2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #52264

The Implementation of Sustainability-Focused Learning Modules for Sophomore Chemical Engineering Core Courses

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Abstract

To introduce sustainability concepts earlier in the curriculum, the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas developed sustainability-focused learning modules for three sophomore-level core courses: Introduction to Chemical Engineering, Fluid Mechanics, and Thermodynamics. Each module included a lesson plan, interactive classroom activity, and sample homework problems centered on a real-world application of sustainability directly connected to course material. The overall goal was to integrate sustainability topics into the courses in a manner that is concise, engaging, and complemented existing course content. This paper describes the implementation and outcomes of these sustainability lesson plans. Interested students may take more advanced sustainability electives later in the curriculum.

Pre- and post-surveys were administered to sophomore-level students to assess learning and shifts in attitudes toward sustainability in engineering. Instructors also provided feedback on the ease of implementation, benefit to the class, and alignment with existing course material. Quantitative and qualitative results from the student surveys showed that the modules increased student awareness and interest in sustainability, however, some students displayed signs of eco-anxiety. Instructor feedback indicated the lesson plans were easy to implement and beneficial for connecting course content to sustainability issues. All of the instructors adapted the lesson plans to enhance student learning, demonstrating the flexibility and scalability of the plans.

Overall, the study demonstrates an effective approach to integrating sustainability topics into sophomore-level chemical engineering courses. The lessons learned in this study provide valuable insights for other programs planning to implement the sustainability lesson plans.

Introduction

Sustainability has become a prominent topic in engineering education as environmental and social challenges escalate. To meet employer demand and student interest, sustainability programs at universities have grown steadily over the past two decades [1]. The number of students entering engineering with the intention to make a positive contribution in this area appears to be increasing. Chemical engineers are uniquely positioned to make contributions in the field as they bring a strong foundational knowledge of energy systems, materials, process efficiency, and engineering design. As such, universities have a responsibility to equip chemical engineering students with sustainability competencies that prepare them to address global challenges and meet corporate sustainability goals [2].

Sustainability can be incorporated into engineering curricula through stand-alone courses [3,4] or by embedding content throughout existing coursework [5,6]. Stand-alone sustainability courses are often offered as upper-level electives, which may limit participation and delay student exposure until the junior or senior year. In order to develop sustainability awareness earlier in the curriculum, some departments integrate concepts throughout their curriculum. In the Ralph E. Martin Department of Chemical Engineering, sustainability topics have been incorporate into core sophomore courses such as Introduction to Chemical Engineering, Thermodynamics, and Fluid Mechanics, allowing students to develop sustainability perspectives along with their foundational chemical engineering knowledge.

Despite growing interest, integrating sustainability into existing courses remains challenging. Previous studies have shown that faculty hesitation is a significant barrier [7]. Faculty mention already full courses, lack of preparation or confidence in teaching sustainability topics, and a preference for relying on stand-alone courses to cover the material.

To address the challenges and increase sophomore-level exposure to sustainability, a set of sustainability-focused lesson plans was developed in prior work to serve as a resource for faculty [8]. The lesson plans were designed to support instructors seeking to integrate sustainability concepts into core sophomore-level chemical engineering courses. They were developed to align with existing course material and require minimal class time (less than 15-20 minutes).

This paper presents the results of implementing four sustainability lesson plans across three core chemical engineering courses: Introduction to Chemical Engineering, Fluid Mechanics, and Thermodynamics. The purpose of this study is to evaluate student interest and learning related to sustainability topics, as well as faculty perceptions of ease of implementation.

Sustainability Lesson Plans

Multiple sustainability-focused lesson plans were previously developed for three core sophomore-level chemical engineering courses: Introduction to Chemical Engineering, Fluid Mechanics, and Thermodynamics. The following lesson plans were designed to introduce sustainability concepts through topics that naturally align with the course material.

Introduction to Chemical Engineering

- CO_2 Emissions from Burning Waste Gases
- The Challenge of Waste Plastics
- Impacts of Dichloromethane (DCM) as an Industrial Chemical

Fluid Mechanics

- Natural Gas Transmission System and Sustainability
- Gravity-Fed Water Supply as an Energy Storage

Thermodynamics

- Environmental Impact of Refrigerants
- Waste Heat Reduction and Recovery

All lesson plans were intentionally designed to be concise, engaging, and easily adaptable. Each

includes background information to support instructors who may not have prior experience in sustainability topics, suggestions for in-class engagement, and a homework problem with a solution. The lesson plans were structured to require minimal preparation time and to be able to be implemented using 15–20 minutes of class time.
In this study, four lesson plans were implemented and assessed.

