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Interdisciplinary Collaboration to Engage Engineering Students' Interest in Renewable Energy Concepts

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Abstract

Students graduating with engineering degrees can be instrumental in addressing the impact of a changing climate. In this work, cross-disciplinary faculty explore students' interest in topics of sustainability within their fields as well as their preparedness to apply academic concepts in a realistic context. Students from two different courses in two different engineering programs, mechanical and computer & electrical, collaborated on a renewable energy project. The project was limited by existing course objectives and content for both programs. The outcome of this study reflects on students' interest and awareness of the impact of climate change on their career path.

Section 1: Background

The University of Wisconsin-Stout holds the values of polytechnic education, based on the "Wisconsin Idea" – a long tradition that embraces the principle that education should influence people's lives beyond the classroom. We strive to provide students with a learning environment that addresses current issues affecting their career path, and raises awareness of how their knowledge, creative ideas, and communication skills will impact the world we live in. In this spirit, cross-disciplinary faculty at the university of Wisconsin-Stout engaged students in developing a renewable energy system for a local building site. Students learned about the design process, regulations, and key participants in residential construction. The study focused on three areas: environmental conditions, project-based energy load calculation, and load offset through renewable energy systems. Students graduating with a mechanical or computer & electrical engineering degree can develop a career within the construction industry. The value of construction activities in the US at the end of 2021 was documented by the Census Bureau at about $1.6 trillion. Within this amount, private, single-family, and multi-family construction are a significant factor of about $0.8 trillion [1]. Even the year 2021 has seen a growth rate despite a pandemic that slowed other areas of the US economy. The construction methods and building esthetics have barely changed since the booming 1950s. However, technological possibilities and the knowledge of the impact, that buildings have on the nation's energy footprint, have increased substantially since then. For the most part, construction is a localized trade driven by regional climate, local building codes, local material availability, and local knowledge base. Building systems like heating, cooling, and ventilation are major components that affect occupants' comfort, health, and wallet. Based on "Residential Energy Consumption Survey" of 2015 [2], households account for 55% of the energy used in buildings in the United States. About half of the energy used in homes is attributed to conditioning (heating or cooling). The design of heating, ventilation, and air conditioning (HVAC), parallel with the building design, can address energy efficiency and consequently carbon output. The world is moving away from fossil fuel as an energy source. Solar energy will be one of the leading renewable options to meet energy demand based on its abundant availability, cost-effectiveness, and efficiency compared to other renewable energy sources. Universities can be leaders in developing strategies and preparing the next generation of professionals to think critically and creatively. A healthy graduation rate in the engineering fields promises that communities can lean on professionals to implement progress.

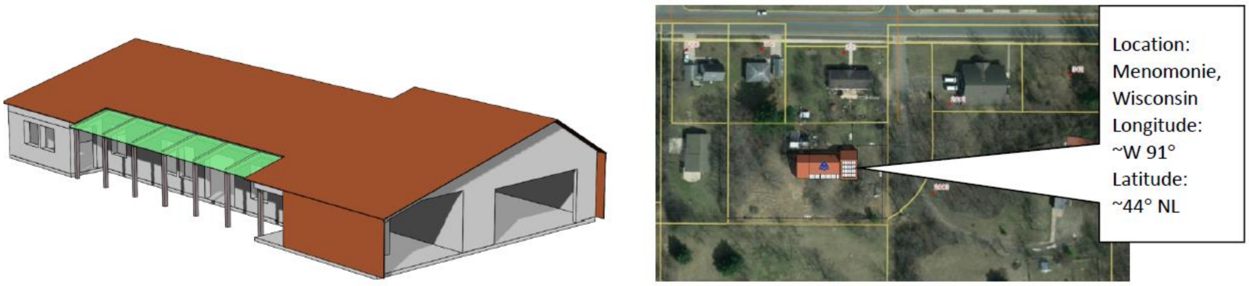
A. Renewable Energy Education in Engineering Schools:

