Analysis and Field-based Learning of Energy Conservation Measures in Engineering Thermodynamics Course

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In this complete paper, author discusses the techniques of introducing the concept of industrial and commercial energy conservation measures (ECMs) to undergraduate mechanical engineering students. To reach this goal, multiple ECMS are selected to be analyzed in Engineering Thermodynamics course to engage senior level students in actual engineering problems, develop their practical engineering skills, and enhance students' knowledge about industrial and commercial energy engineering practice. It is important to note that due to the existing constraints in the Engineering Thermodynamics course, such as time limitations and wide-ranging topics in the course syllabus, author is recommending the most relevant, yet advantageous ECMs, to avoid any unintentional consequences.

Through several years of professional experience in energy engineering, by visiting more than fifty industrial and commercial facilities, and reviewing more than two hundred energy efficiency improvement projects, author selected some of the most cost-effective ECMs which can result in significant energy savings and demand reduction for energy end-users. These ECMs include lowering the lighting power density by installing LED fixtures, affinity law and its applications in variable frequency drives installed on fans and pumps, high thermal efficiency water heating systems, and installation of thermal energy storage. For each of the above ECMs, the author explains the concept of the ECM, how it may save energy, and what equipment is involved in that ECM. The discussion around the concept of each of the ECMs is followed by a real industrial case study where the measure is implemented, and the annual energy savings was realized. Author also provides a discussion around the peak demand reduction, how it relates to the energy savings that may be achieved due to installation of the ECMs.

Finally, author recommends a field trip to help students visualize what they learned in the Engineering Thermodynamics course. This field trip would be visiting an on-site central utility plant which most universities have to meet their heating and cooling loads. A step-by-step procedure is included at the end of this paper which streamlines the field trip planning process and helps the instructors to set and evaluate the goals of the trip. A paper-based students evaluation of teaching (SET) survey was conducted by CSU Chico Department of Institutional Research which captured students' attitude regarding self-efficacy using a Likert-type scale from 1 to 5. This paper discusses the outcomes of this survey.

Tags: Energy Conservation Measure, Engineering Thermodynamics, Energy Efficiency, Energy Savings, Central Utility Plant, Field Trip

I. Introduction

Public policy is a key driver of energy efficiency investment in the United States. State policies that support ratepayer-funded energy efficiency programs, federal and state low-income weatherization efforts, energy efficiency programs administered by state energy offices, and building codes and standards have been major contributors to the increase in energy efficiency investments. Program administrators design and manage efficiency programs that facilitate the implementation of energy-efficient solutions by working with program implementation contractors, manufacturers, distributors, ESCOs, architects, engineers, building and construction contractors and tradespeople, and building owners.

A research conducted by Lawrence Berkeley National Laboratory (LBNL) investigated and identified major challenges to the projected expansion of the energy efficiency service sector (EESS) workforce by conducting interviews with energy efficiency program administrators, program implementation contractors, and building and construction industry professional and trade association representatives [1]. The LBNL-reported challenges, combined by workforce challenges that the author has experienced by working in EESS for more than seven years, are listed below:

- Shortage of applicants with experience in energy efficiency;
- Shortage of experienced energy efficiency engineers; and
- Limited awareness by building and construction contractors and tradespeople that the EESS is poised to expand significantly and their skills will be required.

Once the above challenges are admitted and acknowledged by workforce training entities such as universities and colleges, these entities could make their programs more robust by implementing changes in the program curriculum, and courses syllabus. These changes should gear towards including more real-world examples and case studies of energy efficiency improvements in relevant contexts to provide our future engineers with exposure to energy efficiency improvements projects. The changes in the program curriculum and courses syllabus would result in better serving the community and would bridge the gap between traditional workforce training programs and EESS expectations from future engineering graduates.

While several researches in the past, mainly focused on ideas and recommendations to improve energy conservation courses, which is a technical elective course in mechanical engineering curriculum [2] [3] [4] [5], there are actually only few publicly-available researches on incorporating the energy conservation phenomena in Engineering Thermodynamics as a core mechanical engineering course. In addition, most of the available scholarly work on Engineering Thermodynamics course focus on incorporating new teaching methods such as using video media [6], implementing experiential learning model [7], and developing MATLAB Functions [8] for improvement of student learning in the course. For instance, A. Karimi and R. Manteufel conducted and experiment by implementing Flipped Classroom Concept in their teaching of the Thermodynamics course [9]. As another example, A. Smith and S. Brauer presented an alternate approach to convey the conceptual content of the Thermodynamics course. They played an

online quiz game, called Kahoot!, to reinforce the content covered in the reading assignments [10].

