Sustainable and equitable energy systems: engineers as changemakers and innovative pedagogy in engineering education

Sustainable and Equitable Energy Systems: Engineers as Changemakers and Innovative Pedagogy in Engineering Education

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Abstract

The role of engineers as changemakers is more important than ever, as they are tasked with developing innovative solutions to some of society's most pressing challenges. This paper explores a pedagogical approach for teaching foundation level undergraduate engineering students using Problem-Based Learning (PBL) with scaffolded learning, aimed at developing the necessary skills to become effective engineers. A critical input to the process was a liberal arts and humanities review of the broader societal aspects, including the global challenges addressed by the UN 2030 Sustainable Development Goals (SDGs).

The specific context of this study revolves around a problem scenario in which students were tasked with designing a heat and electricity solution for a typical household. The assignment was designed to simulate real-world engineering challenges, requiring students to think critically, innovate, and design a functional system that integrates renewable energy sources, heat sources, battery storage, electricity grid connections, instrumentation, and control systems. The use of PBL encourages active engagement with the problem, requiring students to identify what they know, what they need to find out and what they need to learn.

Initially, students received a user requirement specification that outlined the need for an integrated heat and electricity solution. They were encouraged to use functional and transactional writing to articulate their understanding of the problem as well as using labelled sketches and diagrams. The importance of listing assumptions as part of overall validation was emphasised. They were also asked to consider the links from the local to the global, including addressing sustainability and social issues.

Students were required to model their design using appropriate digital tools. This allowed them to simulate and visualise their solutions, ensuring that the theoretical aspects of their designs could be tested and refined before final implementation. The integration of digital tools into the learning process mirrors the increasing reliance on technology in engineering design and is critical for students' development as proficient, work-ready engineers.

The final component of the assignment was reflective learning. Students were asked to revisit their design process and critically assess their work, considering both their successes and challenges, and how their proposed solution addresses sustainability and the SDGs.

This paper offers a case study of PBL to equip foundation level students with the skills, knowledge, and mindset required to approach engineering problems holistically and innovatively, addressing requirements of multiple SDGs. By engaging students in real-world problem solving and providing them with the tools to think critically, model solutions, and reflect on their learning, this approach fosters the development of engineers who are well-positioned to become changemakers.

1 Introduction

The role of engineers in society has evolved significantly in recent decades. Traditionally, engineers were seen as technical experts focused on designing, building, testing and maintaining infrastructure, machines, and systems. However, the increasing complexity of global challenges from climate change and energy sustainability to the growing need for technological innovation has expanded the scope of engineering. Engineers today are recognised as changemakers, equipped with the knowledge and skills to address some of the most pressing issues of our time. As noted by Graham (2018), engineering education has recently undergone and continues to undergo enormous change to meet the needs of such challenges. Among other aspects, this includes an increased curricular emphasis on student-centred active learning, interdisciplinarity, social relevance and external engagement.

Innovative pedagogy is central to developing the skills, knowledge, and mindset required for engineers to become effective changemakers. One such approach is Problem-Based Learning (PBL), which has gained prominence for its ability to engage students in real-world problem-solving (Nilson, 2016). PBL fosters critical thinking, creativity, and collaboration, all of which are essential qualities for engineers navigating an increasingly complex and interconnected world.

At the New Model Institute for Technology and Engineering (NMITE) in Hereford, United Kingdom, PBL is embedded within the educational experience presenting students with real-world problems that mirror the challenges they will encounter in their careers (Rogers et al, 2021). The emphasis is on student-centred learning, collaboration, and interdisciplinary approaches, allowing students to draw from various fields and develop practical skills while tackling relevant problems (Hitt & Rogers, 2020). The NMITE Foundation Year was designed to prepare students for the NMITE approach. There was a deliberate move away from the notion of a foundation programme to fill gaps in the usual expected entry level skills, such as A Level mathematics and physics. Instead, this programme focusses on the development of the mindset of the "new engineer" (Goldberg, Somerville, & Whitney, 2014), building creative problem-solving and critical thinking skills, and fostering intrinsic motivation to learn about engineering.