1. Introduction to Chemical Engineering - CO_2 Emissions from Burning Waste Gases
2. Fluid Mechanics - Natural Gas Transmission System and Sustainability
3. Thermodynamics - Environmental Impact of Refrigerants
4. Thermodynamics - Waste Heat Reduction and Recovery

The lesson plans used in this work are included in the Appendix for reference.

Classroom Implementation

Four of the sustainability lesson plans were implemented for three sophomore-level courses at the University of Arkansas – Introduction to Chemical Engineering, Fluid Mechanics, and Thermodynamics. A description of each course and the lesson plan implementation is given below.

Introduction to Chemical Engineering

Introduction to Chemical Engineering (Intro) is the first core course for chemical engineering students at the University of Arkansas and is most typically taken just after the required First-year Engineering course sequence in the freshman year. Intro is offered each fall and spring semester with the fall course being quite a bit larger than the spring offering. The only requisite for the course is University Chemistry II which is a co-requisite. In the fall of 2025 when the lesson plans were implemented, the course had 67 students registered - 60 sophomores and seven freshmen who already had AP credit for University Chemistry. All of the students were either chemical engineering majors or freshmen who planned to major in chemical engineering, and two of the students were pursuing a minor in sustainability.

The course instructor implemented the "CO_2 Emissions from Burning Waste Gases" lesson plan toward the end of the semester and noted that the lesson plan was implemented several weeks after the corresponding mass and energy balance material had been covered in the course. The instructor used a full class period to introduce and discuss the topic of carbon capture and sequestration. A PowerPoint presentation was prepared that provided more context and depth than the original lesson plan. Following the presentation, the suggested classroom activity was implemented. Students worked in small groups discussing the potential and limitations of carbon capture and then contributed to an all-class discussion. The classroom activity was allowed to continue for over 15 minutes. The homework problem from the lesson plan had been assigned when the material was covered in class, so it was not directly linked to sustainability at the time. Of the 67 students in Intro, 56 completed the pre-survey and 47 completed the post-survey.

Fluid Mechanics

Fluid Mechanics (Fluids) is a core sophomore-level course that introduces the fundamental principles of fluid flow. In the Ralph E. Martin Department of Chemical Engineering eight-semester degree plan, Fluids is shown as a sophomore spring course. The course is offered in fall, spring, or summer, with fall and summer generally having lower enrollments. Students may enroll in the general or Honors section, and both sections are combined in the lecture course. The course has a pre-requisite of Differential Equations and a pre- or co-requisite of Intro and Calculus III. Fluids is a chemical engineering course, but biological and biomedical engineering students can also take the course with the appropriate math pre- and co-requisites and their departmental Intro course as a co-requisite. In the fall of 2025, the course had 21 students registered. There were 16 chemical engineering majors, three biological engineering majors, one biomedical engineering major, and one freshman in the First-Year Engineering program. The biomedical and biological engineering students in Thermo and Fluids are most often juniors and seniors, while the chemical engineers are most often sophomores. This might impact the students' previous knowledge of sustainability. None of the students were pursuing minors in sustainability.

The lesson plan implemented in Fluids was "Natural Gas Transmission System and Sustainability". The instructor reported that over 30 minutes was spent covering the lesson plan, including the suggested classroom activity which involved a discussion of the U.S. natural gas pipeline system. The suggested homework problem was assigned and paired with a supplemental reading as an extra-credit opportunity. The supplemental article examines a natural gas compressor station in Ancona, Illinois, which was of particular interest to students and personal relevance to the instructor, as she knew the storage manager at the facility during the 1990s. Of the 21 students in the Fluids course, 19 completed the pre-survey and 18 completed the post-survey.

Thermodynamics

Thermodynamics of Single-Component Systems (Thermo) is the first of two core courses in Thermodynamics in the chemical engineering curriculum. Students may enroll in the general or Honors section, and both sections are combined in the lecture course. Differential Equations is a pre-requisite and Intro is a pre- or co-requisite for the course. Biological and biomedical engineering students may take Thermo with Differential Equations as a prerequisite and their Intro course as a co-requisite. In the eight-semester degree plan, Thermo is shown as a sophomore spring course. It is offered in the fall, spring, and summer semesters, but the fall semester historically has a lower enrollment of chemical engineers and a higher enrollment of other engineering majors. In the fall of 2025, 43 students were registered in the course: 16 chemical engineering students, 26 biomedical engineering students, and one biological engineering student. Thirty-four of the students were enrolled in the general section and nine were enrolled in the Honors section of the course. Both the general and Honors sections of Thermo contained chemical engineering and biomedical engineering students. Three of the students were pursuing minors in sustainability.