Author of the current paper believes in incorporating basics of energy savings evaluations for introductory energy conservation methods to help students in choosing Energy Systems Engineering or similar courses as a technical elective course and potentially train them to serve in EESS in the future of their profession.

California State University, Chico (CSU Chico), is a public university in Chico, California. Founded in 1887, it is the second oldest campus in the CSU system. Mechanical and Mechatronics Engineering and Sustainable Manufacturing Department is one of the seventy-five departments of the university. The department's mission is providing a high-quality undergraduate engineering education. The department accomplishes this mission by offering a curriculum that is firmly grounded in engineering fundamentals while engaging students in projects that build on fundamentals and develop team skills.

Engineering Thermodynamics at CSU Chico is a core course in academic plan of mechanical engineering major. Students who have passed the course prerequisite, Physics Mechanics, are expected to enroll in Thermodynamics course during their third year. Table 1 lists a tentative course schedule outlining the topics covered:

Table 1: Tentative Engineering Thermodynamics Course Schedule

Week	Topics
Week 1	Basic Concepts and Definitions
Week 2	Energy and the First Law of Thermodynamics
Week 3	Properties of Pure Substances
Week 4	Properties of Pure Substances
Week 5	Energy Analysis of Closed System
Week 6	Energy Analysis of Closed System
Week 7	Mass and Energy Analysis of Control Volumes
Week 8	Mass and Energy Analysis of Control Volumes
Week 9	Second Law of Thermodynamics
Week 10	Second Law of Thermodynamics
Week 11	Entropy
Week 12	Entropy
Week 13	Break
Week 14	Gas Power Cycles – Field Trip
Week 15	Vapor Power Cycles
Week 16	Review
Week 17	Finals Week

In this paper, the author recommends real-world examples and a field trip relevant to energy efficiency and energy savings to fit into the table above. These examples are designed as preliminary steps in preparing the student in their path to become energy efficiency engineers

and help our workforce training entities to address the challenges in energy efficiency sector as discussed above.

II. ECM1: Lowering LPD by Installing LED Fixtures

Lecture Topic: Basic Concepts and Definitions

The efficiency for the conversion of electricity to light can be defined as the ratio of the energy converted to light to the electrical energy consumed. For example, common incandescent light bulbs convert about five percent of the electrical energy they consume to light, and the rest of the energy consumed is dissipated as heat, which adds to the cooling load of the air conditioning system in the summer. However, LED lights produce light approximately 90% more efficiently than incandescent light bulbs. It is more common to express the effectiveness of this conversion process by lighting efficacy, which is defined as the amount of light output in lumens per Watt of electricity consumed.

In California Energy Code, which is the sixth section of the California Building Standards Code, lighting power density (LPD) is used as a metric to regulate the maximum allowable lighting energy for each building type, or for each interior space type. The maximum allowable LPD values, in Watt per square foot, are listed in 2016 Title 24 standards Table 140.6-B (for each building type) and in Table 140.6-C (for each interior space type) [11].

Example: The Figure 1, which is from the electrical drawings from construction plans set of an actual building, shows the quantity and type fixtures installed in this space.
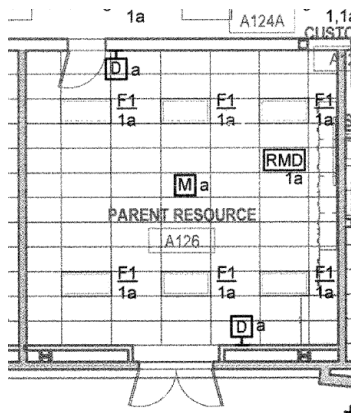

Figure 1: Lighting layout of an office space

If F1 fixture type is Lithonia 2BLT4-40L-ADP-MVolt-EZ1-LP835 which is a 40W LED fixture, and assuming an area of 920 sqft for this office space, does the installed lighting system meet the California Title 24 Standards' requirement for an office space?