Unavailability of qualified professionals in the field of renewable energies has been a major barrier to advances in the field [3]. It has been important to train engineering students in the field of renewable energy sources or improve students' awareness of renewable energy sources [4]. There are several studies on renewable energy education in engineering programs [5-12]. For example, Corey et. al [5] proposed a renewable energy program that can be adapted to existing mechanical engineering programs. Mohamed [6] presented a curriculum at the University of Washington that integrates renewable energy education with its electrical engineering program. Marian and Lise [7] presented a design workshop course in the electrical and computer engineering department at the University of Minnesota Duluth, in which students had to find sustainable solutions to keep comfortable temperatures in solar homes in chilly winters of northern Minnesota. Xingwei and Liang [8] discussed problems and challenges related to the renewable energy curriculum and presented a student-centered inquiry-based model for renewable energy courses. Developing and integrating renewable energy courses in engineering programs is an ideal and long-term solution but it faces constraints, such as limited credits and faculty in a program. In the work presented in this paper, two existing and standard courses in mechanical and computer & electrical engineering programs at the University of Wisconsin-Stout collaborated on a semester-long project in Fall 2021. In the project, students learned how to calculate energy load for conditioning (heating or cooling) while satisfying state regulations related to construction of residential buildings. Students had to come up with solutions to increase energy efficiency and meet required energy load by using only solar energy. Surveys were done to assess students' interest and awareness in the field of renewable energy. Integrating renewable energy concepts in existing courses in different engineering disciplines through collaboration can be an alternative solution that does not face constraints like limited credits in a program.

Section 2: Description of Study

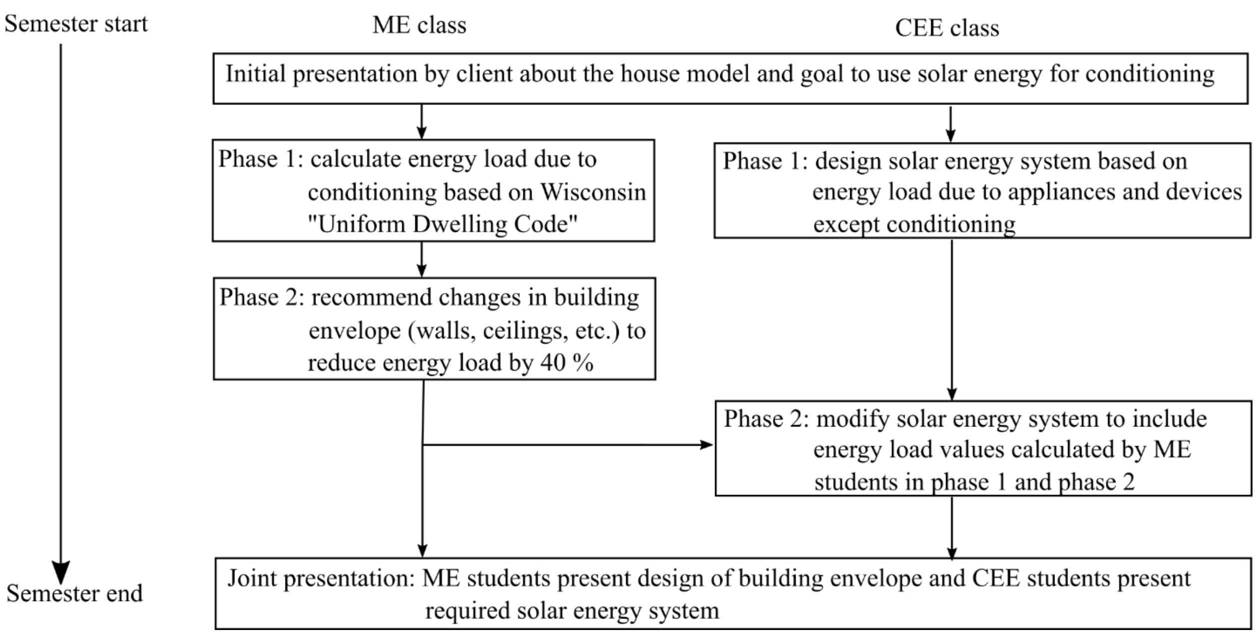
Faculty from three fields (mechanical engineering, computer & electrical engineering, and architecture) engaged students in design, analysis, and specification of a renewable energy system for a local residential building site. In Fall 2021, two student groups from mechanical engineering (ME) and computer & electrical engineering (CEE) were introduced to energy load analysis and solar system design through presentations and lab activities in appropriate senior and junior level courses (ME-492 System Dynamics, CEE-315 Power Electronics and Renewable Energy Systems). At the beginning of the semester, students were invited to participate in a pre-project survey that was approved by the Institutional Review Board (IRB) at the University of Wisconsin-Stout. Following the pre-project survey, students were approached by a "client," an architect and faculty member, who was planning a new home in the neighborhood. Figure 1(a) shows the parametric solid model of the house provided to students. Figure 1(b) shows the site location information provided to students. The client wanted to be advised on what renewable energy systems would be appropriate for their house design, geographic location, and energy consumption. The client also asked for recommendations on balancing the investment in insulating the building envelope with the investment in a solar system. The goal was to cover all the energy needed for conditioning (heating or cooling) the house with a renewable energy source like solar energy.

