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# Sustainability-Focused Learning Modules for Sophomore Chemical Engineering Core Courses

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# Sustainability-Focused Learning Modules for Sophomore Chemical Engineering Core Courses


## Abstract

Sustainability is an emerging field in chemical engineering education, driven by global challenges, employer requests, and strong student interest. In response, many departments are incorporating sustainable engineering content into their curricula. Similar to process safety, sustainability can be taught as stand-alone courses or embedded within existing courses. In many of the departments, sustainability courses are offered as upper-level elective and graduate courses, providing focused in-depth coverage. However, this delays students' introduction to sustainability concepts until their junior or senior year. To provide earlier exposure, the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas has developed sustainability-focused learning modules for three sophomore-level core courses: Introduction to Chemical Engineering, Fluid Mechanics, and Thermodynamics. Each module includes lesson plans, interactive classroom activities, and sample homework problems, some of which extend current course content and require less than fifteen minutes of class time. These modules introduce foundational sustainability principles and emphasize their practical applications in engineering. By incorporating these learning modules, departments can offer an earlier, more integrated introduction to sustainability in their undergraduate curricula.


## Introduction

Sustainability has emerged as a critical focus in engineering education, driven by pressing global challenges, increasing employer demands, and growing student interest. Reports of resource depletion, climate change, and environmental degradation underscore the urgency for academic institutions to prepare the next generation of sustainability leaders. In response, sustainability programs at universities have grown steadily over the past two decades. The Association for the Advancement of Sustainability in Higher Education (AASHE), founded in 2004, states that there are now 756 institutions of higher education that have developed 4086 programs in sustainability [1]. While sustainability education spans disciplines such as business, sciences, humanities, and law, many of its impactful applications can be found within engineering. This has led some to suggest that the education of undergraduate engineers is essential for advancing global sustainable development [2].

Chemical engineers are uniquely positioned to make major contributions in the field of sustainability as they bring a strong understanding of renewable energy sources, sustainable materials, process optimization for efficiency, and the environmental impacts of engineering design. Industry and academia are aware of the growing need for chemical engineers equipped with sustainability mindsets and practical skills, and they are rising to meet the demand. The American Institute of Chemical Engineers (AIChE), the leading organization for chemical engineering professionals, is reflecting this move toward sustainability by adopting "Innovating for Sustainability" as one of its three core pillars and establishing initiatives such as the Institute for Sustainability (IfS) and the Sustainability Engineering Forum (SEF), which provide resources and credentials to advance sustainability within the profession [3-5]. AIChE identifies 218 institutions offering undergraduate sustainability programs [6].

Within undergraduate chemical engineering programs, there are diverse approaches to sustainability education. Some programs offer stand-alone sustainability courses as upper-level electives [7,8], while others introduce sustainability courses earlier in the curriculum as seminars [9]. Many institutions are working to integrate sustainability throughout their curricula [10-12] such as James Cook University which reports that over 30% of its chemical engineering program includes sustainability topics [13]. Dr. Richard Donnelly, a recognized leader in sustainability, argued that programs could benefit from both approaches – offering specialized sustainability courses as well as incorporating aspects of it into all core courses [14].

Work has been done to develop resources to assist chemical engineering educators in integrating sustainability topics into their curricula. AIChE and Engineering for One Planet (EOP) provide education modules online that can be used in specific courses [15,16]. The Environmental Protection Agency (EPA) has also funded the development of instructional models and suggested strategies to implement them in university classrooms [17]. However, barriers such as faculty concerns about adding material to already full courses, lack of confidence in teaching sustainability, and reliance on stand-alone courses to address these topics prevent or slow changes in integration throughout the curriculum [18].

