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Redesigning Petroleum Engineering for a Sustainable Future: Integrating Clean Energy and Biofuels into University Curriculum

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Abstract

The global shift towards sustainability necessitates a transformation in engineering education, particularly within petroleum engineering programs traditionally centred on fossil fuels. This paper proposes a roadmap for evolving the Oil and Gas Engineering program at the University of Huddersfield into a comprehensive, sustainability-focused course that prepares engineers to navigate the complex challenges of climate change, rising CO₂ levels, and increasing waste. The integration of sustainability modules, including biofuels, petroleum contamination and remediation, biorefineries, and carbon capture, is suggested as a means to enhance, rather than replace, existing content. This approach aims to equip students with the knowledge and skills to balance traditional energy demands with emerging green technologies. Central to this initiative is the university's Energy Integration Lab (EIL), which provides advanced facilities such as anaerobic digestion systems, pyrolysis units, and micro gas turbines. Through hands-on learning experiences in the EIL, students will gain insights into the environmental impacts, benefits, and challenges of transitioning from fossil fuels to sustainable bioenergy systems. The lab will serve as a critical hub for interdisciplinary research, fostering collaboration between academia, industry, and local communities to develop innovative solutions in clean energy and waste-to-energy technologies. By embedding sustainability principles into the petroleum engineering curriculum, this project aims to produce graduates who are not only technically proficient but also environmentally conscious and capable of driving the energy transition. Through case studies, real-world applications, and industry partnerships, students will develop the skills necessary to address pressing environmental challenges, contributing to the achievement of global sustainability goals. This paper highlights how evolving the curriculum to focus on sustainability ensures that future engineers are prepared to thrive in an energy landscape increasingly shaped by the need for cleaner, greener technologies.

1. Introduction

Amid the global climate crisis, the need for sustainable energy solutions is urgent, yet fossil fuels still supply over 80% of global energy, making oil and gas engineering vital to the current economy. This creates a challenge for higher education: how to equip future engineers to support ongoing energy needs while advancing cleaner technologies. Rather than replacing traditional curricula, integrating sustainability and biofuel topics into petroleum engineering can develop professionals who are both technically skilled and environmentally aware. Higher education plays a pivotal role in advancing sustainability goals through both institutional leadership and curricular innovation. The United Nations' 2030 Agenda for Sustainable Development, anchored in the 17 Sustainable Development Goals (SDGs), calls for bold, transformative action to end poverty, promote equality, and ensure environmental resilience [1]. Education plays a vital

role in shaping future leaders to act responsibly within their professions and communities. In high-impact fields like oil and gas, engineering education is key to driving change. As Bowser et al. highlight, this requires not just technical training, but also mentorship and hands-on learning that foster inclusivity and real-world problem-solving [2]. Universities, as innovation hubs, must integrate sustainability into all disciplines and reduce their environmental impact to drive both knowledge creation and social transformation [3]. Over the past decade, many institutions have integrated sustainability into their campuses and curricula to create "sustainable universities" that embody sustainability in both philosophy and practice.[4], [5]. Fissi et al highlight the University of Florence case study, showing improvements in efficiency and innovation, but also stressing the need for strategic alignment, stakeholder engagement, and continuous refinement for successful implementation [6]. In the realm of petroleum engineering, these challenges and opportunities are magnified. Despite growing investment in renewable energy, oil and gas will continue to play a vital role in global energy supply for the foreseeable future. Understanding fossil fuel systems, their characterization, extraction, processing, and environmental impact, remains essential to managing the transition responsibly. The solution is to integrate sustainability with petroleum engineering, teaching students both traditional concepts and innovations like carbon capture and biofuels to empower them to drive industry innovation from within. Recent scholarship underscores the urgency of this shift. Robello Samuel argues for a move from traditional "learn to know" frameworks to a "learn to work" approach in petroleum engineering education. The proposed framework calls for aligning academic content with industry needs, emphasizing hands-on learning, curriculum redesign, stakeholder involvement, and faculty upskilling, despite challenges like institutional inertia and resource limitations. [7]. Despite progress, barriers persist. Ceulemans et al. identify limited faculty expertise, resistance to change, and a lack of incentives as major obstacles [8]. Sustainability is often treated as an add-on rather than a fundamental shift in engineering education's purpose. However, initiatives like the UK Engineering Council's sustainability principles and the fourth edition of the Accreditation of Higher Education Programmes (AHEP4) published by the Engineering Council seek to embed sustainability deeply into engineering competencies, emphasizing ethical practice, systems thinking, and global responsibility by embedding it as a core learning outcome for all accredited degrees. It requires students to understand their professional responsibilities to society and the environment, apply engineering principles to develop sustainable solutions, and consider global challenges like climate change and resource depletion [9].