Figure 1: Client house: (a) residential mass model (parametric solid model) provided to students to facilitate calculations, (b) site location provided to students to facilitate the research about climate conditions and solar hours.



(a) (b)

Figure 2: Project phases for mechanical engineering (ME) and computer & electrical engineering (CEE) students.



Mechanical engineering (ME) students were introduced to building code requirements and construction standards and methods. Building codes are within local jurisdiction to be responsive to local conditions. Wisconsin residential construction is guided by the "Uniform Dwelling Code" for most aspects of construction. The chapter that applies to this study is "Chapter SPS 322 Energy Conservation" [13]. ME students used the table SPS 322.31-1 in [13] to determine insulation requirements and calculate heating or cooling load. For example, according to the table SPS 322.31-1, R-Value for a ceiling must be more than or equal to 49 ft^2-°F-h/BTU. Section 3B explains how U-Factors and R-Values in the table are related to energy load calculations.

After calculating an initial energy load based on R-Values and U-Factors given in the table SPS 322.31-1, ME students made suggestions on improving the building envelope to accommodate a 40 % reduction in the energy load. Then both calculated loads were translated into system designs for solar energy by computer & electrical engineering (CEE) students. The phases of the project and collaboration between ME and CEE students are outlined in Figure 2.

A. Limitations

This section briefly discusses the limitations of the project. The course objectives are not changed. Therefore, the project is limited within current course objectives. For instance, energy load for conditioning (heating or cooling) depends on several factors such as building envelope, ventilation, and infiltration, however, this study focuses on building envelope and does not account for ventilation and infiltration.

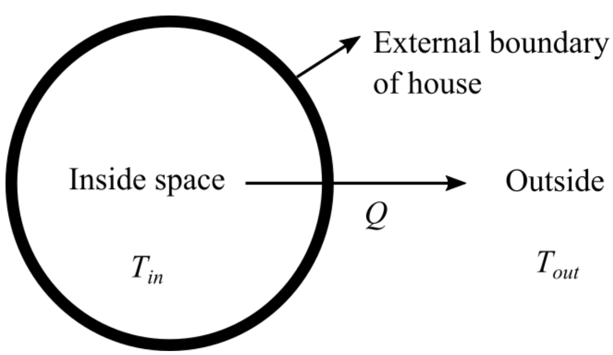
Section 3: Method

This section gives a brief overview of concepts and tools used by ME and CEE students to calculate energy load and design a photovoltaic system to use solar energy to meet the energy load.