Solution: Installed LPD for this space is calculated below:

Installed LPD = Installed Lighting Wattage (Watt) / Area (sqft) = 6 x 40 / 920 = 0.26 W/sqft

The installed LPD is below prescribed value for a large office space (0.75 W/sqft) and is acceptable.

III. ECM2: Application of Affinity Law in Variable Frequency Drives

Lecture Topic: First Law of Thermodynamics/Efficiency of Mechanical Devices

The transfer of mechanical energy is usually accomplished by a rotating shaft. A pump or a fan receives shaft work and transfers it to a fluid as mechanical energy. The Affinity Laws of centrifugal pumps or fans indicate the influence on volume capacity, head (pressure) and/or power consumption of a pump or fan due to change in speed of wheel. Affinity laws relate to the characteristics of pumps operating at different speeds, and in a water distribution network are usually used to predict the pump curve of pumps which are equipped with variable frequency drives (VFDs). VFDs can adjust the pump curve to meet the network requirements more efficiently with resultant savings of energy.

If the diameter is constant, the simplified form of the affinity laws is:

$$\frac{P_1}{P_2} = \left(\frac{q_1}{q_2}\right)^n = \left(\frac{rpm_1}{rpm_2}\right)^n$$

Where:

q = volume flow capacity (m^3/s, gpm, cfm)

n = 3 (theoretical)

P = power (kW, bhp)

However, the Affinity Law is not a law. It is merely a calculation tool. It applies only in a narrow, theoretical case since it assumes:
 * Fully turbulent flow,
 * An incompressible fluid,
 * No "system effects",
 * A closed loop that does not change shape (no modulating valves or dampers),
 * When the flow approaches zero, the brake power goes to zero (no constant static head or pressure set point),
 * Constant pump/fan efficiency,

Most real-world pump and fan systems do not meet all these criteria. The Affinity Law can still be applied in many cases, but it must be modified to better represent the situation. A common method is to reduce the exponent n. The recommended exponents to use are as indicated in Table 2.

Table 2: Recommended exponents for systems of fixed geometry

	Air/Water Loop is:		
	Fully or Mostly Closed	Semi-Closed	Mostly or Fully Open
Fixed Geometry	2.4	2.2	2.0

For recommended exponents for systems of variable geometry and explanation of terms, please see [12].

Example: A supply fan of an air handling unit is a 40-HP fan and as shown in the Figure 2 is operating at 70.5% of the full-load speed. Please estimate the percent energy savings of the fan assuming a VFD efficiency of 98% and same operating hours before and after installation of VFD.
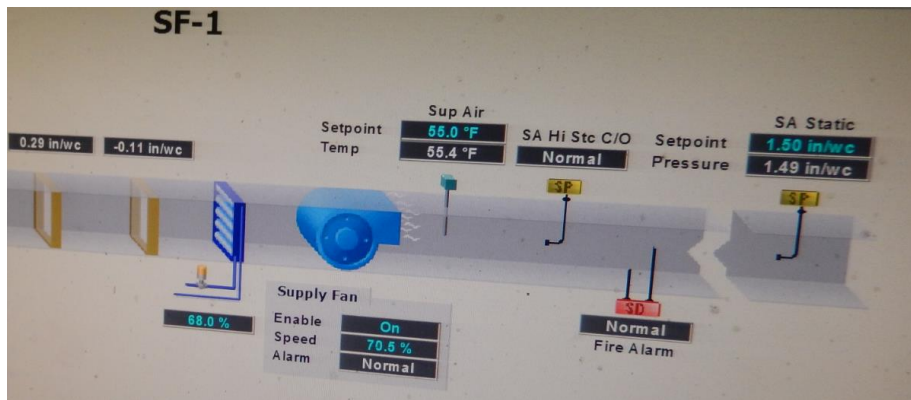

Figure 2: EMS screenshot showing supply fan of a building

Solution: Supply air plenum of a building is usually a semi-closed system, and therefore, recommended exponent in industry is 2.2. knowing that $\left(\frac{rpm_1}{rpm_2}\right) = 70.5\%$, and $\mu_{VSD} = 0.98$

$$\frac{P_1}{P_2} = \left(\frac{rpm_1}{rpm_2}\right)^n \times \frac{1}{\mu_{VSD}} = (0.705)^{2.2} \times \frac{1}{0.98} = 0.473$$

Therefore, installation of VSD results in 52.7% energy savings compared to the baseline system.

