Paper ID #44622

An elective course in Green Chemical Engineering and Sustainability

Dr. Joaquin Rodriguez, University of Pittsburgh

Joaquin Rodriguez is an Assistant Professor at the Department of Chemical and Petroleum Engineering at the University of Pittsburgh since 2018. He received his bachelor degree in Chemical Engineering from Universidad Simon Bolivar (Caracas, Venezuela), MSc. and PhD in the same discipline from the University of Pittsburgh (1990-92). He developed his expertise in thermal cracking processes and advanced materials (cokes, carbon fibers) from oil residues, and became a business leader for specialty products (lube oils, asphalts, waxes, cokes) at Petroleos de Venezuela, PDVSA (1983-1998). He is a founding member of Universidad Monteavila (Caracas, Venezuela) (1998—2018) and became the Chancellor of this university (2005-2015), and the President of the Center for Higher Studies (2015-2018), including teaching in the Humanities. After rejoining the University of Pittsburgh, he has been teaching Pillar courses on Reactive Process Engineering, Process Control, Process Control Lab, and Process Design. In addition to technical courses, his service extends over curriculum development, outreach programs, alumni network, team and leadership skills development, global awareness, sustainability, and diversity, equity and inclusion.

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Introduction

The eco movements, spurred by the landmark publication in 1962 of Rachel Carson's "The Silent Spring" book, raised increasing concerns of negative environmental impacts of chemical products[1]. The concerns about the ongoing damage of the environment due to human activities prompted in 1968 the Economic and Social Council of UN to recommend to the UN General Assembly to convene a conference on "problems of the human environment"[2]. That first world conference on the environment was held in Stockholm in 1972, where a set of 26 principles were drafted for the common declaration and led to the establishment of the United Nations Environment Program (UNEP)[3]. After more than a decade, in 1983, the UN General Assembly established a World Commission on Environment and Development with an urgent call to propose a long-term agenda (targeting the year 2000) to deal effectively with the environmental issues impacting world development. The Commission, chaired by former Norwegian Prime Minister, Gro Harlem Brundtland, delivered the report "Our Common Future" (also known as the "Brundtland report") in 1987. The report presented an integrated perspective on development to also include the role of the international economy, population and human resources, food security, species and ecosystems, energy sources and efficiency, industrial growth, the growth of cities, the managing of the commons (oceans, space, Antarctica), peace, and security[4]. This integral approach would be further consolidated at the sequence of UN Conferences, starting with the UN Conference on Environment and Development in Rio de Janeiro on June 1992 (known as the "Earth Summit")[5]; the Special Session of the UN General Assembly in New York on 1997[6]; the Millennium Summit in New York on 2000, where the Millennium Development Goals (MDGs) were set for 2015 at the start of the new millennium[7]; the World Summit on Sustainable Development in Johannesburg on 2002[8]; the World Summit in New York on 2005[9]; the High-level Meeting on the Millennium Development Goals in New York, on 2008[10]; the Millennium Development Goals Summit in New York on 2010[11]; the UN Conference on Sustainable Development in Rio de Janeiro on 2012 (known as "Rio+20")[12]; the Special Event towards Achieving the Millennium Development Goals in New York on 2013[13]; the UN Summit on Sustainable Development in New York on 2015 (where the Agenda 2030, including the a plan of action for 17 Sustainable Development Goals to be achieved by 2030 was declared)[14]; and most recently the Stockholm+50 Conference on 2022[15].

Engineering education progressively experimented with the introduction of environmental issues in the curriculum[16, 17] in the last part of the 19th century. However, almost no significant institutional programs were advanced on the inclusion of "sustainability" or "sustainable development" in the engineering curriculum before the start of the 20th century[18]. In 1998, the Office of Pollution Prevention and Toxics (OPPT) in the U.S. initiated the "Green Engineering Project" to produce a text on "green" design methods to be included in the chemical engineering curriculum, resulting in the textbook by David Allen and David Shonnard "Green Engineering"[17].

Embedding “sustainability” in the engineering curriculum, and particularly in the chemical engineering curriculum started over two decades ago[16,19-20] spurring from the landmark publication of Anastas and Warner on “green chemistry” in 1998[21] where a set of 12 principles were proposed to guide new developments in the design, production, use and disposal of chemical products. Five years later Anastas and Zimmerman extended the proposal to twelve principles of “green engineering”[22], complemented with a similar proposal from the San Destin conference in 2004[23]. It was early recognized the power of the idea of “sustainable engineering” along with the challenges to develop adequate frameworks, methods, and metrics to be implemented in professional work, and the corresponding teaching and training of engineering students to prepare them for the job. The field was growing slowly during the first part of this 20-year period[24, 25]. Thürer et al.[26] have already presented an extensive systematic review of implementing sustainability development into the engineering curriculum during that period. The efforts were embedded in the UN program for a Decade of Education for Sustainable Development (2005-2014)[27]. However, the field has been gaining increased importance and extended application in recent years, as reflected in some updated reviews[28-30].