A. Calculation of Energy Load for Space Conditioning (Heating or Cooling):

In the mechanical engineering (ME) course, students modeled the house in Figure 1 as a thermal system using the concepts of heat transfer. Students worked in groups of 4 or 5 and were given a timeframe of 3 weeks to complete the load calculation. This section gives a brief overview of the modeling method. The house in Figure 1 is modeled as a thermal system as shown in Figure 3. T_{in} and T_{out} are temperatures of inside air and outside air, respectively. It is assumed that the temperature of the air inside the house is uniform. Indoor space is assumed to be empty and all boundaries inside the house are ignored, e.g., boundary separating kitchen and living room are ignored. The garage volume is treated as the outside air. The house envelope is modeled as an external boundary that separates inside air and outside air.

Figure 3: Modeling of the house in Figure 1 as a thermal system.



The external boundary consists of walls, floor, ceiling, and windows, which create thermal resistance for heat flow between inside and outside. Q is heat flow rate (energy per second). If $T_{in} > T_{out}$, heat flows from inside to outside, which is called heat loss. If $T_{in} < T_{out}$, heat flows from outside to inside, which is called heat gain. Total thermal resistance between inside air and outside air is represented by R_{house}. Students applied concepts of thermal resistances, such as conduction and convection, to formulate R_{house}, which is described with an example later in Section 3B. Heat flow rate (energy per second) Q from inside to outside is calculated using Fourier's law as follows:

$$Q = \frac{T_{in} - T_{out}}{R_{house}}.$$

In winter, i.e., $T_{in} > T_{out}$, to maintain inside temperature T_{in} at a desired value $T_{desired}$, a heater inside the house must generate energy at a rate Q_{heater} that is equal to heat loss Q, which is as follows:

$$Q_{heater} = \frac{T_{desired} - T_{out}}{R_{house}}.$$

For outside temperature T_{out}, a statistical approach is to use temperature bin data [14]. However, students used average daily temperatures as project was limited by current course objectives. The average daily temperature data for the year 2020 was extracted from [15]. Energy load E for a month is calculated as follows:

$$E = \sum_{i=1}^{i=N} Q_{heater}^{i}\ 86{,}400,$$

where N is the number of days in that month and Q_{heater}^{i} is Q_{heater} for i^{th} day. 86,400 is number of seconds in a day. Each month is labeled as summer or winter based on average monthly temperature, which is heating and cooling degree method [16,17]. $T_{desired}$ was set by the client as 77 ^{o}F and 68 ^{o}F for summer and winter months, respectively.

B. Calculating Thermal Resistance

This section gives a brief overview of concepts used to formulate total thermal resistance R_{house}. Figure 4(a) shows an example boundary between inside air at T_{in} and outside air at T_{out}. The boundary is made of three layers. Heat flow is along the direction of lengths L_1 and L_2. Layer 1 and layer 2 are in series and both layers 1 and 2 are in parallel with layer 3. Each layer is made of a uniform material. Thermal conductivities of materials in layers 1, 2, and 3 are k_1, k_2, and k_3, respectively. We account for conduction and convection only. Radiation and contact resistances are ignored.

Figure 4(b) shows resistance network between T_{in} and T_{out}. Table 1 describes all resistances in the network with corresponding formulas. For example, R_1 is thermal resistance for heat transfer through convection between inside air and contact surface area A_1 of layer 1. Heat transfer coefficient for convection is represented by h, and it is assumed to be same for all four convections (R_1, R_4, R_5, and R_7) in this example. R_2 is thermal resistance for heat transfer through conduction in layer 1 in the direction along length L_1. Similarly, rest of the resistances are calculated. $R_{boundary}$ is total thermal resistance for the example boundary and is calculated as follows:

$$\frac{1}{R_{boundary}} = \frac{1}{R_1 + R_2 + R_3 + R_4} + \frac{1}{R_5 + R_6 + R_7}.$$

To find total resistance, resistances in series are added and resistances in parallel are 1) taken inverse of, 2) added, and 3) taken inverse of.

Figure 4: An example boundary: (a) layers in the boundary and dimensions, (b) corresponding thermal resistance network.