This paper explores the integration of PBL with scaffolded learning in the context of Foundation-level undergraduate engineering education. It examines a PBL module in which students were tasked with designing sustainable energy systems for a typical household, encouraging them to think innovatively and apply their learning to develop practical, sustainable solutions.

The students were also challenged to use their learning from this task and generalise it to develop their own problem-solving methodology. Polya's 'How to solve it?' (1945) offered a starting point. They had already encountered the Engineering Lifecycle Model (V-model) and had experience of mathematical problem solving. Generalisation is typical within PBL where much of the learning is inductive rather than the more traditional deductive approach.

Through this approach, it is argued that students not only built essential engineering skills but also became more inclined to consider broader, complex global issues. It also provided opportunity for staff to reflect on recommendations for designing PBL courses.

2 Engineers as changemakers

Most students entering the Foundation Year come from a traditional education system, where STEM subjects are predominantly taught through a deductive approach (Boaler, 2024). Deductive learning, which emphasises the application of established principles to solve predefined problems, contrasts with the inductive nature of PBL. The transition from a deductive to an inductive learning environment is a shift for students, requiring them to adapt to a more open-ended, exploratory approach to learning. PBL challenges students to tackle real-world problems, driving them to develop solutions rather than merely apply existing knowledge. This shift is integral to fostering a change culture and mindset, essential for students as they embark on their journey as NMITE undergraduates.

The concept of engineers as changemakers is grounded in the understanding that modern engineering is no longer merely about technical expertise. Engineers are increasingly seen as responsible innovators who must consider not only the functional and economic aspects of their designs but also the social, environmental, and ethical implications. This paradigm shift reflects growing societal demand for responsible innovation. There is an expectation that engineers will create solutions that contribute positively to society while addressing urgent global challenges. Engineers are tasked with tackling problems such as climate change, resource scarcity, public health issues, and social inequality. As such, the ability to consider the broader impact of engineering solutions is becoming ever more crucial.

The role of engineers as changemakers is evident in numerous sectors. In the energy industry, for instance, engineers are at the forefront of designing renewable energy systems, improving energy efficiency, and ensuring fair access to energy in underserved regions and populations. The increasing complexity of the challenges facing society today demands engineers who not only possess technical prowess but also the ability to critically evaluate and address the full range of societal, environmental, and economic ramifications of their solutions. To be effective changemakers, engineers must be equipped with the skills and mindset necessary for holistic problem-solving; not only understanding the technical dimensions of a problem but also considering the broader context in which solutions are applied. PBL provides a platform for students to develop this holistic perspective. By engaging in tasks that require balancing technical feasibility with social responsibility and global concerns, students learn to approach problems from multiple angles and develop solutions that have the potential to create positive, lasting change in society. Through this process, they are trained to be innovative engineers capable of making meaningful contributions in a rapidly changing world.

3 PBL as a pedagogical approach

PBL is an instructional method that encourages active learning through the exploration of complex, real-world problems. Unlike traditional teaching methods, which often focus on passive learning and memorisation, PBL places students in the role of problem-solvers, requiring them to apply their knowledge to tackle a specific challenge. PBL is particularly well-suited for engineering education as it mirrors the issues engineers face in their professional careers, where solutions must be both innovative and practical.

In PBL, students are presented with an open-ended problem and work collaboratively to develop a solution. They must research relevant topics, identify knowledge gaps, and determine the necessary steps to address the problem. Throughout this process, they are encouraged to engage in self-directed learning, taking responsibility for their education and developing the skills to solve complex problems independently.