Two sustainability lesson plans were implemented in Thermo. The first lesson plan, "Environmental Impact of Refrigerants", was accomplished during the unit on thermodynamic cycles. During the presentation of refrigeration cycles, the instructor discussed the environmental impact of refrigerants and historical policy changes. Following the suggested classroom activity, the students were split into small groups to discuss the trade-offs between environmental impact, safety concerns, and cost for different refrigerants. The homework problem was assigned for reinforcement of the material. The lesson plan and classroom activity were accomplished in less than 15 minutes. Forty-two of the 43 students completed the pre-survey, and 41 students completed the post-survey.

The second lesson plan implemented in Thermo was "Waste Heat Reduction and Recovery". This lesson was covered at the end of the unit on thermodynamic cycles, during a discussion about the large amount of heat exhausted in power cycles. The suggested classroom activity asked the students to consider possible uses of the waste heat streams produced at the campus physical plant. The homework problem was assigned; however, the solution was incorrect, not taking efficiency into account. The lesson plan and activity combined took less than 15 minutes. Thirty-eight of the 43 students took the pre-survey, and 39 students completed the post-survey.

Survey Results and Discussion

Student Surveys and Feedback

Pre-surveys were administered to the students in all three courses shortly before the lesson plans were implemented. Students were not told the nature of the lesson plans in order to avoid a response bias. Pre-surveys were administered as an MS-Forms survey either before or during class and took less than five minutes to complete. The data from the student pre-survey responses are summarized in Table 1. The data show the baseline interest in and exposure to sustainability topics across the three sophomore chemical engineering classes.

Table 1. Student Pre-survey Responses showing Interest and Knowledge of Sustainability Topics in Engineering

	Intro (n = 56)	Fluids (n = 19)	Thermo (n = 42)	Weighted average across classes
Have you previously covered sustainability topics in your university engineering courses?[a]	3.25 (1.090)	3.89 (0.640)	3.36 (0.781)	3.39 (0.951)
I am interested in sustainability topics and applications.[b]	3.45 (1.194)	3.95 (0.759)	3.83 (0.871)	3.67 (1.046)
I am knowledgeable about sustainability topics and applications.[b]	2.75 (0.911)	3.00 (0.795)	2.95 (0.815)	2.86 (0.866)
I am knowledgeable about engineering applications of sustainability.[c]	2.59 (1.031)	3.00 (0.918)	2.9 (0.868)	2.77 (0.973)

Note: all values are reported as mean (standard deviation)
[a] Survey scale: 1 = not at all, 2 = I'm not sure, 3 = Yes - very little, 4 = Yes – some, 5 = Yes – a lot
[b,c] Survey scale: 1 = not at all, 5 = completely/thoroughly

The results of the pre-surveys showed that the students on average reported some, but very little, previous exposure to sustainability topics in their university engineering courses. Notably, students in all three classes reported higher interest in sustainability than their perceived knowledge of sustainability topics. This gap reveals the importance of incorporating sustainability topics in engineering education to leverage student interest and develop competence in the field.

Post-surveys were sent to all students in the classes within a day of the lesson plan implementation. The MS-Forms surveys contained quantitative questions and qualitative open-response questions. The results that directly compare to the pre-survey questions are given in Table 2. For the purposes of reporting, Thermo-R and Thermo-WH correspond to the Refrigerant and Waste Heat lesson plans, respectively.

Table 2. Student Post-survey Responses showing Interest and Knowledge of Sustainability Topics in Engineering

	Intro (n = 47)	Fluids (n = 18)	Thermo-R (n = 41)	Thermo-WH (n = 39)	Weighted average across classes
I am interested in sustainability topics and applications.	3.66 (1.077)	4.00 (0.816)	4.00 (0.733)	3.89 (0.815)	3.85 (0.901)
I am knowledgeable about sustainability topics and applications.	3.17 (0.807)	3.56 (0.497)	3.32 (0.756)	3.62 (0.625)	3.29 (0.734)
I am knowledgeable about engineering applications of sustainability.	3.23 (0.880)	3.50 (0.500)	3.39 (0.620)	3.51 (0.711)	3.34 (0.735)

Note: all values are reported as mean (standard deviation)
[b, c] Survey scale: 1 = not at all, 5 = completely/thoroughly

These post-survey data show a small but consistent increase in all three courses in interest in and knowledge of sustainability topics. Furthermore, in Thermo, where two lesson plans were implemented, the students reported an initial increase of interest with the first lesson plan, but their knowledge of sustainability topics increased after both lesson plans.