Integration of green chemical engineering with traditional chemical engineering

The implementation of sustainability into the engineering curriculum generally starts with the introduction of some sustainability related topics in existing courses, to be followed potentially by an entire module or course, and then it may evolve into a full program[26]. At our institution, the University of Pittsburgh, we have experienced a fast development along this pattern. There is now a wide spread of over one hundred sustainability focused or sustainability related courses across the various disciplines including the humanities, the social sciences, the professional schools (i.e., medicine, law, business), and the engineering. All this teaching effort is supported by sustainability oriented research projects and specific functional structures like the Mascaro Center for Sustainability Innovation, the Office of Sustainability, the Student Office of Sustainability and many more at the various schools, with leading officers at the Vice Provost level.

Our Department of Chemical and Petroleum Engineering has been a main actor in this development, mainly from sustainability-focused research (i.e., process intensification, carbon capture).However, the implementation has been slower at the teaching level. A few instructors have been introducing sustainability related content (i.e., lectures, homework assignments) in their traditional curricular courses (i.e., reaction engineering). The introduction of new content or the proposal of new courses always face the constraint of the limited availability of time in a well-packed traditional curriculum. Chemical engineering students at our institution follow a rigid sequence of six pillar semester courses after the common first-year engineering courses. These pillar courses provide for the career fundamentals (mass and energy balances, thermodynamics, transport phenomena, reaction engineering, process control and process design). These lecture courses are reinforced with simultaneous specific laboratory courses. The curriculum is enriched with additional mathematical and computational courses, chemistry courses (i.e. organic chemistry, physical chemistry, biochemistry), and two product-design courses. There are also requirements for a few elective courses (i.e. polymer engineering, petroleum engineering, or craft brewing) that can also be taken at other engineering departments, as our department have been presenting very limited options. There is also a requirement of six free-choice elective courses in the humanities and social sciences. Additionally, the most common track for students is to participate in three alternating semesters of cooperative experience with industry through internships. Surveys from senior students approaching graduation reveal reduced appreciation for non-technical courses (i.e., intensive writing courses, humanities and social sciences courses) but more demands for industry-oriented practical activities, mainly derived from their experiences at the co-op rotations. These results raise concerns about the lack of interdisciplinary approaches and the limited scope of the education of our students. However, potential proposals in this regard face enormous constraints including restricted class schedules and credit unit requirements, non-existent coordination between different departments and schools, and dominant technical priorities of faculty. In addition, we face limited student pre-existent motivation for courses that they may perceive as no straight job-related, as they are mainly unaware of what is at the frontiers and beyond their technical field, and are pressed by the urgency of finding a qualified job right after graduation. Notwithstanding, students have been asking for a broader offer of elective courses from our department that can connect them with job opportunities.

Our aim is to reorient the education of our engineering students towards more aligned, valuable, and sustainable contributions to solutions to the increasingly complex problems that they are expected to face in their professional careers. In the absence of a more general and concerted institutional approach, we have been exploring singular interventions fitting the curriculum and avoiding critical interference with major constraints like the ones highlighted above. As mentioned above, opportunities so far have been in the realm of existing courses where content and projects can be introduced, and the potential offering of elective courses, both targeting the same aim. In this context, our department decided to explore the introduction of an elective course on sustainability. This topic has been increasingly incorporated into engineering careers for several years now, as highlighted above. In fact, our institution has been also developing a large ecosystem of over 100 sustainability focused or related courses, led by the Geology Science Department and the Civil and Environmental Engineering Department, but also including courses from other departments in the sciences, humanities, and business. In addition, our institution hosts the Mascaro Center for Sustainable Innovation offering certificates, minors, and even a doctoral program in sustainability.

The elective course for our department was labeled GREEN CHEMICAL ENGINEERING AND SUSTAINABILITY. The course was planned during the academic year 2022-23 and launched in the fall of 2023, defined as a three credit units' elective course, with three 50-minute sessions per week, to be taught by one faculty assisted by one teaching assistant (graduate student). The course was targeting junior and senior students in the chemical engineering career, with some previous knowledge on mass and energy balances, separation processes, thermodynamics, and organic chemistry. The enrollment was surprisingly high with 31 juniors and 18 seniors, about 50% of the entire class of juniors, and 25% of the class of seniors (most of them have already taken their required elective courses at this time). This high enrollment contrasts with the enrollment at the five elective courses offered regularly by the department, generally below 10 students per class. Three students dropped the course at different moments in the semester.

Outcomes and teaching methods.