This paper contends that the future of oil and gas engineering education lies in integration, not replacement. It advocates for a deliberate, strategic merging of sustainability content into traditional engineering curricula, reflecting the real-world convergence of fossil and renewable energy systems. By embedding sustainability principles, green energy innovations, and environmental stewardship into the foundation of petroleum engineering programs, universities can prepare graduates to lead the energy transition with both technical expertise and ethical vision. In doing so, they not only contribute to the SDGs, but also ensure the continued relevance and resilience of engineering education in a rapidly changing world.

2. Bridging Conventional and Sustainable Energy: Curriculum Enhancement Strategies

In response to global sustainability goals and the shifting demands of the energy industry, the transformation of petroleum engineering curricula has become imperative. The University of Huddersfield's Oil and Gas Engineering program is evolving into a comprehensive clean energy and sustainability-focused course, reflecting the urgent need to address challenges such as climate change, rising CO₂ levels, and increasing waste. To align oil and gas engineering education with this transition, we propose integrating four critical

categories into the existing curriculum: **biofuels, petroleum contamination and remediation, biorefineries, and carbon capture**. These categories are not intended to replace conventional content but to complement and enhance the curriculum, bridging traditional fossil fuel expertise with emerging sustainable energy technologies.

This integrative approach is further supported by the university's Energy Integration Lab (EIL), a state-of-the-art facility equipped with anaerobic digestion systems, pyrolysis units, and micro gas turbines. Through hands-on learning in this lab, students engage in comparative analyses of fossil fuels and biofuels, gaining first-hand insights into energy transitions. These experiences not only ground theoretical concepts but also prepare students to address real-world complexities in a rapidly evolving energy landscape.

2.1. Differences Between Fossil Fuels and Biofuels

Fossil fuel combustion is a major contributor to greenhouse gas (GHG) emissions, responsible for roughly 75% of global CO₂ emissions [10]. Though seen as "carbon-neutral," biofuels' environmental impact varies due to land use, fertilizers, and processing energy [11]. In contrast, second- and third-generation biofuels have a far more favorable carbon balance and fewer ecological drawbacks [12]. Fossil fuels generally have higher energy densities than biofuels impacting engine performance, fuel economy, and logistics [13]. However, biofuels, especially blends like E10, work with existing technology, and advanced synthetic biofuels can match or outperform fossil fuels using current infrastructure [10]. Biofuels also align more closely with circular economy principles and the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), while also benefiting rural development and energy security [1]. In addition, fossil fuels face growing pressure from policies and global agreements, creating opportunities for students to explore sustainability, carbon mitigation, and energy diversification [14]. Integrating sustainability into oil and gas curricula requires revising course goals to blend technical skills with sustainable practices. Huddersfield's program focuses on strategic design, hands-on learning, and industry collaboration, with the Energy Integration Lab supporting practical, interdisciplinary education and local sustainability efforts. By processing waste from both campus and community sources, the EIL contributes to local electricity generation, positioning the university as a "living lab" for sustainable practices.

To better integrate sustainability, petroleum engineering courses should expand beyond production to include modules on systems thinking, environmental responsibility, and life cycle awareness. A multidisciplinary approach linking carbon capture and biofuels with core subjects promotes real-world problem-solving and collaboration. Project-based learning, case studies, and fieldwork deepen understanding, while industry and policy contexts ensure practical relevance. Assessments should evaluate students' ability to balance environmental trade-offs, make sustainable decisions, and communicate across disciplines, supported by continuous feedback.

2.2. Including Petroleum Contamination and Remediation Methods in the Curriculum

The oil and gas industry continues to have a significant role in global energy production, but the environmental consequences of petroleum extraction and related activities are increasingly drawing attention. Petroleum contamination, resulting from spills, leaks, or improper disposal of oil-based products, poses a substantial threat to ecosystems, water bodies, and soil health [15]. In line with the University of Huddersfield's commitment to sustainability-focused energy education, incorporating petroleum

contamination and remediation into the engineering curriculum is essential. This initiative not only prepares students for environmental challenges they will encounter in the field, but also reinforces the university's broader mission to produce engineers equipped for a low-carbon, environmentally conscious energy sector. By addressing contamination mitigation, students develop a holistic understanding of the oil and gas lifecycle, improving their capacity for critical thinking, sustainability planning, and interdisciplinary collaboration. When combined with practical applications in the Energy Integration Lab (EIL), students can also explore bioremediation processes, contaminant testing, and environmental monitoring using local and synthetic samples.