IV. ECM3: High Thermal Efficiency Water Heating Systems

Lecture Topic: Mass and Energy Analysis of Control Volumes

Service hot water systems are examples of open systems and we need to consider them as Control Volumes when analyzing them. In contrast, the heating hot water loop can be considered a Closed System although a small amount of make-up water is needed. In both cases, to determine how much heat we must provide to supply a steady flow of hot water to a building, we need to know the inlet and outlet water temperature, as well as the service hot water load in gpm. The Table 3, which was captured from mechanical equipment schedule of construction plans for a building, shows the quantity and type of heating hot water boilers and their efficiencies.

Table 3: Heating Hot Water Boilers in Mechanical Equipment Schedule

HOT WATER BOILER SCHEDULE

| SYM. | MFR. & MODEL# | TYPE | CAPACITY (MBH) | | HW (F) | | GPM | | EFF % | BOILER AMP | GAS CONN. | WATER CONN. | ELECTRICAL | | | OPER. WT. |
			INPUT	OUTPUT	EWT	LWT	MAX.	MIN.					V	PH	HZ	
B1 / A	CLEAVER BROOKS CFC750	INDOOR	750	652	115	150	44	15	87	5.3	1"	2.5"	208	1	60	1,600
B2 / A	CLEAVER BROOKS CFC750	INDOOR	750	652	115	150	44	15	87	5.3	1"	2.5"	208	1	60	1,600
B1 / D	CLEAVER BROOKS CFC750	INDOOR	750	652	115	150	44	15	87	5.3	1"	2.5"	208	1	60	1,600
B2 / D	CLEAVER BROOKS CFC750	INDOOR	750	652	115	150	44	15	87	5.3	1"	2.5"	208	1	60	1,600
B1 / E	CLEAVER BROOKS CFC1000	INDOOR	1,000	870	115	150	59	20	87	5.3	1"	2.5"	208	1	60	2,600
B2 / E	CLEAVER BROOKS CFC1000	INDOOR	1,000	870	115	150	59	20	87	5.3	1"	2.5"	208	1	60	2,600

The Table 4, which is a screenshot from plumbing equipment schedule of construction plans for a building, shows the quantity and type of heating hot water boilers and their efficiencies.

Table 4: Service Hot Water Boilers in Plumbing Equipment Schedule

						WATER HEATER SCHEDULE					
ITEM	LOCATION	MANUFACTURE	MODEL NO.	SERVICES	STORAGE CAPACITY	ELECTRICAL DEMANDS				INPUT MBH/HOUR	
						VOLTS	PHASE	AMP	CYCLE		
WH-1	L1- MAIN PUMP RM. 01-015	AO-SMITH	BTH-400A	140 DEG. DHW	119	120	1	5	60	399	
EWH-1	L1 -GRN ROOMS 01-025 & 01-026	CRONOMITE	SR-20L-208	DHW	INSTANT	208	1	15	60	N/A	

In California, the combustion efficiency and thermal efficiency of the gas- and oil-fired boilers is regulated by Title 20 Appliance Efficiency Regulations. Based on this regulation, the minimum thermal efficiency for gas-fired boilers with capacity between 300,000 Btu/hour and 2,500,000 Btu/hour is 80%. Also, minimum AFUE for gas hot water boilers with less than 300,000 Btu/hr capacity and single-phase electrical supply is 82% [13].

Condensing boilers, that are widely used now, achieve high efficiency by condensing water vapor in the exhaust gases and so recovering its latent heat of vaporization, which would otherwise have been wasted. In 2012, Davis Energy Group and Gas Technology Institute prepared a report for California Energy Commission [14]. Table 5 which was extracted from this report, compares the energy efficiency of sampled non-condensing and condensing water heaters.