Students were asked to evaluate each lesson plan along with the associated classroom activity and homework problem. The results for each of the lesson plans are presented in Table 3. These results show that the students had an overall positive response to all of the materials. However, the lesson plan was viewed as the most beneficial element of each lesson.

Table 3. Student Post-survey Evaluations of Lesson Plans, Activity, and Homework

Course	Lesson Plan	Lesson[a]	Activity[b]	Homework[c]
Intro	CO_2 Emissions from Burning Waste Gas	4.13	3.47	3.6

Fluids	Natural Gas Transmission System and Sustainability	3.46	3.19	2.75
Thermo	Environmental Impact of Refrigerants	4.27	3.75	3.93
Thermo	Waste Heat Reduction and Recovery	4.1	3.69	3.79

[a]The numerical value is the average of three questions regarding the lesson plan. "Did you find the lesson plan interesting? Educational? Beneficial?" (1 = not at all, 5 = thoroughly)
[b]Did you find the class activity beneficial? (1 = not beneficial, 5 = very beneficial)
[c]Did you find the homework problem beneficial? (1 = not beneficial, 5 = very beneficial)

The post-survey asked students to evaluate the amount of time spent on the lesson plans. Table 4 shows both the faculty estimate of time and the student evaluation. It is noteworthy that, regardless of the time spent on the lesson, the students reported the duration felt mostly right or slightly short. This could be interpreted that the lesson felt rushed or incomplete, or that the students were interested in the material and wanted to continue the discussion.

Table 4. Student Post-survey Evaluations of the Lesson Duration

Course	Lesson Plan	Time Spent[a]	Student Evaluation[b]
Intro	CO_2 Emissions from Burning Waste Gas	50 minutes	2.91
Fluids	Natural Gas Transmission System and Sustainability	> 30 minutes	2.89
Thermo	Environmental Impact of Refrigerants	< 15 minutes	2.78
Thermo	Waste Heat Reduction and Recovery	<15 minutes	2.90

[a]reported in faculty post-survey
[b]The time spent on the lesson was: 1 = much too short (felt rushed or incomplete), 2 = somewhat too short, 3 = just right, 4 = somewhat too long, 5 = much too long (time outlasted interest or benefit)

Overall, the students reported that the lesson plans increased their interest in sustainability-related topics. The average student across all classes reported a 3.89/5 (1 = not at all, 5 = very much) in wanting to learn more about sustainability applications in engineering. Additionally, the average student across all classes reported a 4.08/5 (1 = not at all, 5 = very much) in wanting to see more sustainability content integrated into engineering courses. These data show that students have an interest in sustainability topics and would specifically like to learn more about these topics within an engineering context. One sophomore student mentioned that she would be interested in other sustainability courses:

> *I think the amount of sustainability included in this class was good as it isn't a sustainability-centered course and made me interested in courses based on sustainability*

Qualitative data from the student post-surveys were coded and categorized to determine key takeaways and emergent themes. First, students were asked to identify what topics they learned from the lesson plan. For each lesson plan, the majority topic was aligned to the lesson objective stated at the top of the lesson plan. Therefore, the anticipated student learning was accomplished. The most common responses are shown in Table 5 for each lesson.

Table 5. Key Topics identified by Students in Post-survey

Class	Key Topic identified by Students
Intro	Carbon Capture Methods
Fluids	Natural Gas Pipelines
Thermo-R	Balancing Trade-offs in Sustainability
Thermo-WH	Waste Heat

One unexpected theme that emerged in the qualitative section was a sense of pessimism regarding sustainability topics. In some lesson plans, the pessimistic comments were the second highest code. This could be due to the student's preconceptions or a reflection of the instructor's viewpoint. Some examples are seen in the following student quotes:

> *this is all really doing us no favors 50 years from now*
>
> *my main takeaway is the futility of it all*
>
> *I learned about the problems and how they're aren't any good ways to deal with it*

These comments are evidence of what some in sustainability education call eco-anxiety [9]. Further study is needed to determine the source of these perspectives. However, these comments serve as a reminder that sustainability topics can lead to psychological responses like hopelessness, worry and distress for students and instructors. In the classroom, it is important for instructors to ensure a balance of time discussing solutions as well as the problems [10,11].

