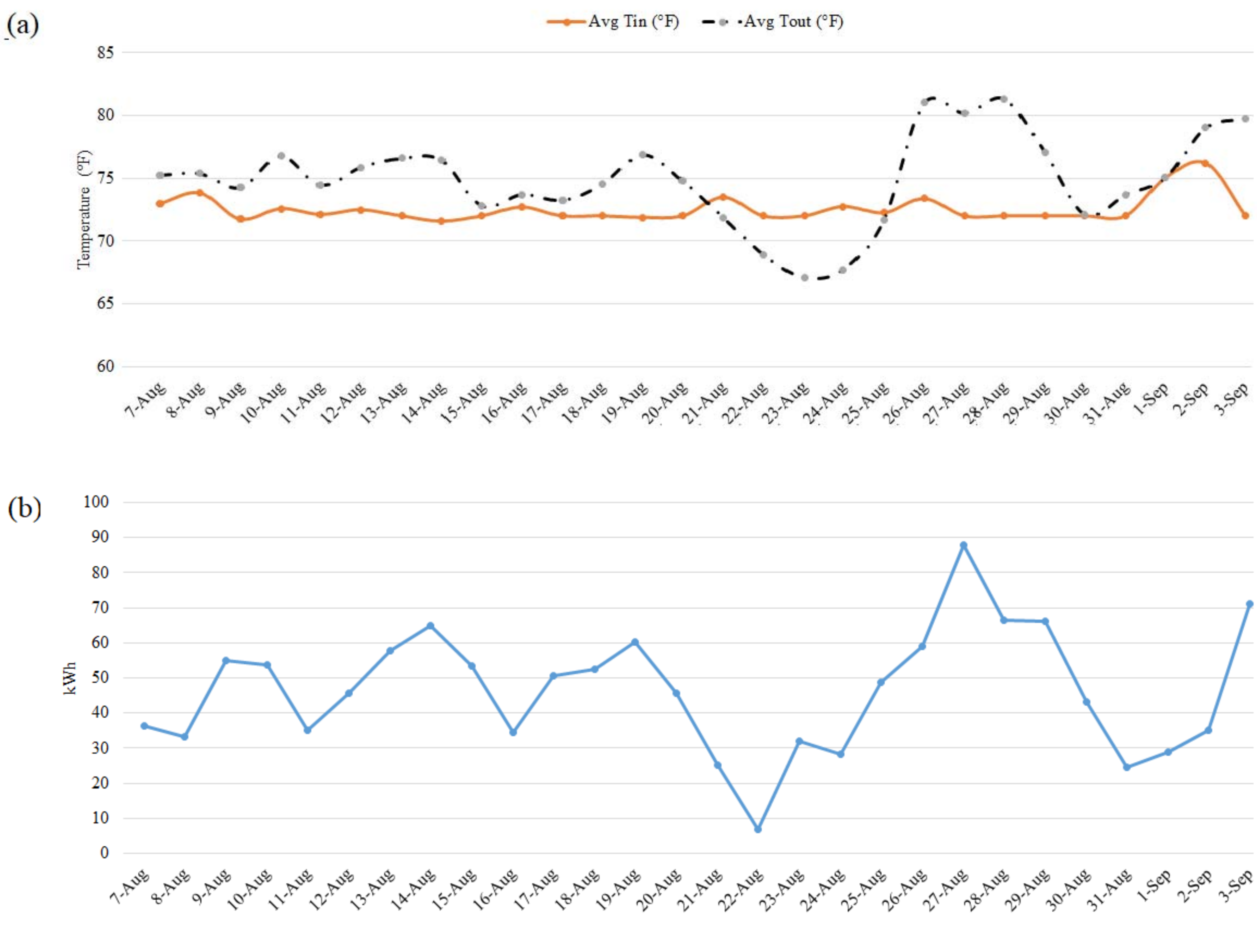

Figure 1. (a) average indoor and outdoor temperatures and (b) daily energy consumption (kWh)

From Figure 1, it was observed that decreasing the house temperature (T_{in}) required higher cooling loads and thus the consumed "kWh" was increased. However, sometimes while keeping the house interior temperature fixed at a certain temperature during different days, the "kWh" has increased due to higher outdoor temperatures. Thus, both the indoor and outdoor temperatures and maybe the relative humidity, which was not measured or tracked, should be considered when designing for a thermal comfort zone.