The importance of teamworking was emphasised; initially the teams discussed their understanding of the problem verbally, utilising the linguistic and analytical mind. Students were asked to articulate a summary of their understanding of the problem to each other and to staff. Verbalisation of the problem became the first key component of the problem-solving methodology. Some students had a strong understanding of the problem at this stage, but other students sought a way to visualise the problem, using sketches and drawings, the design mindset. Visualisation helped to make understanding of the problem more complete. Therefore, *verbalisation and visualisation* (Ve&Vi) became important for the students in their teams (the 'people' mindset of empathy, collaboration and leadership) to reach a satisfactory level of understanding of the problem. The ability to summarise was identified as a key problem-solving skill for the students.

Assumptions are important because they provide a simplified framework that allows preliminary decisions to move towards a potential solution. Consequently, identifying and beginning to validate assumptions were identified as the next problem-solving stage. Students became aware quickly that simplifying assumptions are a valuable aid in the problem-solving process. Ve&Vi and listing assumptions answered the 'WHAT?' part of the problem. The 'HOW?' question was tackled by developing their own problem-solving approach. The students were encouraged to be patient and disciplined, hence practicing aspects of their leadership skills, defining how to solve the problem before using their approach to solve it. This also provided all team members the opportunity to question their understanding of the problem and synchronise before moving to the solution stage. They were reminded that they should keep their approach under review and refine it periodically, as required. Similarly, other early choices in the problem-solving could be modified as the development of the solution progressed; modifying the assumptions being one example and considering the broader aspects of social and economic constraints was another. Students were able to reflect that problem-solving is non-linear and the stages of problem-solving are not necessarily sequential.

A key benefit of PBL is that it encourages students to develop critical thinking skills (Yu and Zin, 2023). By working on a problem, students should not only recall technical knowledge but also assess the feasibility of different solutions, consider trade-offs, consider global concerns, and evaluate potential outcomes. This process helps students to approach real-world problems with a creative and analytical mindset.

4 The Role of Scaffolded Learning in Engineering Education

Scaffolded learning is an instructional strategy that provides structured support to students as they develop new skills and knowledge (Pritchard, 2009). In the context of engineering education, scaffolded learning can help students gradually build the competencies required to become proficient engineers. By providing incremental support and guidance, scaffolded learning enables students to tackle increasingly complex problems with greater independence and confidence.

In PBL, scaffolded learning is often implemented through a series of carefully designed activities that guide students through the problem-solving process. For example, in the sustainable energy systems assignment, students were given a user requirement specification, in the form of a brief, which outlined the parameters of the problem. They were then encouraged within their teams to articulate their understanding of the problem to each other and to the facilitating staff verbally and on paper.

As students progressed, they were introduced to more advanced tools and techniques, which allowed them to test and refine their solutions. This approach ensured that students were not overwhelmed by the complexity of the problem but were instead able to build their knowledge and skills step by step. By scaffolding the learning process, instructors provided the necessary support to ensure that students could succeed while also encouraging them to take ownership of their learning. This approach helped students develop the self-confidence and problem-solving skills required to tackle real-world engineering challenges.

The students identified the importance of support and adequate scaffolding during the process. A high level of support and scaffolding was expected for a foundation level cohort, and staff ensured students were working in the Zone of Proximal Development (ZPD) (Silalahi, 2019). When designing PBL courses, the scaffolding should reduce as undergraduates progress, and the rate of reduction provides an indicator of progress and success, according to Rosenshine (2012) and van de Pol et al. (2015).

It is important here to note that for PBL to succeed and to integrate the wider questions, staff need to be able to satisfactorily distil key areas of learning focus from the real-world problem. A distilled problem statement can act as a bridge or scaffold between real-world complexity and textbook simplicity. For example, the first PBL task for students became 'Design a heat and electricity solution for a typical household using solar panels, battery storage, a heat pump and connection to the electricity grid.' Whereas the real-world question was 'How can households and communities transition to low-carbon, resilient energy systems that are affordable, scalable, and adaptable while balancing technical, economic, and social constraints?' As part of scaffolding, the students were asked to consider the broader aspects and the global SDGs only after the first task was near completion.