When asked what could be done to improve the lesson plans, the majority of students either left no response or mentioned that they enjoyed the material. Of the suggested improvements, responses fit into three categories: have more sustainability concepts throughout the course, allow more time for deeper discussion, and include more pictures or videos to demonstrate applications in industry. Some sample comments from students are shown below.

> *Spread more small bits of information about sustainability in throughout the course of the semester*
>
> *Going more into depth. I would've liked to learn more.*
>
> *Maybe more visuals about how sustainability looks in industry like inside a factory/plant.*

Faculty Surveys and Feedback

The faculty instructors of the three courses completed surveys following the implementation of the sustainability lesson plans. All three instructors scored themselves 5/5 (5 = highest) for being interested in sustainability. However, two of the instructors scored 4/5 for feeling equipped to teach sustainability topics in their class. Their evaluation of the lesson plans is shown in Table 6.

Table 6. Instructor Post-Survey Assessment of the Lesson Plans

Course	Lesson Plan	Beneficial	Class Relevance	Ease of Implementation
Intro	CO_2 Emissions from Burning Waste Gas	4	4	5
Fluids	Natural Gas Transmission System and Sustainability	5	5	5
Thermo	Environmental Impact of Refrigerants	5	5	5
Thermo	Waste Heat Reduction and Recovery	5	5	5

In the post-surveys, the faculty instructors all gave the lesson plans a 5/5 (5 = best) for ease of implementation. The lesson plans also scored high in being beneficial (4.75/5) and relevant to the course material (4.75/5). While it was not necessary, each of the instructors extended the lesson plans to encourage further student learning. These implementation methods and qualitative comments are given below.

The instructor for the Intro lesson plan extended it to cover an entire 50-minute class period. He prepared a PowerPoint that introduced the topic of carbon capture and sequestration. The instructor of the Intro lesson plan mentioned that it was taught weeks after the corresponding material balance content. He acknowledged the lesson plan and activity would be better when aligned to the course content. However, he still felt it was beneficial to the students.

> *It fits well with what I am already teaching and gets students to think about sustainability from an angle that they might not have thought about in the past. It also reinforces student interest in sustainability and relates it to what the students are currently studying.*

The instructor of Fluids reported spending over an hour preparing the associated lesson plan. Besides the activity and homework, she provided an extra-credit opportunity that included a supplemental reading of Clear and Present Danger: The Leak [12]. The article is an investigative report of a natural gas leak that would be of interest to the students and was relevant to the instructor, due to her knowing the store manager. The instructor had this to say about the lesson plan used in Fluids:

> *I appreciated that it created an opportunity for students to engage in meaningful classroom discussion, offering a welcome change of pace from the typical lecture format.*

The instructor who implemented the lesson plans in Thermo reported that she teaches another sustainability elective in the chemical engineering curriculum. She mentioned bringing her knowledge of sustainability topics to supplement the material in the lesson plan.

> *I mentioned the history of refrigerants, particular to the automotive industry - starting with R-12, then Freon, and the recent move to R-1234yf* [13]. *The students were very interested to learn the progress that has been made and the impact of policy. I tied the tradeoffs to the 3 pillars of sustainability (people, planet, profit)* [14] *which the students seemed very interested in.*

In the Waste Heat lesson plan for Thermodynamics, it was discovered that the solution to the homework problem was incorrect. This did not impact the students' experience with the lesson, but it required the instructor to determine the correct solution. For future implementation, efficiency needs to be considered in the homework solution.

Conclusions and Future Work

Four sustainability-focused lesson plans were implemented across three sophomore-level chemical engineering courses in the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas. Each lesson was delivered including an associated classroom activity and homework problem for assessment. Student pre- and post-surveys, along with faculty post-surveys, were collected and analyzed to determine changes in student interest, knowledge, and attitudes toward sustainability, as well as instructor perception of the lesson plans.
Overall, the lesson plans were effective in increasing student interest and self-reported understanding of sustainability topics. The majority of students responded positively to the material and indicated a desire for more sustainability content in their engineering classes. However, some students expressed pessimism regarding sustainable solutions, which may be a sign of emerging eco-anxiety. This highlights the importance of intentionally balancing the presentation of sustainability challenges with actionable solutions.

Although the lesson plans were designed for implementation within 15-20 minutes, instructors adapted them to fit their course content and teaching styles. This demonstrates that the lesson plans are flexible and scalable, allowing instructors to adjust them to achieve different time constraints and instructional goals.

For future implementation of the lesson plans, instructors should consider allocating more time for greater depth of discussion. Faculty also noted that the lesson plans may be most effective when implemented concurrently with related course material. Student feedback suggests incorporating more visual elements, such as images and short videos, as well as examples from industry.