To meet the growing demand for sustainability education among chemical engineering undergraduates, the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas has taken significant steps to incorporate sustainability into its curriculum. Since 2022, the department has introduced two upper-level/graduate elective courses—Introduction to Sustainable Process Engineering and Environmental Life Cycle Assessment [19]. These courses provide in-depth focused coverage of introductory topics and the fundamentals of life cycle assessment. While these courses have been successful, their limited capacity (25 students maximum) and upper-level placement restricts the audience to a portion of the junior and senior students, along with a few graduate students. To address these limitations, the department is planning to expand its sustainability efforts by integrating dedicated lesson modules into three sophomore core courses. This approach aims to establish an early and consistent foundation in sustainability concepts, emphasizing their importance and ensuring that all chemical engineering students have exposure to these important topics in advance of their internships or co-op experiences.

This paper focuses on the development of sustainability-focused learning modules for three sophomore core courses: Introduction to Chemical Engineering, Fluid Mechanics, and Thermodynamics. By addressing known barriers of implementation and offering practical, accessible resources for instructors, these modules aim to serve as a method of early integration of sustainability into undergraduate chemical engineering education.

## Development of Lesson Plans

The lesson plans were developed with the primary goal of integrating sustainability concepts into sophomore-level core chemical engineering courses in a manner that is concise, engaging, and aligned with existing course content. Each lesson plan is based on relevant examples and includes an interactive classroom activity and a sample homework problem with solutions. The lessons are designed to require less than 15 minutes of class time and build upon material already covered in the courses' learning objectives.

The following lesson plans were developed for each of the associated courses.

*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

Each lesson plan highlights the associated United Nations Sustainable Development Goals (UN SDGs) [20]. This attempts to raise visibility of the global framework among students and faculty and emphasize the broader application of the work [21]. Additionally, in accordance with the three pillars of sustainability [22], some of the lesson plans consider social and economic aspects to keep the emphasis from being exclusively on the environment.

## Overview of Lessons Plans

Each of the lesson plans are provided in the Appendix. An overview of each of the lesson plans, along with the interactive activity and homework assignment, is provided below.

### *Introduction to Chemical Engineering (Intro)*

As the first course for chemical engineering students, *Introduction to Chemical Engineering* (Intro) provides an ideal opportunity to introduce sustainability concepts and terminology. This foundational course covers topics such as careers in chemical engineering, mass and energy balances, unit operations, and chemical processes, all of which lend themselves to sustainability applications. For example, career opportunities in sustainability can be highlighted, as studies have shown that a basic understanding of sustainability applications in engineering can increase student motivation [23]. When teaching mass and energy balances, concepts like resource optimization and waste minimization can be incorporated. Discussions of energy efficiency can be introduced in unit operations, while stoichiometry lessons on combustion equations can address $CO_2$ production and carbon capture. Examples of chemical processes can highlight topics such as toxicity, process safety, recycle, and waste reduction. Given its foundational importance, Intro is a critical point to begin the integration of sustainability concepts. To support this, lesson plans for Intro courses have been developed on topics including $CO_2$ emissions from the burning of waste gases, the environmental challenge created by the abundance of waste plastics, and the health and environmental impacts of dichloromethane (DCM) as an industrial chemical.

*$CO_2$ Emissions from Burning Waste Gases*

As a supplement to the unit on material balances with reaction and, more specifically, the burning of hydrocarbons with excess air to produce energy, the students will learn about the environmental impacts of burning waste gases to produce stack gases containing $CO_2$, CO and unburned hydrocarbons and the potential use of carbon capture to mitigate global warming. The suggested activity engages students in small-group discussions to evaluate the benefits and challenges of carbon capture. The homework problem requires students to calculate feed gas composition from an Orsat analysis and assess the feasibility of implementing carbon capture for the process. This lesson plan introduces key concepts related to greenhouse gases, global warming, and carbon capture technologies, aligning with the UN SDGs 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 Climate Action.

*The Challenge of Waste Plastics*

As part of a unit that introduces students to topics in chemical engineering that are of interest to society, students will learn about the challenges of recycling plastics including waste collection, public incentives to recycle, energy use, potential products from recycled plastic and simplified economics. The lesson includes an instructor-led presentation that highlights technical and economic difficulties associated with recycling waste plastics. An interactive classroom activity encourages students to analyze one of the key challenges of recycling plastics and propose potential solutions. As a follow-up homework, groups will research topics like microplastic pollution, biodegradable plastics, or plastic bans and present their findings in a report or presentation. This lesson plan introduces the key concepts of waste minimization, pollution prevention, and the need for sustainable materials. It supports the UN SDGs 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land).