A compact selection of general outcomes is listed in Table 1. Specific outcomes were detailed for every lecture, guided by articulated Bloom's taxonomy statements. We made use of three predominant teaching methods: lectures, software demonstrations and in-class activities, and guest speakers, as detailed below. In addition, students were requested to develop two projects for team-based learning experiences and teamwork skills development. The structure and general content of the course was introduced in a 16-page syllabus providing orientation also for the assignments and projects. Though an elective course, deliverables were aligned with each ABET outcomes 1-5 and 7 for Criterion 3.

Table 1. List of selected general outcomes.

- Appraise the relevance of sustainability as an overall driving force for policies, regulations, industry, business, research, community service, and career development.
- Identify and apply the principles of green chemistry and green engineering.
- Analyze the scope of environmental, health and safety issues for green chemical engineering.
- Assess the use of relevant metrics for chemical reactions and chemical processes.
- Evaluate developments in chemical synthesis, reaction conditions, and the use of solvents, reagents, and catalysts in green chemical engineering.
- Describe innovations in bioprocesses for green chemical engineering.
- Compose process synthesis by combining flow diagrams, mass and energy balances, and main unit operations in the context of green chemical engineering.
- Describe heat and mass integration in green chemical processes.
- Contrast the approach for process intensification.
- Assess life cycle analysis for green engineering.
- Evaluate the impacts of material, procurement, energy, and waste in green engineering.
- Appraise the scope of total cost assessment of chemical processes.
- Examine methods for technology evaluation.
- Interpret circular economy.
- Revise special topics of high impact in green chemical engineering.
- Describe sustainability concepts and applications to non-technical audiences.
- Assemble teamwork skills to excel in green chemical engineering projects.

Lectures.

Lectures were arranged in the main blocks listed in Table 2. Lecture contents extensively drew from the adopted textbook "Jimenez-Gonzalez, C., and Constable, D. J. C., Green Chemistry and Engineering: A Practical Approach. Wiley, 2011"[31], but substantially complemented with other textbooks, articles and website sources, adding numerous pictures and diagrams to illustrate concepts and applications, and providing references for further research by students particularly interested in specific topics. Every lecture was presented with several homework problems (many taken from the selected textbook), but students were to select only one for every lecture or developing a proposal for homework based on the lecture content. The rationale was to open possibilities for student choices on the content and method of the assignment, while requiring some effort on exploring the various prompts. This strategy wanted to reinforce the underscoring diversity of topics and approaches in sustainability, and it is intended to expand on the homework problems in future editions of the course. In addition, every lecture was followed by concept quizzes (4-6 questions per lecture) posted on a virtual platform (Top Hat) to be reviewed and answered before the next class (generally within 30-40 hours availability to give opportunity to review the assigned lecture).

Table 2. Main blocks for lectures

- Introduction to sustainability, including the Sustainable Development Goals, the Environmental-Social-Governance (ESG) framework, and the Global Reporting Initiative (GRI)
- Principles and metrics of green chemistry and green engineering
- Process synthesis for green chemical engineering (reactors, separation units, conditions, heat and mass integration, solvents, catalysts), with scattered introductions to novel technologies and process intensification
- Bioprocesses
- Life cycle assessment, total costs, and circular economy
- Special topics

Guest speakers.

A strategic component of the course was the invitation of guest speakers. They addressed not only special topics but also main lectures of the course. Fourteen speakers enriched very significantly the scope of the course, presenting students with various and different perspectives on sustainability. Nine guest speakers came to the classroom, and five presented on remote. Six invited lecturers came from industry, four from academia, two from businesses, one from a governmental agency, and one from a non-profit organization. Table 3 lists the topics presented by speakers. Speakers were asked to introduce their talks referring to their personal journeys in sustainability, some of them recently incorporated into their starting jobs, some others already retired, most of them are in prominent positions in their careers. Students were asked to report the major takeaways after each presentation of guest speakers, collected through Top Hat. Student comments were compiled and shared with the invited speakers for reflection and appreciation. Some examples are posted in Table 4. The compilation of over 500 statements from students provides a rich assessment on the impacts that sustainability concepts and applications produce on the next generation of professionals.

Table 3. Topics presented by guest speakers.

Source	Topic
Academia	University Sustainability Plan and organized groups and activities on campus
Industry	Sustainability as Applied to Industrial Chemical Engineering
Industry	Sustainability Concepts and Drivers
Industry	Introduction to Environmental, Health, Safety and Sustainability (EHS&S) Consulting
Academia	Fundamentals of Life Cycle Analysis
Non-Profit	Innovation, Policy, and Climate Change
Industry	Reshaping Plastics
Government	Major Decarbonization Challenges of the Century. Opportunities at OE
Industry	From Chemical to Green Chemical Processing. Experiences developing processes for the Oil and Natural as industries
Academia	Process Intensification
Academia	Circular Economy
Industry	Green Chemical Engineering
Business	Starting Journeys in Sustainability
Business	Regional Business Network for Sustainable Development

Table 4. Selected examples of student takeaways after invited speakers' lectures.