Table 5: Energy efficiency of sampled non-condensing and condensing water heaters

| Description | Firing Rate (Btu/hr) | | Certified Performance | | | Water side volume (liter) |
	Min	Max	Efficiency	Max GPM	At del T (°F)	
Noncondensing	11,000	199,900	0.82	4.3	77	0.875
Condensing #1	9,500	199,000	0.93	4.4	77	1.7
Condensing #2	19,900	199,000	0.91	6.7	55	0.92
Condensing with small buffer tank	17,000	199,000	0.95	5.1	77	3.7

Example: Find annual energy savings resulting from installation of a condensing water heater with 93% efficiency in a building with 63 gallons per day usage compared to a regular water heater with Title 20 minimum efficiency. Assume entering water temperature of 67°F and leaving water temperature of 144°F.

Solution:

Annual energy usage of a minimum efficiency unit:

E1 = m x C_p x del T

= 63 (gal/day) x 365 (day/year) x 8.33 (lb/gal) x 1 (Btu/lb °F) x (144-67)°F / 100,000 (Btu/therm) / 0.82

= 179.9 therms

E2 = m x Cp x del T

= 63 (gal/day) x 365 (day/year) x 8.33 (lb/gal) x 1 (Btu/lb °F) x (144-67)°F / 100,000 (Btu/therm) / 0.93

= 158.6 therms

Therefore, the installation of condensing water heater results in energy savings of 21.3 therms per year.

V. ECM4: Thermal Energy Storage

Lecture Topic: Vapor Compression Refrigeration Cycle

The basic vapor refrigeration cycle can be adapted for special applications such as thermal energy storage (TES). In this application, chilled water or ice is made during the off-peak period, usually overnight or weekends, and chilled water/ice is stored in tanks until needed for cooling.

Installation of TES results in energy savings as explained below:

- TES are usually filled over the night to avoid chiller operation during peak load hours. Since the coefficient of performance of a refrigeration cycle if inversely proportional to T_H/T_L, and T_H (ambient temperature) is lower at night, the system would operate with higher COP.
- To fill up the TES with chiller water, chillers operate at or close to full load. The efficiency of regular chillers is usually higher at full load compared to their part-load operation during the day.

Running the TES at night, when less power is required for its operation due to cooler ambient temperatures and when electricity rates are lowest, the refrigeration unit makes chilled water for storage. The chilled water produced is stored in the accompanying tank. When cooling is required by building occupants during the day. Depending on local climate, TES can provide all cooling required by the occupants or work in tandem with vapor-compression or other comfort cooling system to meet needs.

Currently, California Statewide Customized Offering Program offers incentive demand reduction above and beyond baseline energy performance [15]. Peak demand reduction is evaluated using the Database for Energy Efficiency Resources (DEER) peak approach. The DEER peak method is defined as "an estimated average grid level impact for a measure between 2 p.m. and 5 p.m. during a 'heat wave' defined by three consecutive weekdays for weather conditions that are expected to produce a regional grid peak event." Figure 3 shows the 1.4-million-gallon Thermal Energy Storage Tank at the CSU Chico Central Utility Plant.

Figure 3: Thermal Energy Storage Tank at the CSU Chico Central Utility Plant

VI. Field Trip to University Central Utility Plant

Many universities across the U.S. have Central Utility Plants (CUP) that provides chilled water and heating hot water (or steam) for HVAC and process use for their campus. Some of the benefits of the CUP compared to in-house plant are:

- Higher energy efficiency campus-wide,
- Higher safety and security for students and faculty,
- Improvement in building performance and comfort,
- Streamline operations,
- Reduction in operational expenses, and
- long-term financial sustainability.

Scheduling a field trip to university CUP, if available, provides a unique opportunity for Mechanical Engineering major students to visualize what they learn in several courses of their curriculum, including Engineering Thermodynamics course. Some of the common equipment in a university CUP are chillers, cooling towers, boilers, heating hot water pumps, chilled water pumps, heating hot water pumps, and VFDs. In addition, there is usually a control room adjacent to a CUP in which operators have access to the EMS. Operators can control and respond to the needs from the control room.