*Impacts of Dicholoromethane (DCM) as an Industrial Chemical*

As part of the unit on chemical reactions and stoichiometry, students will learn about the environmental impacts and health risks of dichloromethane (DCM) and explore sustainable strategies for reducing its use and mitigating its impact on the environment. The lesson provides an overview of DCM's applications as a solvent and the significant risks it poses to human health and ecosystems [24-27]. Recent EPA regulations will be discussed which are forcing industry to look for safer solvents. Through the interactive activity, students will consider the trade-offs and challenges of transitioning to safer chemicals. A homework problem covering stoichiometric calculations connects the concepts to practical applications. This lesson plan incorporates key concepts such as green chemistry and the impact of policy, connecting to the UN SDGs 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), and 13 (Climate Action).

### Fluid Mechanics

*Fluid Mechanics,* a core sophomore-level course, introduces fundamental principles of fluid flow (both compressible and incompressible), the equipment used in operations involving fluids, and system design. This course offers numerous opportunities to connect its content to sustainability concepts. For example, fluid flow principles can be applied to the design and optimization of systems that conserve energy, minimize resource consumption, and reduce environmental impact. These connections to sustainability can help students realize that a strong understanding of fluid mechanics can impact engineering design in ways that contribute to a more environmentally responsible future [28]. Lesson plans have been developed on topics of natural gas transmission and the use of a gravity-fed water supply for energy storage.

*Natural Gas Transmission System and Sustainability*

As a supplement to the unit on compressible flow, students will learn to evaluate greenhouse gas emissions associated with natural gas transmission systems based on flowrate and power requirements. Since natural gas production in the U.S. is projected to accelerate in the coming years, this lesson emphasizes the environmental impacts, energy demands, and efficiencies of transmission systems. During an interactive activity, students will analyze a map of the U.S. natural gas pipeline system to identify challenges and propose strategies for reducing emissions [29]. A homework assignment builds on these concepts by having students calculate greenhouse gas emissions in carbon dioxide equivalent units for a long-distance pipeline with compressor stations. By integrating real-world applications, this lesson highlights key concepts of energy infrastructure, emissions, and efficiency, supporting UN SDGs 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action).

*Gravity-fed Water Supply as an Energy Storage*

As a supplement on the applications of the Bernoulli balance to incompressible flow, students will learn to evaluate the energy conserved in a water supply tower system and overall efficiency as an energy storage system. With the recent interest in pumped storage hydropower as part of the alternative energy mix, this lesson plan applies foundational fluid mechanics concepts to the use of water towers for energy storage. Through an interactive group activity, students will evaluate the feasibility of installing a turbine in a water supply tower system to generate sustainable energy, balancing energy savings with cost considerations. In the follow-up homework assignment, students will calculate the pumping power required, power generated by the turbine, and overall system efficiency of a water supply tower system. This lesson plan highlights key concepts in renewable energy and energy storage while aligning with UN SDGs 7 (Affordable and Clean Energy) and 11 (Sustainable Cities and Communities).

***Thermodynamics***

The sophomore-level *Thermodynamics* course introduces foundational concepts such as energy conservation, entropy, efficiencies, and power and refrigeration cycles. These topics naturally align with sustainability principles, offering multiple opportunities for integration [30]. For instance, energy balance discussions can include renewable energy sources such as solar, wind, geothermal, and biomass. Lessons on entropy and the Second Law can explore waste heat recovery methods and strategies to improve energy efficiency. Power cycles provide a platform to examine energy production, storage technologies, and their environmental implications. Similarly, the refrigeration unit offers an opportunity to address the environmental impact of refrigerants and the importance of transitioning to eco-friendly alternatives. To support these connections, lesson plans have been developed on the environmental impact of refrigerants and waste heat reduction and recovery, providing students with real-world applications of sustainability in thermodynamic systems.