"I thought it was super interesting to learn about the consulting side of things rather than working directly at the manufacturing site. I think there are a lot of things that people working at the site daily could overlook or ignore in terms of sustainability or safety, so it seems beneficial to have someone from the outside make sure you are in compliance and attaining your goals."
"It was reassuring that she was able to build a career around sustainability. I could see myself in some of the roles that she described."
"I liked how he kept reinforcing the positive outlooks about sustainability and the growth of the sustainable movement throughout his career. Usually this field is filled with much pessimism relative to sustainability, so it was refreshing to hear that innovation was moving in the right direction towards environmental considerations."
"My major takeaway is creating a circular economy is the key to making the world more sustainable and the culture of consumerism is working against that."
"It was cool to hear how many steps go into analyzing a company's environmental impact. LCA is extremely important for a company to be able to make changes to have a better impact on the environment."
"I learned how CO2 has affected us historically which was new information. It was good to learn his perspective on challenges we might face in the workplace when trying to be more sustainable such as proving a cost benefit and navigating the different requirements and organizations."
"I thought it was interesting how sustainability work in industry encompasses other groups of people in a company such as HR and executive leadership. I never really realized how broad it has to be to be successful."

A unique experience was the opportunity to share with the author of the adopted textbook. She asked for students to prepare questions in advance. We collected those questions by way of a homework assignment a few weeks before the talk, close to the end of the course. Students were requested to provide some rationale for their questions. The compilation provided an insightful selection of typical concerns that young professionals may have on sustainability after being introduced to the topic as provided in the course. Some examples are reported in Table 5.

Table 5. Questions and rationale from students for the textbook author.

What do you think the next major breakthrough in sustainability will be? I just am wondering where she thinks the field is headed. Sustainability seems to be ever changing and we are so far removed from the world in the bubble of university. So I want to know what is actually happening and what we should actually expect to come next.
Does the government play a big role in what advancements can be made in Green Chemistry/Green Chemical Engineering? The reason I ask this question is certain politicians find environmental issues to be less important than other politicians do. So, are there any instances of local/national politicians restricting the freedom in research or the funding received for research? Do policy changes often occur where green chemistry is impacted in any way?
I would like to ask Dr. Jimenez for her take on how students can gain a greater influence over the carbon footprints of the companies they work for. I think that a lot of what we have learned is important for our future development when we embark into the workplace, but there are still the questions that arise of how we can make a greater impact through the companies that we work for by making a difference in terms of sustainability. It's more difficult as a single person or as an employee who has less influence to try and make a difference on a larger scale. There is only so much we can do as individuals to make a difference that making those changes on a larger scale would have a much greater impact. I am interested in this question because I feel as though I understand what I can do on my own as an individual to reduce my carbon footprint and live a more sustainable lifestyle, but I do not always know how to approach this on a larger scale. Since I am getting older and will be moving to industry soon, I think being able to make larger changes is more important because they will have the greatest impact to make the world a better place. I would like to hear from Dr. Jimenez how she got to the spot where she is today and what she did to make changes when she had less influence that could reduce the carbon footprints of where she worked.
Will we ever be to a point where all catalysts used in a chemical process are derived from earth-abundant, non-toxic materials? I know that catalysts play an important role in making chemical process efficient, and a lot of catalysts are non-abundant earth metals, and we are at risk of running out of these catalysts.
With companies creating sustainable goals for the future like achieving carbon neutrality or having all recyclable products by a certain year, are those goals realistic? With cost being a huge issue, it is hard for companies to make sustainable changes. Even if companies do have the money to make changes, there is little incentive for them to put the money towards sustainability instead of reporting an increased profit margin to shareholders.
How Green Chemical Engineering will continue to enforce requirements onto businesses and factories in the future? Also, how will these laws implement changes in the current factories that have unsustainable processes? This question is interesting to me because I want to know what the industry will look like and how it will have to adapt in the future. For many years, companies have been in conversation about becoming more sustainable but when will the time come when harsher requirements are imposed. I think I am most interested in this concept because it seems there is a lack of laws and enforcements for the change to happen at a faster rate. I for see that the changes will happen in my lifetime and especially my career therefore I want to know what I should anticipate and where I could position myself to work in helping to create more sustainable ideals within companies and processes.

The set of questions was submitted to the author two weeks in advance of her talk. It was impressive how the author sorted out all the questions in four categories (Technical, Social, Influencing, and The Future) and provided insights for all of them, under the heading “Ask the right questions” already planned in her lecture. Some examples of students’ reactions to this approach are presented in Table 6.