5 The PBL Task: Sustainable energy systems for a typical household

The students were tasked with designing sustainable energy systems for a typical household. In more detail, the assignment's objective was to develop a strategy for reducing the energy costs of a 2-bedroom flat in Birmingham, UK, by exploring various energy technologies. Students were asked to generate and compare at least three scenarios, adapting energy profiles to account for seasonal and technological changes. The assignment was designed to simulate a real-world engineering challenge, requiring the integration of renewable energy sources, battery storage, bi-directional converters and optional sustainable heating systems such as air-source heat pumps.

The problem scenario began with a user requirement specification that outlined the needs of a household, including its energy demand as well as possible energy systems that could be used to meet its needs. Students were encouraged to think critically about how to integrate different technologies into a cohesive and functional system. They were also asked to consider the overall environmental impact of their designs, ensuring that their solutions were sustainable and cost-effective, by considering both the respective source and site energy consumption and consequent emissions.

A key aspect of the PBL approach is for the students to establish what they know, what they need to find out and what they need to learn. The scenario was recognisable and understandable to the students, and they had some familiarity with the three key components: batteries, solar panels, and heat pumps. Despite the battery being the most familiar component, the students discovered many other relevant technical concepts early in the task, including energy capacity, power rating, lifecycle, charge and discharge efficiencies, depth of discharge and battery electrochemistry. Whereas the battery provoked curiosity for knowledge, the least familiar component, the heat pump, provoked curiosity for understanding. Conversations included comparisons with refrigerators and air-conditioners, the meaning of the Coefficient of Performance (COP), why COP is greater than 1, and how this relates to the 1st and 2nd Laws of Thermodynamics.

With a greater knowledge and understanding of the key components, the students considered the systems aspect of the challenge which included making assumptions and exploring ways of validating them. This supported other discoveries, such as the role of realistic assumptions.

Students were required to use digital tools to model their designs and simulate their solutions. The resulting digital artefact was to enable testing of the feasibility of ideas and refinement of designs. In practice, the student teams chose Excel to model and simulate. The integration of digital tools into the learning process not only mirrors the increasing reliance on technology in engineering design but also provided students with hands-on experience using the types of software routinely employed in industry. At this point in the problem-solving process, the students used the Right-Hand-Side of the V-model to check their work using Verification & Validation (V&V).

Besides the digital artefact and the report requested for the techno-economic aspect of the brief, the third assignment was preparation and delivery of a presentation. Students were asked to critically evaluate the broader societal impacts of their proposed energy solutions, focusing on the challenges faced by vulnerable individuals and households unable to afford new energy-saving technologies. Therefore, emphasis was given on the equity aspect of the so-called energy trilemma, i.e. the trade-off between security, sustainability and affordability, and the consequences of energy poverty (World Energy Council, 2024), including the increased vulnerability to fluctuating energy prices, continued reliance on grid electricity at higher rates and risk of exacerbating energy poverty (Guayo et al., 2020).

Additionally, students were instructed to suggest strategies to make energy-saving technologies more accessible and to explore the role of engineers in promoting equitable solutions. Students were able to include in their presentations their own research, beyond any taught material, on issues of through-life implications of the technologies involved, and of the environmental concerns beyond the local region. In this way, the multidisciplinary, global, and complex nature of energy technologies was highlighted, as an example of how modern problems rarely are unidimensional or just technical.

Finally, a critical part of the module was reflective learning. Students were asked to critically assess their design process, identifying both successes and challenges. This reflection encouraged students to think about what they had learned, how they had approached the problem, and how they could improve their designs in the future. Reflective learning is an essential component of the development of professional engineers, as it fosters continuous improvement and self-awareness; the 'mindful mind' (Goldberg, Somerville, & Whitney, 2014).

6 Conclusions

The integration of PBL with scaffolded learning provides a powerful pedagogical approach for developing the skills and mindset required for engineers to become changemakers. By engaging students in real-world problem solving, providing them with the tools to think creatively and critically, model solutions, and reflect on their learning. This approach equips students with the competencies needed to address complex challenges.