*Environmental Impact of Refrigerants*

As a supplement to the unit on refrigeration cycles, students will learn to evaluate refrigerants based on safety aspects, environment impact, and expense. This lesson introduces students to the environmental challenges posed by traditional refrigerants, recent global efforts to phase them out, and the challenges of transitioning to environmentally friendly alternatives. In the interactive group activity, students will compare refrigerants based on criteria such as global warming potential (GWP), ozone depletion potential (ODP), efficiencies, hazards and cost, and discuss the trade-offs required in refrigerant selection. A follow-up homework assignment asks students to recommend a refrigerant for a specific application, balancing environmental impact, safety, and economic considerations. This lesson plan introduces key concepts of global warming, ozone depletion, and environmental policy and aligns with UN SDGs 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action).

*Waste Heat Reduction and Recovery*

As a supplement to the unit on thermodynamic cycles, students will learn the importance of identifying and recovering waste heat to conserve energy resources, improve operational efficiency, reduce emissions, and produce cost savings. This lesson introduces the concept of waste heat as an inevitable byproduct of heat engines and industrial processes and emphasizes the role of waste heat recovery in enhancing energy efficiency. Through an interactive classroom activity, students will brainstorm practical uses for waste heat streams from a campus power generation plant. A follow-up homework assignment requires the students to use an energy balance to analyze a heat recovery unit and propose applications for the recovered heat [31]. This lesson highlights key principles of energy conservation and sustainable design and aligns with UN SDGs 7 (Affordable and Clean Energy) and 12 (Responsible Consumption and Production).

## Future Work

Future work includes the planned implementation of the sustainability-focused learning modules during the upcoming fall semester. This initial rollout will allow for the evaluation of their effectiveness. Pre- and post-assessments will be conducted to measure changes in students' knowledge of sustainability concepts and their ability to apply these principles in engineering contexts. The results of these assessments will inform future improvements to the modules, ensuring they meet educational goals and student needs.

Additionally, learning plans could be developed for junior-level courses, such as Heat and Mass Transfer and Reactor Design. Student learning could be enhanced by further development of learning modules for the laboratory classes. Introducing sustainability topics at both the sophomore and junior levels will provide students with a progressive and integrated understanding of sustainability as they advance through the curriculum.

## References

[1] Association for the Advancement of Sustainability in Higher Education (AASHE), AASHE Campus Sustainability Hub, https://hub.aashe.org/browse/types/academicprogram/#charts-panel, 2023, accessed 9 January 2025.