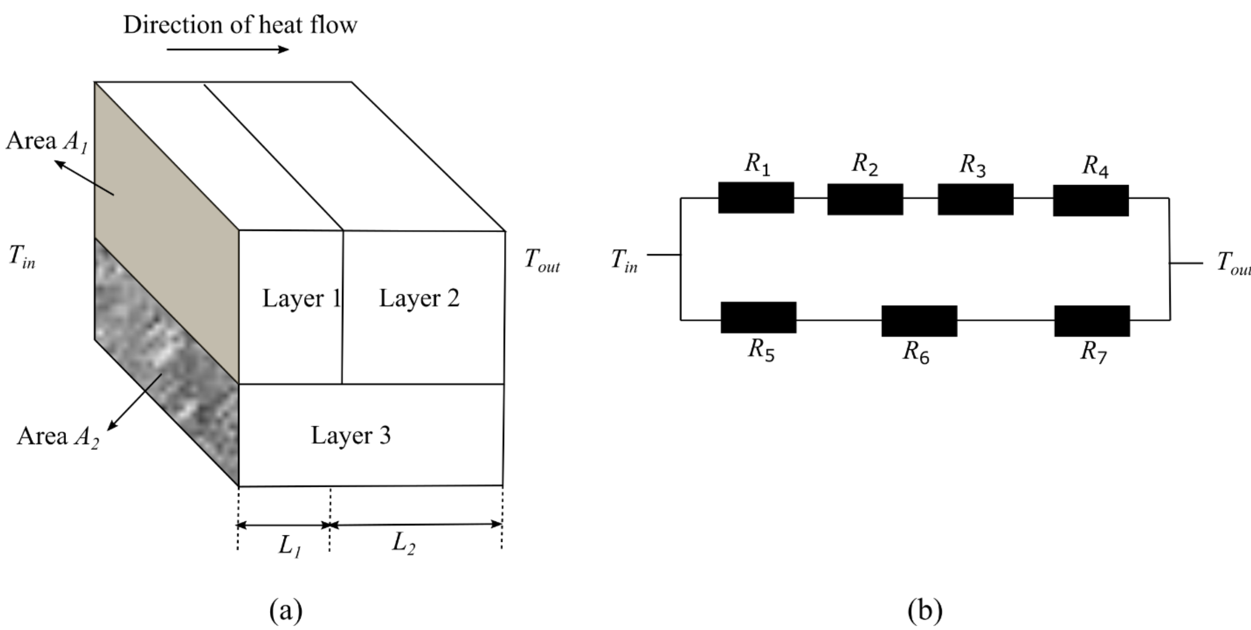


Table 1: Description and formulation of thermal resistances in the boundary shown in Figure 4.

Resistance #	Description	Formula
R_1	Thermal resistance for convection between inside air and area A_1 of layer 1.	$\frac{1}{hA_1}$
R_2	Thermal resistance for conduction through layer 1.	$\frac{L_1}{k_1A_1}$
R_3	Thermal resistance for conduction through layer 2.	$\frac{L_2}{k_2A_1}$
R_4	Thermal resistance for convection between outside air and area A_1 of layer 2.	$\frac{1}{hA_1}$
R_5	Thermal resistance for convection between inside air and area A_2 of layer 3.	$\frac{1}{hA_2}$
R_6	Thermal resistance for conduction through layer 3.	$\frac{L_1 + L_2}{k_3A_2}$