A second step toward analyzing the results of this project was by looking into tariff rates for each kWh consumed sector. These rates as obtained from Duke Energy's bills and website are provided in Table 3. The monthly bill was estimated based on energy consumed by each day; i.e. assuming the energy consumed for each day was the same for 30 days and then calculating the monthly energy bill. This was necessary for comparison reasons, since the tariffs were based on monthly kWh sectors and this would not be shown based on daily kWh. In addition to the tariffs shown in Table 3, there were two more tariffs: the first one was a $9/month flat fee, and the second one for other auxiliary fees such as fuel transfer, coal cost, environmental compliance, transmission and distribution, reliability, federally mandated cost and renewable energy costs incentives, etc. which summed up to approximately $0.04766 per kWh of the total monthly kWh. The associated monthly electrical bill for each outdoor temperature day are shown at the top of each day in Table 2.

Table 3. Primary rates for different kWh ranges

Margin (kWh)	0-300	300-1000	> 1000
$/kWh	0.092945	0.054178	0.044464

To check on energy consumption trends, days of similar outdoor air temperature were categorized together. This was done by looking into similar average outdoor temperatures. These groups are shown in Table 4. An outdoor temperature was the average of the day and night time of each specific day. The kWh consumed for each group is plotted in Figure 2.

Table 4. Groups of days sharing similar average daily outdoor temepratures

Group #	Average outdoor temperature (°F)	Days in Aug. unless otherwise stated
1	67	22, 23, 24
2	72	15, 21, 25, 30
3	73	16, 17, 31
4	74	9, 11, 18
5	75	7, 8, 12, 20, 1-Sep
6	76	13, 14, 19
7	77	10, 29
8	79	2-Sep, 3-Sep
9	81	26, 27, 28

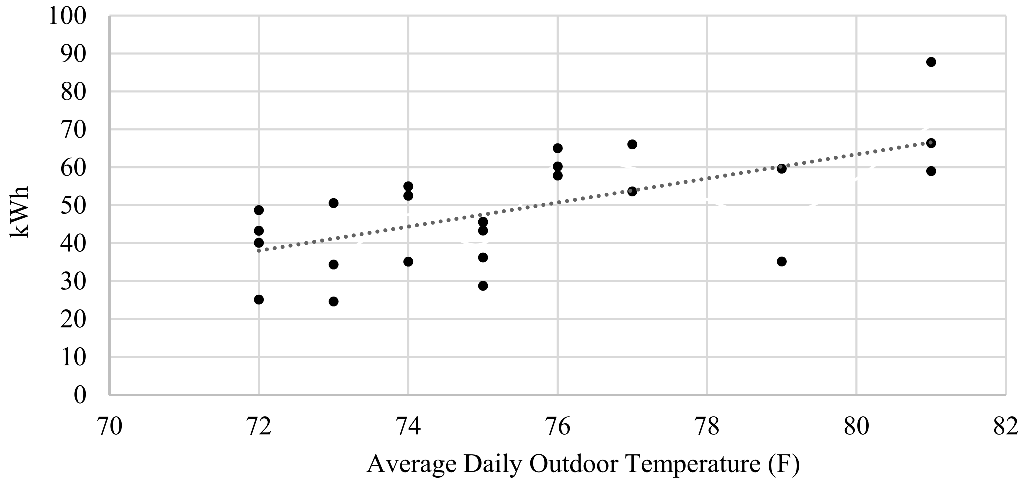

Figure 2. Actual daily kWh collected versus average daily outdoor temperature

The associated monthly cost behavior looks like the behavior of the consumed kWh shown in Figure 2. An analysis showed that the monthly bill would change exponentially with the outdoor temperature as shown in equation (1).

$$\text{Monthly bill (USD / month)} = 2.7904\, e^{0.0542 T_{out}} \quad (1)$$

It should be mentioned that the electrical bill changes from day to day although it might have the same indoor and outdoor temperatures. The first reason for this discrepancy would be averaging the outdoor temperature and thus diluting the peak day temperatures. Other variables participating towards this difference in the consumed kWh are the exact number of people residing in the house day to day, the behavior of the people, washing machines, dryers, etc. Figure 3 shows the kWh for the three reported days when T_{out}=81°F. It can be seen how the electric consumption (kWh) differed although the same schedule was followed during these 3-days (T_{in}=72°F) and had the same average daily outdoor temperature (Data shown in Table 2).