[2] Crofton, Fiona S. "Educating for sustainability: opportunities in undergraduate engineering." *Journal of Cleaner Production*, vol. 8, no. 5, pp. 397-405, 2000.
[3] AIChE. "The Global Home of Chemical Engineers." https://www.aiche.org/. Accessed 4 January 2025.
[4] AIChE Institute for Sustainability. https://www.aiche.org/ifs/. Accessed 5 January 2025.
[5] AIChE Sustainable Engineering Forum. https://www.aiche.org/community/sites/divisions-forums/sustainable-engineering-forum-sef. Accessed 4 January 2025.
[6] American Institute of Chemical Engineers (AIChE), Undergraduate Sustainability Programs. https://www.aiche.org/ifs/undergraduate-sustainability-programs, Accessed 9 January 2025.
[7] Walker, Heather L., and Edgar C. Clausen. "Development of an introduction to sustainable engineering course as a chemical engineering elective." *2024 ASEE Annual Conference & Exposition*. 2024.
[8] Rodriguez, Joaquin. "An elective course in Green Chemical Engineering and Sustainability." *2024 ASEE North Central Section Conference*. 2024.
[9] Stanford Chemical Engineering, "Chemeng 65Q: Chemical Engineering for Sustainability", Stanford University. https://cheme.stanford.edu/news/chemeng-65q-chemical-engineering-sustainability. Accessed 20 December 2025
[10] Chen, Christopher V.H.-H. and Courtney Pfluger, "Work-In-Progress: Integrating Sustainability Across the Chemical Engineering Curriculum". *ASEE Annual Conference & Exposition.* 2024.
[11] R. Hadgraft and J. Goricanec, "Engineering sustainability?!," in *Proceedings of the 2007 Annual Conference & Exposition*, Honolulu, Hawaii, June 2007, 10.18260/1-2—2352.
[12] Hoffmann, S., & Hua, I., & Blatchley, E., & Nies, L. "Integrating Sustainability Into Courses Across The Engineering Curriculum: A Faculty Workshop Model.", *ASEE Annual Conference & Exposition*. 2010.
[13] The Chemical Engineer. https://www.thechemicalengineer.com/features/embedding-an-awareness-of-sustainability-into-chemical-engineering-curricula/. Accessed 28 December 2024.
[14] Donnelly, Richard, and Carol Boyle. "The Catch-22 of engineering sustainable development." *Journal of Environmental Engineering* 132.2 (2006): 149-155.
[15] AIChE Sustainable Engineering Forum. "Education Modules." https://www.aiche.org/community/sites/divisions-forums/sustainable-engineering-forum-sef/education-modules. Accessed 4 January 2025.
[16] Engineering for One Planet. "Resources". https://engineeringforoneplanet.org/resources/. Accessed 9 January 2025.
[17] Slater, C.Stewart, Robert Hesketh, Daniel Fichana, Jim Henry, Ann Marie Flynn, and Martin Abraham, "Expanding the Frontiers for Chemical Engineers in Green Engineering Education." International Journal of Engineering Education, vol. 23, no. 2, 309-324, 2007.
[18] Matthew, Victoria, Cynthia Anderson, Cindy Cooper, and Surbhi Godsay Lipkin-Moore. "Integrating Sustainability into Engineering Education: Building a Pathway to Scale." *2023 ASEE Annual Conference & Exposition*. 2023.
[19] Reference will be provided upon acceptance of the paper.
[20] United Nations. "The 17 Goals." https://sdgs.un.org/goals. Accessed 10 January 2025.
[21] Ramirez-Mendoza, R.A., Morales-Menendez, R., Melchor-Martinez, E.M., Iqbal, H.M.N., Parra-Arroyo, L., Vargas-Martinez, A., and Parra-Saldivar, R., "Incorporating the sustainable development goals in engineering education." *International Journal on Interactive Design and Manufacturing*, vol. **14**, 739–745. 2020.

[22] United States Environmental Protection Agency (US EPA), "Sustainability Primer." https://www.epa.gov/sites/default/files/2015-05/documents/sustainability_primer_v9.pdf. Accessed 10 January 2025.
[23] Klotz, Leidy, Geoff Potvin, Allison Godwin, Jennifer Cribbs, Zahra Hazari, and Nicole Barclay. "Sustainability as a route to broadening participation in engineering." *Journal of Engineering Education*, 103.1 (2014): 137-153.
[24] US EPA, "Fact Sheet: Methylene Chloride or Dichloromethane (DCM)." [Online]. Available: https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-methylene-chloride-or-dichloromethane-dcm-0. Accessed 9 December 2024.
[25] R. Hossaini, M. P. Chipperfield, S. A. Montzka, A. A. Leeson, S. S. Dhomse, and J. A. Pyle, "The increasing threat to stratospheric ozone from dichloromethane," *Nat. Commun.*, vol. 8, no. 1, p. 15962, Jun. 2017, DOI: 10.1038/ncomms15962.
[26] M. Shestakova and M. Sillanpää, "Removal of dichloromethane from ground and wastewater: A review," Chemosphere, vol. 93, no. 7, pp. 1258–1267, Oct. 2013, DOI: 10.1016/j.chemosphere.2013.07.022.
[27] US EPA, "Risk Management for Methylene Chloride." [Online]. Available: https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-methylene-chloride. Accessed 9 December 2024.
[28] Rezek, Richard P., and Jeffrey R. Seay. "Educational Module: Incorporating Sustainability Principles into the Fluids Mechanics Course." https://www.aiche.org/sites/default/files/docs/org-entity/SustainableFluidsModule-Final.pdf. 2011. Accessed 4 January 2025.
[29] 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.
[30] Rezek, Richard P., and Jeffrey R. Seay. "Educational Module: Incorporating Sustainability Principles into the Chemical Engineering Thermodynamics Course." https://www.aiche.org/sites/default/files/docs/org-entity/SustainableThermodynamicsModule-Final.pdf. 2011. Accessed 4 January 2025.
[31] 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.