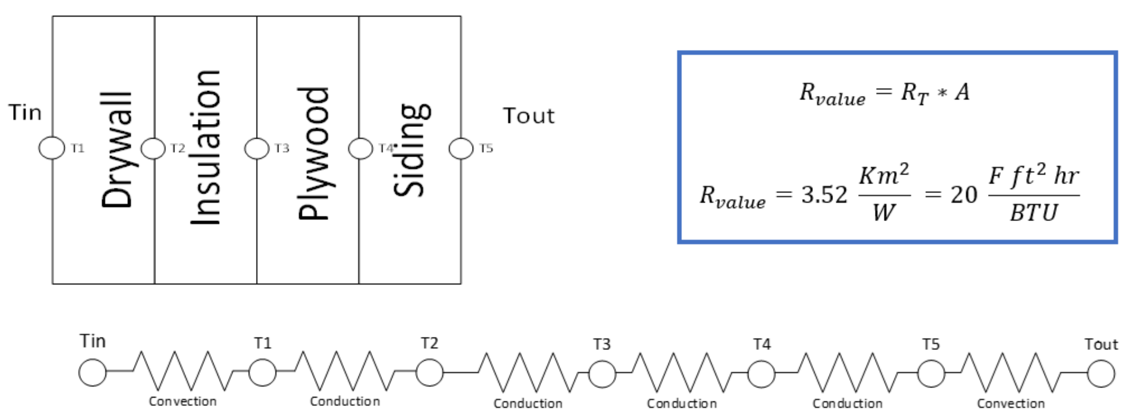
R_7	Thermal resistance for convection between outside air and area A_2 of layer 3.	$\frac{1}{hA_2}$

To calculate R_{house}, the house external boundary is divided into walls, ceilings, windows, etc. For each boundary, total resistance is calculated and all of those are added in parallel configuration using the method described above in this section. ME students used MATLAB [18] for calculations. Figure 5 shows an example of thermal resistance model of the exterior wall in the house, done by ME students. The wall consists of four layers: drywall, insulation, plywood, and siding. The resistance network between inside and outside has six resistances in series, which are calculated using formulas for conduction and convection as shown in Table 1. R_T is total thermal resistance for the wall between inside and outside air. R_{value} is R-Value used in building code requirements [13]. R_T and R_{value} are related as follows:

$$R_{value} = R_T\, A,$$

where A is surface (or cross-sectional) area of the wall. In [13], U-Factor is inverse of R-Value. For the wall shown in Figure 5, R_{value} is 20 ft^2-°F-h/BTU from the table SPS 322.31-1 in [13]. The R_{value} is used to select appropriate insulation material and thickness by using the resistance equations in Figure 5. For every boundary, R_{value} is selected from the table and then layer properties as thickness and conductivities are calculated.

Figure 5: An example of student work: model one student team used for the exterior wall.



$$R_T = \frac{1}{\bar{h}A_{wall}} + \frac{L_{drywall}}{k_{drywall}A_{wall}} + \frac{L_{insulation}}{k_{insulation}A_{wall}} + \frac{L_{plywood}}{k_{plywood}A_{wall}} + \frac{L_{siding}}{k_{siding}A_{wall}} + \frac{1}{\bar{h}A_{wall}}$$

C. Designing the Photovoltaic (PV) System:

The project goal for the computer & electrical engineering (CEE) students was the design of a grid-tied residential solar photovoltaic (PV) system on the roof of the proposed house to meet the client's expectation of balancing the energy needed with a renewable energy source. The project was divided into two parts. Phase one focused on plug load and phase two included the energy required for space conditioning.

Phase 1: All students calculated an average monthly electricity consumption (plug-load) in kilowatt-hours (kWh). Students used their personal utility bill or added up the following equation:

$$W = P * t = V * i * t,$$

where W, P, V, i, and t, are energy, power, voltage, current, and time, respectively, for each appliance and other electric devices they use in their household. In addition, they calculated how much carbon dioxide is produced by the number of kWh consumed per year, depending on the energy source for the electricity (e.g., coal, natural gas, and petroleum) using data from U.S Energy Information Administration (EIA) website [19]. Figure 6 shows an example of student work for total carbon emission per month by fuel type. For example, carbon emission per month due to coal is 3737.23 pounds.

Figure 6: An example of student work: total carbon emission (in pounds) per month by fuel type.