Table 6. Examples of student reactions to the textbook author addressing their questions

“I am so glad that Dr. Jimenez looked at our questions beforehand and was able to answer everyone's inquiries. I feel like oftentimes people do not ask questions in person due to nervousness, but this time around an anonymous forum to ask about what sustainability concepts we were confused about greatly increased the value of the discussion and tailored it to the students' needs.”
“I feel that having the format of submitting questions before a guest lecture present was a great idea. A lot of people in the class have great questions but are anxious to ask in class. The answers were informative and throughout and I learned a great amount.”
“It was great to hear from Dr. Jimenez! It was nice that we had the chance to send in our thoughts beforehand. Hearing more about Life Cycle assessments helped to build on the knowledge we have covered earlier in the semester. I used some of this information to discuss life cycle assessments in another class’s group project this semester.”
“it is important to ask the right questions to improves sustainability and there is much room for improvement on small and large scales”

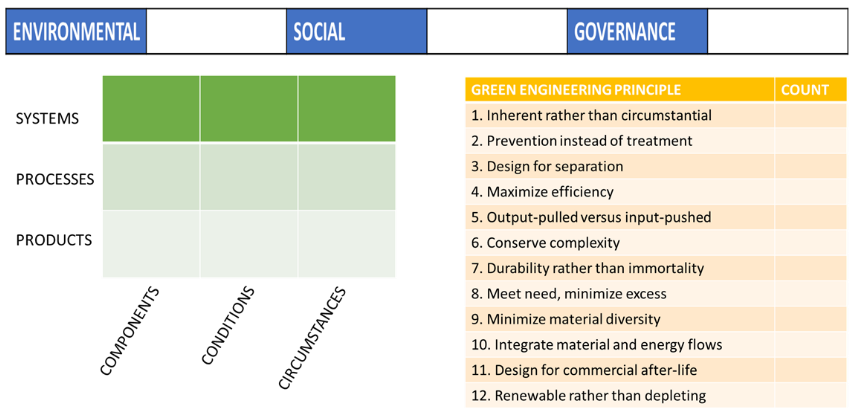
Software training and in-class activities

The course included two hands-on demonstrations of software applications. In the first experience, we introduced the task of selecting a solvent for a general situation described by a generic statement “Identify a solvent to be used in a reaction at 240 °C, lighter than water and with extreme low affinity for organic matter.” This approach provided the opportunity for open discussion in the class to understand and elaborate on the statement and to handle uncertainties in information. Then we introduced the “Solvent Tool” from the American Chemical Society Green Chemistry Institute[32], and proceeded through sequential steps to narrow down the selection to the best two candidates analyzing their rankings for Safety, Health, and Environment. After reviewing the characterization and engineering properties, we explored the availability from commercial suppliers.

The teaching assistant, a fourth-year graduate student, with experience on Life Cycle Analysis (LCA) software, conducted an entire session with a hands-on demonstration of OpenLCA[33] software for a case study to compare reusable vs. single use plastic water bottles, with a final evaluation of the impacts in areas like global warming, acidification, eco-toxicity, eutrophication, carcinogenic, etc.

There were several in-class activities fostering students' engagement, teamwork skills, and comprehension of concepts and applications included in lectures. Figure 1 illustrates the activity where students were to mimic a task group to assist the ESG CEO of the company on examining the acquisition of a start-up company.

Your team is assisting the CEO supervising sustainability (ESG) in your company.
She will be attending a Board of Directors meeting to discuss buying a start-up company.
Your task is to provide her with a list of selected questions that she can handle in the meeting to address the potential impacts and risks of adding that start-up to the company's portfolio.
There is no available disclosure of the startup's product or service. It is on final research step (patent pending).
Team members propose individual questions. No rejections. Team can refine questions.
Locate questions in the following maps. Submit questions in Top Hat.



GREEN ENGINEERING PRINCIPLE	COUNT
1. Inherent rather than circumstantial	
2. Prevention instead of treatment	
3. Design for separation	
4. Maximize efficiency	
5. Output-pulled versus input-pushed	
6. Conserve complexity	
7. Durability rather than immortality	
8. Meet need, minimize excess	
9. Minimize material diversity	
10. Integrate material and energy flows	
11. Design for commercial after-life	
12. Renewable rather than depleting	

Figure 1. In-class activity "Assist the ESG CEO"

Figure 2 illustrates the activity where student teams were asked to propose a budget distribution to fund projects on mitigating environmental impacts.