In this case study, students demonstrated their ability to think creatively, work collaboratively, and apply their knowledge to design a functional and sustainable solution for an energy system. The domain of energy provides a rich and relevant environment to encourage early awareness of global issues and the SDGs. The combination of PBL and scaffolded learning not only helped students develop technical skills but also fostered important soft skills and of the changemaker mindset.

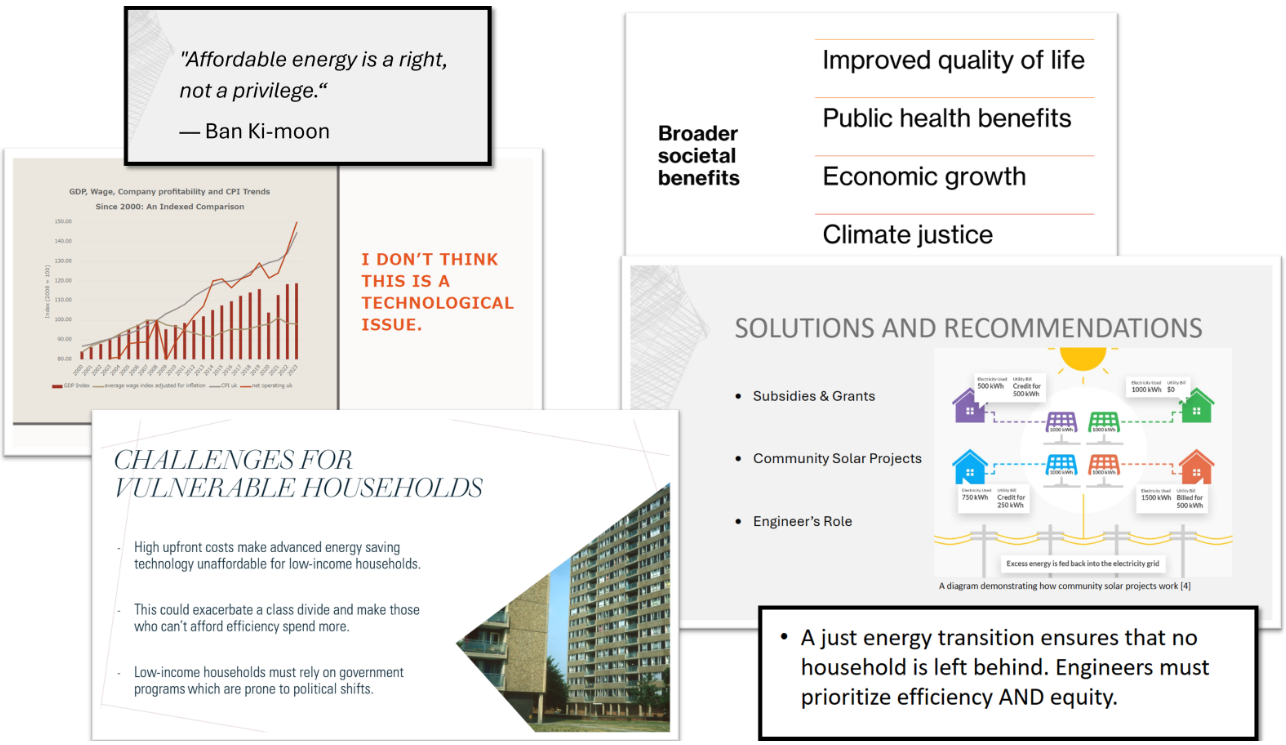

Figure 1: Samples from student presentations

The general problem-solving process began by understanding 'WHAT?' the problem was about, which included Ve&Vi and stating assumptions. The 'HOW?' part of the problem was tackled by developing the modelling approach. Students checked their resulting digital models using standard Verification and Validation (V&V) and were encouraged to further develop and refine their problem-solving methodologies.

As society continues to face pressing challenges, the role of engineers as changemakers will grow in importance. By adopting innovative pedagogies that prepare students for the complexities of the real world, engineering educators can help develop the next generation of engineers who are ready to create solutions that make a positive impact on society and the world.

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