**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.

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**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.

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**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: The Challenge of Waste Plastics**
**Course: Introduction to Chemical Engineering**

**Learning Objective:** Students will learn about the challenges of recycling plastics including waste collection, public incentives to recycle, energy use, potential products from recycled plastic and simplified economics.

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**Teaching** - During the discussions of the research and employment opportunities for chemical engineers, the students choose topics for group presentations that are of interest to society as well as chemical engineering. A sample presentation will be made by the instructor which helps the students to understand the technical and economic difficulties in dealing with waste plastics. This presentation will be augmented to address multiple sustainability issues related to the recycle/reuse of waste plastics. **(20 minutes)**

1. **Overview of Waste Plastics and Their Effect on the Environment:**
   - Briefly discuss how plastics are produced by polymerization of petrochemicals.
   - Discuss the quantities of waste plastics, including microplastics, that enter the environment and the problems this creates.
   - Discuss the energy use of recycling plastics compared to the energy use of recycling aluminum cans, paper, cardboard and glass.
2. **Things We Can Do to Limit the Quantities of Waste Plastic Entering the Environment:**
   - Educate the public about the problems related to waste plastics.
   - Reduce the production of plastics by transitioning to other materials (packaging).
   - Charge consumers for using plastic bags or buying drinks in plastic containers.
   - Increase (mechanical and chemical) recycling efforts to offset the demand.
3. **Challenges:**
   - Waste plastic collection from the massive amount currently in the environment.
   - Physical property degradation of recycled plastics, limiting their application.
   - The cost of recycling plastics can be greater than the cost of virgin plastic.
   - Product development for recycled plastics, especially greater than 20%.

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**Interactive Classroom Activity – "Discuss one of the current challenges" (5-10 minutes)**

**Activity:** Divide students into groups of 3-4 students. Select one of the current challenges (instructor choice) for discussion in the small groups. The student groups will better define the problem and provide one or more ideas as potential solutions.

**Debrief:** Each group will report their findings to the instructor and class. The class will spend a few minutes commenting on the benefits and challenges of waste plastic collection and the potential for success of the ideas that are presented.

**Sample Homework Problem**

**"Assign other significant challenges to each group and have the groups prepare a short report on the findings and suggestions"**

**Question for Discussion and Reporting:** Consider these further significant challenges:

- How do we collect the massive quantities of plastic and particularly bottles that are in the environment? Think about the density of plastic and the many places we have plastic waste.
- Which countries or populations produce the most waste plastic pollution? Which countries or populations have been the most impacted by waste plastic pollution? Who should be responsible for the cleanup?
- Recycled plastic products typically incorporate 20% or less recycled material, meaning the remaining 80% consists of virgin plastic. Why is the incorporation of recycled plastic so limited? What needs to be done so that useful products can be produced containing more than 20% recycled waste plastic?
- What can we do, or should we do with recycled plastics? Make more plastic, generate energy, produce other chemicals or chemical intermediates?
- Should we ban plastic containers? Which countries are already banning plastic containers and what has been the outcome?
- Should we charge a refundable fee for plastic bags or bottles? Where has this been done and what has been the outcome?
- What is the current state of technology for biodegradable plastics? What limitations would there be in their application?
- What are microplastics? What are their health effects and what can we do about the problem?

Define the challenge that is assigned to your group and do a short background search of potential solutions found in the literature. Make one or more recommendations on one or more potential approaches for solving the challenge and prepare this as a short group report for grading. At the instructor's discretion, the groups could also prepare short Powerpoint presentations, which will also address oral communication.

**Lesson Plan: Impacts of Dichloromethane (DCM) as an Industrial Chemical**
**Course: Introduction to Chemical Engineering**

**Learning Objective:** Students will learn about the environmental impacts and health risks of dichloromethane (DCM) and explore sustainable strategies for reducing its use and mitigating its impact on the environment.