NATURAL RESOURCE	POUNDS PER KWH	TOTAL POUNDS OF EMISSIONS PER RESOURCE
COAL	2.23	3737.23
NATURAL GAS	0.91	1525.05
PETROLEUM	2.13	3569.64

Based on the calculated electricity need (kWh), students determined the number of solar panels required to offset the load. They used PVWatts® Calculator tool [20] developed by National Renewable Energy Laboratory (NREL) and other online resources provided (e.g., commercially available solar panels). They calculated the battery bank capacity needed to store enough energy for a day. They sized and selected the solar charge controller, inverter, circuit breakers, junction box, and other components and developed a one-line electrical diagram for the solar PV System.

Phase 2: In phase two, students included the energy load for conditioning the house provided by mechanical engineering students. ME students provided two different energy loads; one based on a building envelope compliant with the Wisconsin Residential Dwelling Code [13], and the other with a significantly optimized/improved building envelope to lower the energy load by 40 % for conditioning. CEE students used the same method as in phase 1 to design the solar PV system for these two energy loads.

Section 4: Findings

Integrated with course objectives - students learned about critical parameters driving energy needs, and carbon emissions associated with conditioning of residential buildings. Students designed a renewable energy system that can offset the energy load. Discussions included state regulations that guide construction methods and insulation requirements, as well as environmental commitments that count on the building industry to adapt to changing environmental conditions.

Mechanical engineering (ME) students calculated energy load per month. For February month, they calculated energy load of 2,827.36 kWh for a code-compliant building envelope and 1,653.34 kWh (around 40 % reduction from 2,827.36 kWh) for an improved envelope. This load covers only the space conditioning (heating or cooling). CEE students designed the solar photovoltaic (PV) system based on the two energy loads, 2,827.36 kWh and 1,653.34 kWh. Students used the following equation to calculate the number of panels:

$$Number\ of\ panels = \frac{(energy\ requirement\ per\ day)*(efficiency\ factor)}{(average\ peak\ sun\ hours)*(solar\ panel\ wattage)}.$$

Space conditioning for the improved building envelope will require an approximate number of 54 panels (350 W) to offset the energy load. Based on the panel size, about 1,053 ft^2 of roof area is required for the system. Students also provided an estimate for material cost. The client found the results useful in deciding to either invest in additional insulation and a smaller solar system or build to building code standard and add a large-scale solar system.

At the end of the semester, students were invited to participate in a post-project survey. Both pre- and post-project surveys were approved by IRB at the University of Wisconsin-Stout. Table 2 shows the number of students in each course and number of students who chose to complete the survey. Out of total 68 students, 66 students completed the pre-project survey, and 62 students completed the post-project survey.

Table 2: Number of students and responses to pre-project and post-project surveys.

	Pre-project survey		Post-project survey	
	CEE	ME	CEE	ME
Number of students in class	22	46	22	46
Number of students who completed the survey and gave consent to use the survey data	21	45	19	43

The surveys consist of both objective and subjective questions. Table 3 shows student responses to some of the objective questions in the surveys. NA means that a question was not asked. 55% of students completing the surveys were not aware of Wisconsin's goal of a 100 % carbon-free electricity by 2050 [21]. Only 33% of students feel topics of sustainability and renewable energy are sufficiently covered in their program courses. 82% of students found the project informative regarding energy use in residential buildings, as shown in Table 3.

This section further discusses student responses to some subjective questions.

For this question, asked in post-survey, some CEE student responses are:
"Can you suggest topics that could be included in the engineering curriculum to prepare you better to participate in a climate change discussion?"

- *"All types of renewable energy sources, and not just solar. Talking about wind, nuclear, and other sources would provide a better understanding."*
- *"More talk about the effects of carbon emissions on the planet and timelines for what has changed to the planet over the years of emissions."*

For the same question, some ME student responses are:

- *"Sustainability. Some sort of basic understanding how fuels are made (both petrol and ethanol). Follow the track of how recycled plastics move and where they actually end up."*
- *"Learning more about the pros and cons of renewable energy, most of all learning what works better than other things and debunking common misconceptions"*

Table 3: Student responses to objective questions in pre-project and post-project surveys.