Your team has been assigned to a Task Force for assessing EPA in setting next year budget to support research on environmental issues. Please develop a proposal to allocate $ 1 million in funding. Include the team proposal in your individual homework assignment (HW5)

Area	$ K	Goal/Project. To develop research for advancing technology for
Climate change/CO2 emissions		
Ozone layer depletion		
Ground level ozone formation		
Soil/water acidification		
Eutrophication		
Organic matter in water		
"PFAS"		
Metals		
VOCs		

Figure 2. In-class activity "Assess EPA budget"

One of the most engaging in-class activities is illustrated in Figure 3. Students were informed on the last day of classes of a recent report[34] published a few days before. The report summarized the perception of about 3,500 experts and 20,000 people on the top future risks (out of a former list of 25 risks). Students were presented with the list of the top 12 risks (derived from the top 10 list from experts and general population) and asked to rank them according to their critical importance, without knowing the ranks on the report. Students were asked to produce first individual lists, then to share in pairs and agree on a common list, then in teams of 5-6 members and agree on a common list prioritizing consensus, followed by voting, and followed by heads-and-tails decisions. Finally, the entire class had to produce a consensus list, open to leadership dynamics to get it accomplished. After this sequence of activities, students were presented with the results from the report, and provided with a simple metric (Figure 3) to assess the differences comparing their individual, pairs, teams, and class lists with the one produced by the experts. In addition to reflect on the knowledge from topics presented in the course as related to global risks, the activity was intended to showcase the importance of dialogue and negotiations, and to show the incremental value of integrating diverse perspectives in the analysis of a problem. As reported in Figure 3, there was a closer approximation to the selection by experts, as students moved from the individual assessment to the assessment in pairs, in teams, and finally as the entire class. In addition, the activity was very engaging and it was interesting to observe all the team dynamics exercised to complete the ranks.

EXPERTS
3,500
50 COUNTRIES

GENERAL POPULATION
20,000
15 COUNTRIES

1. Climate change
2. Cyber security risks
3. Energy risks
4. Financial stability risks
5. Geopolitical instability
6. Macro-economic risks
7. Natural resources and biodiversity risks
8. New security threats and terrorism
9. Pandemics and infectious diseases
10. Pollution
11. Risks related to AI and big data
12. Social tensions and movements

FUTURE RISKS

INDIVIDUAL	PAIRS	TEAMS	CLASS	EXPERTS	POPULATION
				1	1
				2	9
				5	2
				11	12
				3	3
				7	8
				4	4
				12	10
				9	5
				6	7

CONSENSUS → VOTES → HEADS AND TAILS

SCORING
- If you hit the same position = +1
- If your choice is ± 1 position = +0.5
- If your choice is ± 2 position = +0
- If your choice is ± 3 position = -0.5
- If your choice is ± 4+ position = -1

CATEGORY	AVERAGE
INDIVIDUALS	-3.05
PAIRS	-2.39
TEAMS (5-6 MEMBERS)	-1.67
CLASS (31)	+1.00
POPULATION	-3.50

Figure 3. In-class activity "Rank the global risks with the experts"

Student-driven projects

The course has been intended to promote a committed involvement of students regarding sustainability as an overarching perspective for their professional and personal development. For this purpose, students were organized in self-selected 6-member teams to develop two projects. The technical project aimed to research one topic of interest that is a challenge for sustainable development. The outreach project, to be developed by the same team, was targeting to reach a non-technical audience with an activity to illustrate and promote concepts and practices for sustainable development. The technical project earned 40% of the final grade, and the outreach project 30%.

Technical projects included an initial 3-min presentation on the selected topic (due on the 2nd week of the course), a poster, a final 6-min presentation, and a report due on the last day of classes. In addition, students were requested to report a project management assessment (including a team contract, a project plan, a plan follow-up, and peer- and self-assessments on team performance). The essential instruction was to document the analysis of the problem with well-grounded scientific information (literature search) and then to propose a solution for a substantial improvement towards sustainable development, open to bold and imaginative proposals. Table 7 presents the topics developed in the technical projects by their titles and suggested proposals. The projects addressed a broad range of critical issues for sustainable development including maximization of energy efficiency (SDG 7), reducing negative impacts on health and the environment (SDG 13), clean water (SDG 6), and improved use of land resources (SDG 15).