Key concepts include understanding petroleum contamination, such as toxic substances and their persistence in different environments [16], and exploring remediation methods like bioremediation, soil washing, phytoremediation, and pump-and-treat systems. Students also study regulatory frameworks, such as the IMO and EPA guidelines, to ensure compliance with environmental laws [17]. Interdisciplinary collaboration is encouraged through case studies and group projects, and practical applications, such as the Exxon Valdez spill, illustrate real-world remediation strategies [18]. This case study, along with other smaller-scale incidents, will help students analyze and evaluate the effectiveness of different approaches. This approach provides students with a holistic understanding of environmental challenges, sustainability, and regulatory compliance, fostering practical problem-solving skills for future engineers.

2.3. Including Biorefineries in the Curriculum

As the demand for sustainable and renewable energy sources grows, there is a rising interest in bio-refineries as a means of transitioning from conventional petroleum-based systems to more environmentally friendly and resource-efficient alternatives. Bio-refineries are integrated systems that process biomass into various biofuels and value-added chemicals, offering a potential solution to the depletion of natural resources and the environmental challenges posed by petroleum reliance [19]. Given the increasing importance of biomass-derived biofuels and circular economy (CE) approaches, it is essential to incorporate bio-refinery concepts into oil and gas engineering curricula. As noted by Goswami et al., emerging technologies such as Big Data, blockchain, and the Internet of Things (IoT) will play a critical role in optimizing bio-refinery processes [20]. By including these topics in academic modules, particularly within the Energy Integration Lab (EIL), students will be equipped with the knowledge and tools necessary to innovate and design bio-refineries, creating solutions that bridge the gap between fossil fuel dependence and sustainable, green energy systems.

To ensure a comprehensive understanding of bio-refinery concepts, the curriculum should cover several key areas. First, students must grasp the principles of bio-refining, which uses renewable biomass feedstocks such as agricultural residues, algae, and food waste, and processes like hydrolysis, fermentation, and gasification to produce biofuels and bio-based chemicals [21]. Next, the concept of circular economy (CE) should be integrated, explaining how bio-refineries contribute to sustainability by recycling materials and reducing dependence on petroleum-based chemicals, aligning with global sustainability goals [20]. The transition to bio-refineries represents a significant move toward resource-efficient and sustainable production systems, aligning well with global sustainability goals such as those outlined in the United Nations Sustainable Development Goals (SDGs). Teaching students about the intersection of bio-refining, CE, and SDGs will provide them with the necessary perspective on the broader impact of bio-refinery technologies. Technological advancements like Big Data, blockchain, and IoT are also crucial for

optimizing bio-refinery processes, and students should learn to apply these tools in process control and supply chain management [19]. Introducing these technologies in the curriculum will equip students with the knowledge to leverage them in future bio-refinery designs, ensuring that they are prepared to meet the demands of modern, high-efficiency, and sustainable energy production. They can benefit from digital simulations and EIL-based IoT installations to replicate such process control systems in a controlled environment [22]. Practical applications and case studies offer insights into the diverse applications of bio-refineries beyond biofuels, such as producing biodegradable plastics and chemicals. The integration of these topics will enhance students' sustainability awareness, technological adaptability, cross-disciplinary knowledge, and practical problem-solving skills.

2.4. Including Carbon Capture in the Curriculum

As energy shifts toward sustainability, reducing carbon emissions is crucial. Carbon capture, utilization, and storage (CCUS) technologies help mitigate CO₂ emissions by capturing, transporting, and storing or converting them into useful products. Integrating CCUS into oil and gas curricula is essential to prepare engineers to develop and manage these technologies. As noted by Goswami et al., the transition toward cleaner energy systems cannot be fully realized without a comprehensive understanding of carbon capture, especially in the context of ongoing reliance on fossil fuels [20]. Including CCUS in educational modules will allow students to explore how this technology fits within broader sustainability frameworks and how it can be integrated into existing energy systems.