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Lesson Plan: CO_2 Emissions from Burning Waste Gases
Course: Introduction to Chemical Engineering

Learning Objective: Students will learn about the environmental impacts of burning waste gases with excess air to produce a stack gas containing CO_2, CO and unburned hydrocarbons and the potential use of carbon capture to mitigate global warming.

Teaching – As a supplement to the unit on material balances with excess air, a brief presentation will be made on the environmental impacts of producing CO_2 and water in the stack gas in the presence of ~20% excess air vs. the presence of CO, CO_2 and unburned hydrocarbon in the presence of <20% excess air. Carbon capture as a method of mitigating global warming will also be discussed. **(5 minutes)**

Environmental Effects of CO, CO_2 and Hydrocarbons in the Stack Gas:

- As a review, discuss the potential of producing a product gas containing, CO_2, CO and unburned hydrocarbons as a function of the % excess air. Note the operating problems that could occur in a plant that led to the presence of CO and unburned hydrocarbons in the stack gas in addition to CO_2.
- Briefly discuss the effects of CO, CO_2 and selected hydrocarbons on air pollution and global warming.
- Explain the concept of carbon capture for CO_2 removal from point sources that contain 4-5% CO_2, how it works and in what cases it is most likely to be implemented.

Interactive Classroom Activity – "Carbon capture on stack gases" (5-10 minutes)

Activity: Divide students into groups of 3-4 students. The student groups will discuss carbon capture as a way to mitigate global warming by comparing the following:

- CO_2 removal from a power plant stack gas that burns coal to produce 2 gigawatts of electricity and 800 $\frac{\text{tons}}{\text{hr}}$ of CO_2 at a concentration of 3%.
- CO_2 removal from the air surrounding the power plant that contains more than the 0.04% CO_2 in air but far less than the 3% concentration fund in the stack gas.

Debrief: Each group will report their findings to the instructor and class on the potential and limitations of using carbon capture to mitigate global warming. The class will spend a few minutes commenting on the benefits and challenges in using carbon capture.

Sample Homework Problem

"Material Balance Involving Combustion with Excess Air"

The Problem: A feed gas consisting of CH_4, CO_2 and N_2 is burned with 12% excess air to produce a product gas with the following Orsat analysis in mole %:

84.19% N_2
11.97% CO_2
2.86% O_2
0.99% CO

The following stoichiometric equations apply:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$$
$$CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O$$

a. Using material balances, determine the composition of the feed gas (%CH_4, %CO_2 and %N_2 on a molar basis).
b. Explain why the product gas contains undesirable CO based on the % excess air. What are some of the possible reasons for employing <20% excess air in the combustion of the feed gas?
c. What are some of the factors that determine whether carbon capture should be used in this process?

Solution:

a. The feed gas contains **69.7% CH_4, 22% CO_2** and **8.3% N_2** on a molar basis
b. If the process operates nominally at <20% excess air, there is a good chance that CO and CH_4 will be present in the product gas. In this case, CO is present. The operators did not likely choose to use <20% excess air but there could be problems with the air or feed gas flow (air flow too low or feed gas flow too high) or problems with the burner (perhaps clogging) which affects the flow.
c. Carbon capture could be an option if the product gas rate is high and there is a need or method of storage for the captured CO_2. The product gas contains <3% CO_2, which makes carbon capture a bit more difficult. The costs of purchasing and installing a carbon capture system and storing the captured CO_2 must also be considered.

Lesson Plan: Natural Gas Transmission System and Sustainability
Course: Fluid Mechanics

Learning Objective: Students will learn to evaluate greenhouse gas emissions associated with natural gas transmission systems based on flowrate and power requirement.

Teaching - During the unit on compressible flow, extend the teaching to integrate sustainability principles in the context of greenhouse gas emissions and energy use. **(15 minutes)**

1. **Overview of Natural Gas Transmission System in U.S.:**
   - Briefly discuss intrastate and interstate natural gas pipelines including pipeline structure and compressor stations.
   - Discuss the power requirements in compressor stations and efficiencies of the natural gas (NG) transmission system that impact the greenhouse gas emissions
   - Explain the fundamentals of global warming potential
2. **Environmental Concerns:**
   - Greenhouse gas emissions due to NG leaks during extraction and transport.
   - Greenhouse gas emissions due to energy use and combustion.
   - Disruption of ecosystems due to pipeline construction.
   - Potential watershed or groundwater contamination from methane leaks.
   - Air pollution (NO_x, CO, PM, VOCs, etc.) from the combustion of methane.
3. **Challenges:**
   - Evaluating environmental impacts
   - Mitigation approaches

Interactive Classroom Activity – Small Group Discussion of Pipeline System (5 minutes)

Materials: Provide a map (EIA, 2008) and figures showing the US interstate and intrastate natural gas pipelines and compressor stations.