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**Teaching** - During the unit on chemical reactions and stoichiometry, discuss the industrial production of DCM and the move to reduce its use in industry due to its long-term impacts on health and the environment. **(5 minutes)**

1. **Overview of DCM**
   - DCM is a chemical that is widely used across industries, including pharmaceuticals, chemicals, textiles, and food processing. It is particularly valued for its ability to dissolve organic compounds.
   - DCM has been found to contribute to ozone depletion. It is highly persistent in groundwater (versus surface water) and toxic to aquatic organisms. It poses significant human health risks through inhalation and contact.
   - In 2024, EPA introduced strict workplace protections and prohibited most industrial and commercial uses of DCM due to its health hazards.
2. **Environmentally Friendly Alternatives:**
   - Transition to safer solvents such as methyl acetate and methyltetrahydrofuran.
   - Advantages due to production from renewable resources and recycling.
3. **Challenges:**
   - The transition to alternative solvents will add cost, require changes to existing systems, and increase complexity to the system.

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**Interactive Classroom Activity – "The Health & Environmental Impact of DCM" (4-8 minutes)**

**Activity:** Divide students into groups of 2-3. Have students look online to consider answers to one of the following questions:

- What types of processes utilize DCM in industrial and consumer applications?
- What are the health hazards associated with DCM?
- How can DCM contamination in groundwater be prevented and removed?
- What are the recent rulings on DCM from the EPA?

**Debrief:** Discuss how trade-offs between environmental impact, health risk, and cost influence decision-making in solvent selection. Hazards: human health risk through inhalation and contact, risk to aquatic life, ozone depletion, among other things.

**Sample Homework Problem**

**DCM and byproduct calculations**

**Question:** In an industrial chlorination process, methane ($CH_4$) reacts with chlorine ($Cl_2$) to form chlorinated methane compounds and hydrochloric acid (HCl) through a radical chain reaction. Initially, 160.0 kg/min of methane ($CH_4$) and 1420.0 kg/min of chlorine ($Cl_2$) are introduced into a continuous reactor operating at 400°C. The reactions are as follows:

**Initiation Step**

$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$

Reaction rate: 128 kg of $CH_4$/min.

**Propagation Step 1**

$CH_3Cl + Cl_2 \rightarrow CH_2Cl_2 + HCl$

70% of $CH_3Cl$ from Step 1 undergoes this reaction.

**Propagation Step 2**

$CH_2Cl_2 + Cl_2 \rightarrow CHCl_3 + HCl$

60% of $CH_2Cl_2$ from Step 2 undergoes this reaction.

**Termination Step**

$CHCl_3 + Cl_2 \rightarrow CCl_4 + HCl$

50% of $CHCl_3$ from Step 3 undergoes this reaction.

1. Calculate the mass of each chlorinated product ($CH_3Cl$, $CH_2Cl_2$, $CHCl_3$, $CCl_4$) and HCl at the end of the 4-hour reaction process.
2. Determine the mass of unreacted $CH_4$ and $Cl_2$.
3. How can the unreacted methane and chlorine gas be utilized?
4. What treatment strategies could be used for the HCL produced?

**Solutions:**

1. The mass of the chlorinated products at the end of four hours:

| | | | | | |
|---|---|---|---|---|---|
| $CH_3Cl$ | **29,082 kg** | $CHCl_3$ | **48,134 kg** | $CCl_4$ | **62,020 kg** |
| $CH_2Cl_2$ | **45,658 kg** | HCl | **163,148 kg** | | |

2. $CH_4$ Consumed: 30,720 kg Unreacted: **7,680 kg**

   $Cl_2$ Consumed: 316,809 kg Unreacted: **23,991 kg**
3. Unreacted methane and chlorine gas can be effectively separated, recaptured, and recycled back into the reactor system to enhance overall efficiency. Also, methane can serve as a fuel source for the heating process, resulting in improved energy utilization.
4. The hydrochloric acid (HCl) produced can be managed through several treatment strategies. It can be condensed and sold as a valuable by-product, captured directly for further use, or neutralized to minimize its environmental impact.