Table 7. Sustainability technical projects and proposals

Team	Project
1	H2Hop Recovery Company Proposal for a start-up company to collect residues from local breweries, recycle and convert to some value-added products
2	Rainwater collection Proposal for organizing rainwater collection from university buildings and recycle
3	Replacing Toluene Proposal for alternative solvents identified as good replacement for toluene
4	Electric Arc Furnaces for Steelmaking Proposal for replacing blast furnaces with electric arc furnaces for steel production
5	Alternative Methods to High Impact Nitrogen-Based Fertilizers Proposal for advancing implementing of more environmentally friendly fertilizers replacing ammonia-based fertilizers
6	Hemp: A Green Alternative Proposal for expanding hemp farming to restore land and produce natural fibers
7	PFAS Removal from Drinking Water Proposal for technology to remove PFAS from contaminated drinking water streams
8	Maximizing Energy Efficiency of Nuclear Fuel Proposal for changing U.S. policies and allow for recycling nuclear fuel wastes

Outreach projects included an initial 3-min presentation (on week 2) to introduce the topic and the intended non-technical audience, a portfolio with documentation on the performed activities, a poster, a final 6-min presentation, and a short individual assessment on the impacts of the project. The portfolio should include edited videos of communicating with the audience, a quantitative assessment of the feedback from the audience, and an evaluation of the impact of the activity by the person responsible of the audience. Table 8 reports on the scope of the outreach projects. Students reached out about 350 people, 113 of those were young students at Middle or High School, 81 college students at youth clubs or sororities, 140 young people over social media, and 15 adults in a food-toy donation campaign.

Table 8. Sustainability outreach projects

Team	Project
1	A Greener Way to Get Around: Bike resources in the city
2	Community Gardens
3	Communicating Green Chemical Engineering in Social Media
4	Sustainable Art: from Trash to Treasures
5	Sustainability Practices as a Student
6	Green Roofs and Walls
7	Water Treatment Outreach Education
8	How to participate in the Circular Economy

Students took a very enthusiastic participation in these projects and realized the impact of their initiatives. The assessments from students, delivered as a main component of the project, were very insightful on the richness of the experience. One student summarized in the statement "I think our project was important because as college students we are the ones who are going to be responsible for the sustainability initiatives of the future. Many of us are soon to be entering the workforce where our decisions will impact sustainability for companies. It is important to do outreach work to not only educate oneself about the environment, but also to ensure that younger generations have the necessary knowledge to take care of the planet and feel passionate about sustainable development."

Finally, the CHE Sustainability Day event was established just in the basis of this course to have the students present their technical and outreach projects to a larger audience, including their classmates, and invited "judges" from industry and academia. The event was introduced as a celebration of the passion and commitment of students for a more sustainable development. Eleven representatives from industry and nine representatives from various academic departments and schools attended the event. Students made brief presentations of their projects, followed by a poster session for judges to engage in lively conversations with students. Judges used a standard rubric for the evaluation of the projects. Student teams were presented with five awards for their performance and alignment with the interests of companies or academic departments. In addition, a virtual competition for the most popular teamwork reached 210 votes in total.

Student performance and perceptions

Student performance was assessed by several methods. A series of concept quizzes, presented after every lecture, based on 4-6 multiple selection questions per lecture, for a total of 106 questions and graded by correctness was targeting to test for knowledge acquisition and keeping on track of lectures. A series of homework assignments, presented every week, with an extended list of problems for students to select 2-3 for solutions, many of them being open-ended, was targeting to test student application of the information presented in the lectures and in the suggested scientific literature. The technical project provided a convenient space for students to develop solutions to complex engineering problems, including considerations of public health, safety, welfare, and global, cultural, social environmental and societal contexts, and to function effectively on a team. The outreach project added the component of effective communication with a range of audiences. Table 9 summarizes the evaluation for these instruments, demonstrating average competency around 90%.

Table 9. Student performance evaluation

Evaluation	Grade %	Points	Maximum	Minimum	Average	St. Deviation
Concept quizzes. A total of 106 questions (multiple selection) by a student response web-based system (Top Hat)	10	106	105	41	89.15	13.73
Homework assignments. A total of 13 homework assignments (1-3 problems each)	20	100	100	20	94.44	13.50
Technical project. Including a proposal presentation, a team management report, a poster, a final presentation, and a team project report evaluation	40	100	97.50	75	88.12	6.62
Outreach project. Including a proposal presentation, a project portfolio, a poster, a final presentation, an individual assessment of impacts	30	100	98.76	70.07	91.71	5.24

One further assessment on student performance is derived from the evaluation of invited judges from industry and academia attending the CHE SUSTAINABILITY DAY 2023 where the students presented their technical and outreach projects. The 2-hour event included 5-minute presentations, technical project posters, and outreach project posters. A selection of 10 judges from industry and 9 judges from academia attended the presentations and interviewed students at poster sites. Table 10 reports a summary of the scores from judges, with averages around 80%, demonstrating a very satisfactory evaluation for team final products.

Table 10. Summary of scores for projects presented at the CHE SUSTAINABILITY DAY 2023. Results are normalized to 100%. Evaluation scale was 1-5.