To effectively incorporate carbon capture into oil and gas engineering courses, the curriculum should cover several key topics to provide students with a comprehensive understanding of the technology and its applications. First, students must learn the science of carbon capture, focusing on methods such as post-combustion, pre-combustion, and oxy-fuel combustion, each with distinct applications depending on the emission source and industrial processes. Emerging capture methods, including chemical absorption, membrane technologies, and cryogenic separation, should also be introduced. Next, the curriculum should address the transport and storage of captured CO₂, explaining the infrastructure involved, including pipelines and geological storage in deep rock formations, such as oil reservoirs and saline aquifers [23]. Enhanced oil recovery (EOR), a method that involves injecting CO₂ into oil reservoirs to extract more oil, also provides an economic incentive for CO₂ storage [24]. Case studies such as the Sleipner and Weyburn-Midale projects can demonstrate real-world applications [23]. Carbon utilization technologies, including CO₂ conversion into biofuels and chemicals, also play a role in emissions mitigation, and students should learn about methods like carbon mineralization and algae-based biofuels [25], [26]. Real-world examples like the Sleipner, Boundary Dam, and Petra Nova projects provide practical insights into the challenges and successes of carbon capture [27]. Lastly, incorporating these topics into the curriculum offers several educational benefits, including an understanding of climate mitigation technologies, economic and policy insights, and the promotion of sustainability and environmental responsibility.

2.5. Embedding the Engineering Professors' Council Sustainability Toolkit in Core Modules

To operationalize sustainability in petroleum engineering education, the University of Huddersfield has adopted the Engineering Professors' Council Sustainability Toolkit across four core MSc modules: *Enhanced Oil Recovery*, *Downstream Oil and Gas Processing*, *Upstream Oil and Gas Engineering*, and the *Individual Project*. By using the Toolkit's structured guidance on integrating the UN Sustainable Development Goals (SDGs), systems thinking, and inclusive innovation into teaching practices, we ensured

that sustainability was not treated as an add-on, but as a foundational theme permeating technical learning. This integration has resulted in a measurable shift in student engagement, particularly in their approach to final-year projects. A growing number of students, especially those sponsored by petroleum companies, are now choosing sustainability-focused research topics aimed at solving real-world industry challenges. These students are empowered not only to improve traditional processes but also to drive sustainable innovation within their organizations post-graduation.

Three notable examples of student-led sustainability projects include:

1. Optimization of Oil Production at Waha Oil Station through Effective Utilization of Separated Water – targeting water reuse and energy efficiency.
2. Impact of Crude Oil Spillage on Surface Wettability and Fluid Displacement Mechanisms in Recovery Processes – addressing environmental impact mitigation during enhanced recovery.
3. Comparative Analysis of Carbon Capture and Storage (CCS) Implementation in Developed and Developing Countries – evaluating global equity and feasibility in decarbonization strategies.

These projects reflect the Toolkit's core aim: to prepare engineers who can tackle the climate crisis and resource limitations without abandoning the technical rigor of their discipline. By equipping students with both domain expertise and sustainability competencies, the program helps close the gap between traditional petroleum engineering education and the needs of a rapidly evolving energy industry.

3. Conclusion

In response to the global climate crisis and the need for sustainable energy solutions, this paper advocates for the integration of key sustainability topics into petroleum engineering curricula. Rather than replacing traditional content, the proposal suggests enhancing existing programs by incorporating four critical areas: biofuels, petroleum contamination and remediation, biorefineries, and carbon capture. These topics would be introduced through dedicated modules within current courses, using comparative studies, real-world case studies, and practical lab work to bridge theoretical knowledge with hands-on skills. For example, biofuels and lifecycle analyses would be taught alongside fossil fuel systems, while contamination and remediation strategies would be integrated into environmental impact assessment courses. Biorefinery processes and carbon capture technologies would be included in chemical engineering and energy systems courses, emphasizing emerging technologies such as Big Data, blockchain, and IoT in optimizing sustainable operations. The University of Huddersfield's Energy Integration Lab (EIL) will play a central role in providing students with practical experience in these areas, including biofuel combustion, carbon capture experiments, and energy system simulations. Complementing this hands-on learning, the integration of the Engineering Professors' Council (EPC) Sustainability Toolkit across core modules has further embedded sustainability thinking into the MSc Oil and Gas Engineering program. This has led to a notable shift in student engagement, with many, particularly those sponsored by petroleum companies, choosing sustainability-focused individual projects that address real-world industrial challenges. This curriculum enhancement aims to produce graduates who are not only technically proficient but also environmentally conscious and innovation-driven, preparing them to lead the transition to a more sustainable energy future. By embedding sustainability into petroleum engineering education, universities can better align with global environmental goals and ensure that future engineers are equipped to address the complex challenges of the evolving energy landscape.

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