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US EPA, "Fact Sheet: Methylene Chloride or Dichloromethane (DCM)." [Online]. Available: https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-methylene-chloride-or-dichloromethane-dcm-0. Accessed 9 December 2024.

**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.

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**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 (NOx, CO, PM, VOCs, etc.) from the combustion of methane.
3. **Challenges:**
    - Evaluating environmental impacts
    - Mitigation approaches

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**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 **$4.06 \times 10^7$ $ft^3$ per hour**
  Power required is **$5.51 \times 10^5$ 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 **$1.84 \times 10^7$ 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: Gravity-Fed Water Supply as an Energy Storage**
**Course: Fluid Mechanics**

**Learning Objective:** Students will learn to evaluate the energy conserved in a water supply tower system and overall efficiency as an energy storage system.

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**Teaching** - During the unit on the mechanical energy balance, extend the teaching to consider the feasibility of energy conservation in a sustainable manner by installing a turbine in the water supply tower system. **(15 minutes)**

1. **Overview of Fluid Flow Systems:**
    - A water supply system is a common application in fluid mechanics.
    - Demonstrate the Bernoulli equation with pump work and friction factors to describe the energy interconversions that occur in flowing fluid.
    - Discuss fluid properties, static head, pipe sizing, power required by pump, power generated by turbine, and efficiencies using the same fluid flow systems.
2. **Environmentally Friendly Applications:**
    - Gravity flow can be used to generate sustainable energy.
    - Improving pumping efficiency is beneficial for both energy saving and mitigating environmental impact.
    - Optimization of pipe diameters and analysis of pressure changes can impact the energy requirements of a process.
3. **Challenges:**
    - The flow and pressure must be large enough to buy and maintain the turbine.
    - Electricity generating turbines must be close to existing electrical infrastructure. If it is far away, the project revenue will not be able to cover the cost of the line extension.

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**Interactive Classroom Activity – Evaluation of Water Supply Tower System (5 minutes)**

**Materials:** Provide a schematic diagram of a water supply tower system with an installed turbine.

**Activity:** Divide students into small groups. Ask them to evaluate and discuss the feasibility of a water supply tower system as an energy storage system. Groups present their calculations with a brief justification.

**Debrief:** Discuss how trade-offs between energy saving and cost influence decision-making in a water supply tower system.

**Sample Homework Problem**

**Calculating energy recovery**

**Question:** The city of Fayetteville purchases treated surface water from Beaver Water District at night when demand is low and pumps it to a hilltop water tower 500 ft above the lake. The water at 50 $^{o}$F is directed to flow through a turbine to generate electricity and to provide a reliable water supply to homes and businesses. For a 12-inch diameter pipe, 3,000 ft long and carrying 5,000 gallons per minute, what pumping power is needed if the pump efficiency is 60 percent? The friction loss is estimated to be 150 ft of water. How much power can be generated by the turbine, which operates at 85% of efficiency using the same flow rate? What is the overall efficiency of this installation as an energy storage system?

**Solution:**

- Using Bernoulli equation with some assumptions, calculate work done by pump by applying pump efficiency (60%) and friction loss. Then multiply the water flowrate to estimate pumping power required.

  Pumping power required: $\mathbf{1,380}\ \boldsymbol{hp}$

- The efficiency for the turbine is 85%. The potential energy and the kinetic energy are recovered, but friction loss occurs again.

  Power generated by the turbine: $\mathbf{380}\ \boldsymbol{hp}$

- Evaluate the overall efficiency of turbine installation in a water supply tower system as an energy storage system.

  Overall efficiency: **27.5%**

**Lesson Plan: Environmental Impact of Refrigerants**
**Course: Thermodynamics**

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

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**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.

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**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.

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**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.

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

**Activity:** Explain that the power generation plant on campus produces medium- (250ºC) and low-temperature (65ºC) 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°C. It is proposed that the waste heat be recovered by using it to preheat a 20 kg/s water stream at 25°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°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.

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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.