Team	Presentation	Technical project poster	Outreach project poster	Overall
A	85.63	86.67	90.00	88.15
B	61.25	73.33	80.00	70.00
C	78.13	78.33	77.50	79.23
D	82.50	84.62	85.38	85.00
E	66.88	80.00	84.00	76.67
F	58.75	68.00	76.00	69.64
G	94.38	90.00	89.09	91.67
H	86.88	87.00	92.00	86.67
Average	76.80	80.99	84.25	80.88

A selection of student comments on the course is presented in Table 11, showing a very good appreciation for the introduction of this course in the curriculum

Table 11. Selected student comments about the course

"I think lectures were very informative, I really enjoyed all the invited lectures. The class was interesting and I would recommend to others because I think it covers a variety of areas."
"The instructor helped me to learn more about sustainability in the chemical engineering industry, we were able to apply many different sustainability principles."
"Homework stimulated independent thinking and projects were very open to different paths."
"Provided clear lectures and assigned projects that left an impact on me."
"I liked the homework assignments and in class exercises."
"Bringing in guest speakers was very interesting. It was cool to see people established in industry working in sustainability."
"The lecture slides were very detailed and some of the guest lectures were very interesting."
"There was a lot of material that got covered a bit too quickly sometimes. Possibly slowing down on some material would be helpful. In class activities were a great way of engaging us and I think you should do more of these in the future. Guest speakers were always fantastic and I learned a lot about real world applications from them. I think the sustainability project was a lot for us, especially when trying to find a local organization to work with to help develop ideas."
"I would suggest finding more opportunities to have in–class activities. I thought that the few that we did were very fun and engaging, and I would have liked to do more."
"I really enjoyed this class."
"I overall I enjoyed the class. I thought the information was informative and helpful. I really liked hearing from the invited lecturers about their experience and how they apply this into their job. I would recommend to someone else to take the class if it is offered again."
"I really liked the format of this class and how passionate and knowledgeable you were about the material."
"Ultimately, I am very satisfied that I took this course. It was interesting to hear about some of the subject matter and some of the guest speakers were fantastic. I would say that the class leans a little towards too easy, but as an engineer, it's nice to have a more relaxed, yet still informative and impactful class."
"The class was great and really enjoyable. I appreciated how it was low stress."
"I appreciate Dr. Rodriguez's initiative and courage to teach this much needed class this semester. While I do think there is room for improvement, I think this was a great first semester."

Conclusions

The inclusion of "sustainability education" in the engineering curriculum, and particularly in the chemical engineering curriculum, have evolved during the last two decades upon early adoption of environmental topics, with increasing importance in the last years, but still offering many needed opportunities for institutional contributions to the education of the next generation of engineers in this critical area.

Traditional chemical engineering curriculum offers limited opportunities to include new topics due to constraints on credit unit requirements, schedules, faculty priorities, student motivation, etc. However, changes in world development, industry and job markets, and students' interests are asking for convenient revisions.

A new elective course on Green Chemical Engineering and Sustainability developed for the Chemical Engineering Department and launched on fall 2023, attracted 49 students (about 1/3 of the combined population of junior and senior students).

A major contribution to the impact of the course came from fourteen invited speakers, including the author of the adopted textbook, who provided various perspectives on sustainability, as derived from their experiences in industry, academia, government and non-profit organizations. Students were asked to prepare questions and report major takeaways to enrich the reflection on the topics presented.

In-class activities and student driven projects (technical and outreach) provided for engaging and committed involvement of the students, moving beyond the presentation of concepts and theoretical approaches, into practical and lively applications.

The course brought the opportunity to establish a CHE SUSTAINABILITY DAY event at the department, targeting to integrate industry and academia representatives around the proposals from students on their projects. It provided for the opportunity to celebrate the passion for contributing to a better world, even with modest steps to realize the challenges that our societies are facing and the hopes to contribute to their solutions.

Acknowledgements

The author wants to express his deep gratitude to many colleagues who made this course possible. In the first place to Dr. David Sanchez, Dr. Ian Nettleship, and Dr. Tony Kerzmann, because their teaching on sustainability at the University of Pittsburgh was an inspiration for developing this new elective course. To Cliff Kowall and Dr. Conchita Jimenez-Gonzalez who provided the orientation and shared abundant materials for the content of the course, besides contributing as invited speakers and encouraging with their life-commitment for sustainability. To the invited speakers who shared their knowledge, experience and passion for sustainability: Omar Gadalla (AXEL JOHNSON), Ana Benavides (ARCADIS), Alan Schrob (NOVA-Chemicals), Dr. Caleb Woodall (U.S. Department of Energy), Dr. Natasha Vidangos (Environmental Defense Fund), Dr. Pedro Pereira (NANOS TECH), and Dr. Eric Beckman, Dr.

Götz Veser, Dr. Melissa Bilec, Robert Hacku, Lou Tierno and Cara Steinberg, all from the University of Pittsburgh.

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