Activity: Divide students into small groups. Ask them to discuss how the natural gas transmission system is relevant to sustainability in terms of energy use, emissions and efficiency.

Debrief: Each group will report their findings to the class on the potential of mitigating greenhouse gas emissions.

Sample Homework Problem

Question: A natural gas (NG) company is responsible for managing long-distance pipeline systems that transport natural gas across 1,000 miles in the U.S. Due to the inevitable pressure drop through the pipeline system, the company operates a series of compressor stations, which require a considerable amount of power in electricity. Although the company is working to minimize its environmental impact through practices like improving efficiencies and conserving energy, the company must first quantify the extent of the environmental impacts associated with its operations. In the following problem, consider the environmental impacts, specifically in the context of climate change, associated with the natural gas transmission system.

Natural gas consisting essentially of methane is transported through a 36-inch inside diameter steel pipeline over flat terrain. Each compressor station increases the pressure to 750 psia, and the pressure drops to 500 psia at the inlet to the next compressor station, which is 50 miles away. By assuming isothermal flow, determine the natural gas flowrate in cubic feet per hour and power requirement in kW, measured at 60°F and 14.7 psia. Additionally, evaluate the annual greenhouse gas emissions, expressed in carbon dioxide equivalent (CO_2-eq), resulting from the electricity use and natural gas combustion associated with these operations, using the data provided below.

Component	Information
Pressure drop between stations	250 psi
Electricity emission factor	0.7 kg CO_2-eq/kWh consumption
Natural gas emission factor	2.7 kg CO_2-eq/kg NG combustion

Solution Approach:

- Calculate the natural gas flowrate in cubic feet per hour and power requirement in kW. Using an equation to solve isothermal friction flow, calculate the natural gas flowrate. Then calculate the power requirement as the product of flow rate and pressure drop.

  Natural gas flowrate is **4.06×10^7 ft^3 per hour**
  Power required is **5.51×10^5 kW**

- Convert natural gas flowrate to kg per year then evaluate annual greenhouse gas emissions in carbon dioxide equivalent (CO_2-eq) using the information given in the table.

  Annual greenhouse gas emission is **1.84×10^7 metric ton CO_2-eq**

(US EIA, 2008). U.S. Natural Gas Pipeline Compressor Stations Illustration, Energy Information Administration, Office of Oil and Gas, Natural Gas Division, Natural Gas Transportation Information System. https://www.eia.gov/naturalgas/archive/analysis_publications/ngpipeline/compressorMap.html. Accessed 11 January 2025.

Lesson Plan: Environmental Impact of Refrigerants
Course: Thermodynamics

Learning Objective: Students will learn to evaluate refrigerants based on safety aspects, environment impact, and expense.

Teaching - During the unit on refrigeration cycles, extend the teaching to consider the impact of different refrigerants. **(5-6 minutes)**

1. **Overview of Refrigerants:**
    - Discuss how traditional refrigerants (chlorofluorocarbons, CFCs, and hydrochlorofluorocarbons, HCFCs) have been found to contribute to ozone depletion and climate change (high GWP).
    - Explain that The Montreal Protocol (1987) and Kigali Amendment (1992) were established as global agreements to phase out ozone-depleting refrigerants. Industry is transitioning to more environmentally friendly refrigerants.
2. **Environmentally Friendly Alternatives:**
    - Transition to new environmentally friendly refrigerants (R-134a, R-22) and natural refrigerants (Ammonia NH_3, Carbon Dioxide CO_2).
    - Seek refrigerants with low global warming potential (GWP).
    - Seek refrigerants with low (or zero) ozone depletion potential (ODP).
    - Mention the consideration of energy efficiency in applications.
3. **Challenges:**
    - Safety concerns (flammability, toxicity).
    - Higher costs and compatibility issues with existing systems.

Interactive Classroom Activity – "Choose the Best Refrigerant" (4-8 minutes)

Materials: Provide a table comparing three refrigerants (e.g. R-134a, R-1234yf, CO_2) based on their GWP, ODP, energy efficiency, flammability, and cost. The instructor can provide this information, or for a longer activity, allow students to look online for these values.