Survey question	**Survey response**	**Pre-survey**		**Post-survey**	
		CEE	ME	CEE	ME
Many communities and states have set goals to reduce carbon emissions. Wisconsin is aiming for a 100% carbon-free electricity target by 2050. Are you aware of this goal?	Yes	11	19	NA	NA
	No	10	26	NA	NA
Do you think this is a relevant goal for society?	Yes	20	40	NA	NA
	No	1	5	NA	NA
Do you think this is an achievable goal?	Yes	14	27	15	25
	No	7	18	4	18
Have you watched any movies or documentaries, dealing with climate change or renewable energy?	Yes	8	21	NA	NA
	No	13	24	NA	NA
For your career goals - would you consider knowledge about renewable energy sources to be:	Indispensable	4	14	2	9
	Relevant	16	28	13	31
	Unimportant	1	3	4	2
Are you interested in pursuing a career within the field of renewable energies?	Yes	13	27	9	25
	No	8	17	10	18
Do you feel topics of sustainability and renewable energy are sufficiently covered in your required program courses?	Yes	10	12	12	7
	No	11	32	7	35
Do you anticipate that the goal of carbon reduction and transition to renewable energy sources will impact your career path?	Yes	17	36	16	36
	No	4	8	3	7
Was the collaborative semester project informative regarding energy use and renewable energy in residential buildings?	Yes	NA	NA	16	35
	No	NA	NA	3	6

One unexpected result was that the number of students interested in pursuing a career within the field of renewable energy dropped slightly in post-survey compared to pre-survey. We do not have an indicator to determine the reasons for this result in the surveys. As mentioned above, 85% of students found the project informative. Also, instructors had positive feedback from students about the project during the semester. It might be related to the program curriculums. For example, CEE program curriculum focuses more on embedded systems. The field of renewable energy is not closely related to embedded systems. It is closely related to power electronics, electronic control, and power systems. There are few courses in the program related to those areas to help students develop interest. In future, post-survey can be modified to have better indicators to measure reasons behind the slight drop in students' interest in pursuing a career within the field of renewable energy.

Overall students expressed interest in having classes on renewable energies.

For this question asked in post-survey, some CEE student responses are:
"Was the collaborative semester project informative regarding energy use and renewable energy in residential buildings?"

- *"It was interesting to see how the mechanical engineers did their part on the project and how they got the values they needed to get us our information."*
- *"This class made us look at individual charges for an electricity bill, it was very informative about renewable energy as we were designing a renewable energy system"*

For the same question, some ME student responses are:

- *"I found it very interesting how few changes had to be made to the structure of the residential home in order to reduce the energy load by 40%, and thus the carbon emission by 40% also. I also think that attending the CEE collaborative presentation was very informative as to seeing the estimated costs of how a residential building could (essentially) reduce their carbon output to 0."*
- *"Provided ideas for how a single person, such as a homeowner, can take a small step in the right direction of a more energy-efficient home, which subsequently leads people in a position closer to a solution of a broader and national issue of energy usage, waste, and inefficiency."*

Section 5: Conclusion and Future Direction

This study explores students' interest in topics of renewable energy, carbon reduction, and climate change. After the coursework was completed and students presented their work to peers and engineering and technology department at the University of Wisconsin-Stout, students presented their work at an annual event "Research in the Rotunda" organized by the State of Wisconsin. In this event, students present and discuss their research with State politicians.

Currently, this project is embedded in the course objectives and content of existing course curriculum. For future work, we propose that additional time should be contributed to background information, student discussions and peer-to-peer interaction. Students need more time to reflect. Other factors such as ventilation should be introduced to students and accounted for in energy load calculation. Students should be introduced to a high-fidelity energy simulation program such as EnergyPlus [22] to obtain a baseline solution. The sample size in current study is small. In future, we propose to include other programs such as engineering technology, manufacturing, and construction in the renewable energy project.

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