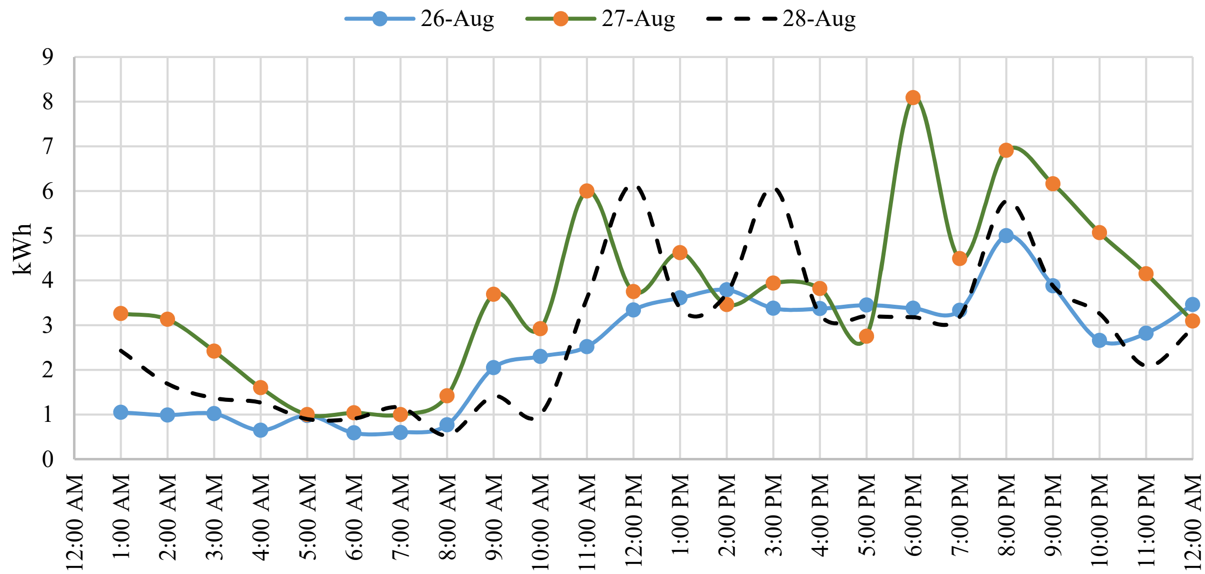

Figure 3. Energy consumption kWh for days sharing the same average outdoor temperature (81 F) showing the difference in daily kWh behavior despite the same outdoor conditions

Project Assessment

Through the implementation of the project, the involved students gained extensive experience in the field of HVAC, energy and cooling load calculations, controls and measurements, statistical analysis, and commercial software utilization that can help in future career placing. Project outcomes were evaluated against ABET learning outcomes summarized in Table 6. Performance assessment and feedback were done through the evaluation of biweekly submitted reports by the students. The project constituted 50% of the final GPA of the course. There were four main categories toward the project grade: biweekly reports (15%), final report (50%), presentation (25%), and team evaluation (10%). The details of the four categories are as follows:

1) Biweekly reports: constituted 15% of the project grade. These reports summarized the work of the previous two weeks. Each report was recorded on a log-book that included the following activities:
    i. Agendas and minutes of meetings identifying decisions and action items taken.
    ii. A weekly prioritized to-do list.
    iii. A weekly list summarizing goals achieved during the previous two weeks including the time spent (in hours) working (how much of the to do list was completed?)
    iv. Notes from outside research.
    v. Notes of how to accomplish a task.
    vi. Calculations, graphs (handmade and/or computer generated), drawings.
    vii. Drawings and schematic diagrams, including changes or updated versions, with detailed explanations of what was changed or updated.
    viii. Test plans, collected data, analyses, and conclusions regarding testing.

Each of the biweekly reports had a general theme as follows:

Report 1 Proposal
Report 2 Conceptual Design
Report 3 Preliminary Design
Report 4 Critical Design
Report 5 Proceed to Test

Each report was evaluated based on rubrics given in Table 5.