Activity: Divide students into small groups. Ask them to rank the refrigerants from most to least environmentally friendly based on the given criteria. Groups present their rankings with a brief justification.

Debrief: Discuss how trade-offs between environmental impact, safety, and cost influence decision-making in refrigerant selection.

Sample Homework Problem

Selecting a Refrigerant

Question: A refrigeration company is evaluating three refrigerants: R-134a, NH_3, and CO_2. The company prioritizes environmental impact and safety. Based on the following data, which refrigerant would you recommend and why?

Refrigerant	GWP	ODP	Flammability	Cost ($/kg)
R-134a	1430	0	Low	5
NH_3	0	0	Flammable	0.5
CO_2	1	0	Non-flammable	0.2

Solution:

- **Environmental Impact:** CO_2 is less harmful (GWP = 1, ODP = 0).
- **Safety:** CO_2 is non-flammable, while NH_3 is flammable and explosive.
- **Cost:** CO_2 and NH_3 is significantly less expensive ($0.2-0.5/kg vs. $5/kg).

NH_3 is the best choice based on environmental impact and cost. However, if safety issues are considered too much of a risk for the application, CO_2 is a good choice overall as a balance of environmental impact, safety, and cost.

Lesson Plan: Waste Heat Reduction and Recovery
Course: Thermodynamics

Learning Objective: Students will learn the importance of identifying and recovering waste heat to conserve energy resources, improve operational efficiency, reduce emissions, and produce cost savings.

Teaching - During the unit on heat engines, extend the teaching to point out the waste heat and explain the methods and benefits of waste heat recovery. **(8 minutes)**

1. **Overview of Waste Heat Recovery:**
   - Briefly discuss how heat engines inevitably produce waste heat streams, according to the second law of Thermodynamics. Additionally, many industrial processes produce waste heat in the form of hot exhaust gases, heated cooling water, and heat lost from hot surfaces.
   - Explain that recovering these waste heat streams reduces energy requirements which leads to cost savings and emission reductions, depending on the heat source, and can improve equipment efficiencies.
   - A good practice of engineering design is to look for waste heat streams in a process and consider how the waste heat can be recovered.
2. **Methods of Waste Heat Reduction and Recovery**
   - Waste heat can be reduced through insulation of equipment and pipelines.
   - Waste heat can be recovered and reused within the process through various methods such as heat recovery units (HRU), Combined Heat and Power (CHP), economizers, preheaters, and waste heat boilers. An Organic Rankine Cycle (ORC) is one method of recovering waste heat from low-temperature sources.
3. **Challenges:**
   - High cost of equipment compared to energy cost savings.
   - Low demand for low-temperature heat streams.

Interactive Classroom Activity – "Campus use of Waste Heat" (6 minutes)

Activity: Explain that the power generation plant on campus produces medium- (250^{o}C) and low-temperature (65^{o}C) waste heat. Have students on different sides of the room work in teams of three to brainstorm uses for the two waste heat streams.

Debrief: Have student groups report ideas back to the large group. Possible ideas are: Medium temp – preheat feed to the turbine to reduce fuel consumption and cost. Low temp - heat offices in the building, pre-heat hot water in the restrooms, provide heat to the agricultural greenhouses. Mention that medium-temperature waste heat sources have more value and applications than low-temperature heat sources.

Sample Homework Problem

Heat Recovery Exchanger Design

Question: A chemical process generates 5000 kW of waste heat through an exhaust gas that leaves at 400^{o}C. It is proposed that the waste heat be recovered by using it to preheat a 20 kg/s water stream at 25^{o}C. The heat capacity of liquid water can be assumed to be 4.184 kJ/kgK.

a. If 70% of the waste heat is transferred to the water stream through a heat recovery unit, what is the outlet temperature of the water stream?
b. Suggest possible uses for the water stream at that temperature.
c. What are the downsides to doing this?

Solution:

a. Outlet temperature = **84.8^{o}C**.
b. Uses of the warm water include preheated water in the process, hot water in the bathrooms, and heating for the offices, among other things.
c. Downsides include the cost of installing and maintaining a heat recovery unit. A low-temperature energy stream would be produced which has limited applications. A full cost analysis would need to be done to see if there is a true cost benefit.

Hussam Jouhara, Navid Khordehgah, Sulaiman Almahmoud, Bertrand Delpech, Amisha Chauhan, and Savvas A. Tassou. "Waste heat recovery technologies and applications." *Thermal Science and Engineering Progress*, vol. 6, 2018, pp. 268-289.