Based on the author's experience, there are multiple steps that need to be taken before scheduling a field trip to the university CUP. These steps may vary depending on syllabus of Thermodynamics course and requirement of CUP at each university. In addition, authors found that it makes the process easier if the site visit is optional for students. Here is a noncomprehensive list of recommended steps:

- Including the field trip as a tentative optional activity in the course syllabus to motivate students (1st week of classes)
- Contacting the CUP facility management team (four weeks prior to the planned visit) regarding
  - Their personnel availability.
  - Number of students to be accommodated in each visit.
  - Recommended plan for the visit
  - Available HVAC equipment to visit
  - Access to the control room
  - Implemented ECMs and who can explain them to the students
  - Any current or recent energy efficiency retrofit projects
  - If any of plant personnel can explain day-to-day work of a plant engineer
  - Required personal protection equipment (PPE)
- Contacting department office to understand the university procedure for field trips. Some universities require a signed liability waiver form each student, while this requirement might be waived if CUP is located inside the campus. This step is recommended to be done three weeks prior to the planned visit.

- Set the date and plan the day with students two weeks prior to the planned visit and inform them about:
  - What they should expect at the site,
  - What they need to have to take notes,
  - What deliverables are expected after site visit
  - Photo taking policy
  - What PPE is required during the visit

To increase the effectiveness of the field trip, make sure students are attentive, and to let students practice report writing for an inspection, the author found it beneficial to recommend students to write a two-page report for their trip. These reports were collected and graded as an extra-credit work, and students were given feedback on their submitted report.

VII. Assessment of Teaching Effectiveness

Students provided positive comments at the end of the semester through SET survey. A paper-based SET survey was conducted by CSU Chico Department of Institutional Research. Out of 27 students enrolled in the course, 15 students participated in the SET. After gathering the student's name and major, the survey captured their attitude regarding self-efficacy using a Likert-type scale from 1 (strongly disagree) to 5 (strongly agree). Table 6 outlines a summary of Likert-type scale items relevant to the implemented teaching methods explained above:

Table 6: Summary of Likert-type scale items from SET surveys

Statement	Mean	Standard Deviation
My overall knowledge of the subject matter has increased due to the instruction of this course.	4.27	0.46
The course assignments contribute to learning.	4.29	0.92

In the SET, students were asked to explain "What did your instructor do to make this class a good learning experience for you?" as free-form responses. Multiple students directly mentioned the "field trip" in their responses. It was also mentioned that "the field trip expanded the knowledge" of student and "really solidified the class and made a relation with real world engineering application." Students even expressed interest in more field trips in response to "What could instructor do in the future to make this a better class?" Finally, majority of the students in the class evaluated overall quality of teaching "Very Good" in their responses to SET questions.

In addition, the author observed that students asked more conceptual and in-depth questions about the concepts related to their observations such as Second Law of Thermodynamics, energy

efficiency, coefficient of performance, and more after participating the field trip. The longitudinal assessment of the recommended ECMs to the course curriculum is a work in progress and can be completed in few years after the students graduate and their involvement in various industries is monitored.

VIII. Conclusion

Researches show that energy efficiency service sector has been experiencing shortage of experienced energy efficiency engineers. Workforce training institutions such as universities and technical colleges are expected to address this issue and take steps to address it by improving the syllabus of their existing courses and adding new courses to their curriculum. In the current paper, author recommended introduction to the concept and calculations of four ECMs in Engineering Thermodynamics course. In addition, the author provided a step-by-step procedure manual for a field trip to the university central utility plant, which is available in many universities across the U.S. A paper-based SET survey was conducted to capture students' attitude regarding self-efficacy using a Likert-type scale from 1 to 5. Based on the SET outcomes, "My overall knowledge of the subject matter has increased" received a 4.27 out of 5 which reflects the effectiveness of the implemented teaching methods discussed above. Moreover, multiple students directly mentioned that the field trip was among reasons that the Engineering Thermodynamics class was a good learning experience for them.

Introducing common ECMs, such as lowering lighting power density, application of affinity law in variable frequency drives, high efficiency water heating systems, and installation of thermal energy storage, along with visualizing what they learned about in Engineering thermodynamics course in central utility plan, will help students to decide about taking more advanced technical elective courses in energy engineering, such as Energy Systems Engineering. By having more students attracted to the energy engineering field and providing more exposure to ECMs, including what was explained in this paper, for student in mechanical engineering major, the EESS will be helped to overcome the experienced workforce shortage and eventually, the society will benefit.

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