Table 5. Rubrics used for evaluating biweekly reports

Points	**4**	**3**	**2**	**1**	**0**
Weekly notes from supervisor and other parties	Notes exceeded expectations	Notes were appropriately relative to meeting content	Notes qty & quality were missing some meeting contents	Some evidence of notes	No evidence of notes
Legibility	Exceeded expectations	All entries clear & legible	75% or less clear & legible	50% or less clear & legible	25% or less clear & legible
Readability	Exceeded expectations, cross-referenced	Well identified entries	< 75% are identified, erratic flow in places	50% are identified, erratic flow in most places	< 25% identified, erratic flow
Completeness	Well documented, flow and content of entries demonstrated forethought, connections, and results, in and between process phases	75% of flow and content of entries demonstrated forethought, connection, and results	50% of flow and content of entries demonstrated forethought, connection, and results	Flow and content were spotty and unconnected	No evidence of forethought, connections, or results in and between process phases
Lab Notebook Guidelines (items i-viii above)	Followed all criteria	Criteria followed about 75% of the time	Criteria followed about 50% of the time	Criteria followed about 25% of the time	No evidence of following guidelines

2) Presentation (25% of project score): the students presented their projects to interested MET faculty members and their class mates.
3) Final report (50% of project score): submitted by the end of the semester.

4) Team evaluation (10% of project score): the team members evaluated each other and submitted, separately, their evaluation for themselves and other team members. This self-evaluation was half the 10% assigned to team evaluation category. The other half was obtained through oral testing where the instructor asked each team member some questions and evaluated their knowledge to check their individual and team contribution.

Table 6 shows the relation between the ABET learning outcomes and the category/ies that were used to meet these expectations.

Table 6. ABET ETAC students learning outcomes rubrics used for project assessment and the respective means used to meet these outcomes

ABET ETAC Rubric/Learning Outcomes		Means used to meet the rubrics
(a)	Apply knowledge, techniques and skills to engineering technology activities	Final Report and biweekly reports
(b)	Apply knowledge of mathematics, science, engineering, and technology to engineering technology problems	Final report and biweekly reports
(c)	Conduct tests, measurements, calibration and improve processes	Biweekly reports, and final report
(d)	Problem Solving: ability to identify, formulate, and solve engineering problems	Project proposal and biweekly reports
(e)	Team work	Team evaluation forms and instructor oral evaluation and assessment
(f)	Effective Communication: ability to communicate effectively	Presentation and biweekly reports

Conclusions

This project investigated potential savings in the consumed energy and electrical bill related to cooling load needed by a 3-bedroom house during summer season. It was shown that savings could reach up to $80 per month if the indoor temperatures were reduced by 1-5°F for 3-4 hours in the afternoon. Even with high outdoor temperatures, savings could be seen if a schedule is adequately followed during night and in the early hours of morning. For example, when the average outdoor temperature was 76 °F, increasing the indoor temperature by 4 °F during night time and by 2 °F for most of the daytime can significantly decrease the consumed kWh and the monthly bill.

Through the implementation of this project, the students applied various learning outcomes required by the course such as cooling load variables, measurements and control techniques, collecting data, improving their analytical skills and reasoning, and communication skills both written and oral. The project also engaged the students in more advanced topics related to energy conservation, simulation, and green buildings design. These topics are usually discussed in the upper level classes related to HVAC and energy conservation. From the students' feedback by the end of the course, the students showed interest in such projects as it helps them understand the material within an active learning environment and while experiencing the benefits to the real world applications. One major pit fall in such techniques is that these projects are usually conducted in teams and the instructor finds it hard to evaluate the performance of each member adequately. The instructor used two techniques to help in providing an unbiased team evaluation: the first one was the self-evaluation where each member evaluated him/herself and the other team members and the second one was conducted by the instructor by asking each students some basic and detailed questions related to the project. The instructor is still looking into better ways to best evaluate the performance of each member.

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Dr. Shehadi is an Assistant Professor in the School of Engineering Technology at Purdue University. His academic experience has focused on learning and discovery in areas related to HVAC, indoor air quality, human thermal comfort, and energy conservation. While working in industry, he oversaw maintenance and management programs for various facilities including industrial plants, high rise residential and commercial buildings, energy audits and condition surveys for various mechanical and electrical and systems. He has conducted several projects to reduce CO_2 fingerprint of buildings. His current work focuses on sustainable energy resources.