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The Role Of Earth System Literacy In Sustainability Education For Engineers

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THE ROLE OF EARTH SYSTEM LITERACY IN SUSTAINABILITY EDUCATION FOR ENGINEERS

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ABSTRACT

Engineers should be able to demonstrate sustainability competencies transcending their specialised discipline. But all cross-disciplinary sustainability competencies are not targeted adequately in engineering education and are often mismatched with competencies required by engineers in their professional roles. Future engineers should have an understanding of the environment alongside technical knowledge, with all engineering design and product showing consideration to sustainability. The study of the Earth system is relevant to the understanding of environmental issues and the interplay between the sub-systems of the Earth (atmosphere, geosphere, biosphere and hydrosphere) . Yet, integration of Earth system literacy in the engineering curriculum has received minimal attention. This paper discusses the sustainability competencies in engineering education and, investigates if they can be addressed through Earth system literacy where weak or lacking. Based on two geology courses delivered to engineering students focusing on the sustainable management of different Earth resources with an understanding of their formation and extraction, it is evident that Earth system literacy can strengthen system thinking and, strategic and normative competencies in engineers. Most importantly it can target anticipatory competency that is not addressed adequately in conventional engineering courses.

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1 INTRODUCTION

Sustainable competency skills for engineers are very important in their professional lives for problem solving and bringing in engineering solutions relevant to the twenty-first century. The knowledge, skills, values and attitudes of engineers should transcend their specialised engineering discipline, with a shift in attitude from applying known solutions to well-defined problems for system optimisation, to facilitating system change by addressing complex cross-disciplinary challenges with no obvious solutions (Leifler and Dahlin 2020). It is crucial that engineers find sustainable solutions with due attention to global challenges such as climate change, pollution and loss of biodiversity, often triggered by excessive consumption of natural resources and the discharge of chemicals into the environment. This can occur at ant stage of a product development, from its discovery and design to the disposal of products at the end of its life cycle.

Sustainability education should be leading curriculum development and integrated to it, encompassing interdisciplinary, social and ethical knowledges. Although this has received considerable attention recently, engineering education is primarily focused on technical knowledge (Crofton 2000). Also, there is a mismatch between the sustainable competencies that engineering graduates possess and those required by industry. Besides, both qualitative and quantitative aspects of engineering sustainability are generally introduced to students through stand-alone modules, without being embedded in the curriculum design to complement the technical knowledge. In this study, we looked at the feasibility of Earth system literacy bridging some of these existing gaps in engineering sustainability education.

2 EARTH SYSTEM LITERACY FOR SUSTAINABILITY EDUCATION IN ENGINEERING

The Earth is a complex, open dynamic system with continuous interactions through cycling of matter and flow of energy between its interrelated sub-systems (atmosphere, geosphere, biosphere and hydrosphere). Although the Earth is continuously evolving, Earth processes (erosion, evolution, plate tectonics) are unchanging, driven by physical and chemical principles (Ladue et al. 2010). However, the rates of such processes might change both naturally and due to impacts from human activities which can result in rapid changes through Earth systems. The focus of Earth system literacy should be to foster understanding of the fundamental concepts of Earth systems to enable making informed and responsible decisions regarding Earth and its resources, to address the global challenges of changing climate, water shortage and depletion of natural resources. As human behaviour continues to threaten the sustainability of the Earth subsystems, the feedback mechanism of the Earth system might allow the subsystems to bounce back to balance. However, in this process, there can be considerable changes to all the spheres that will be damaging for human beings (Boyce et al. 2023). It would be very important to understand the realistic role of humans on Earth towards this.

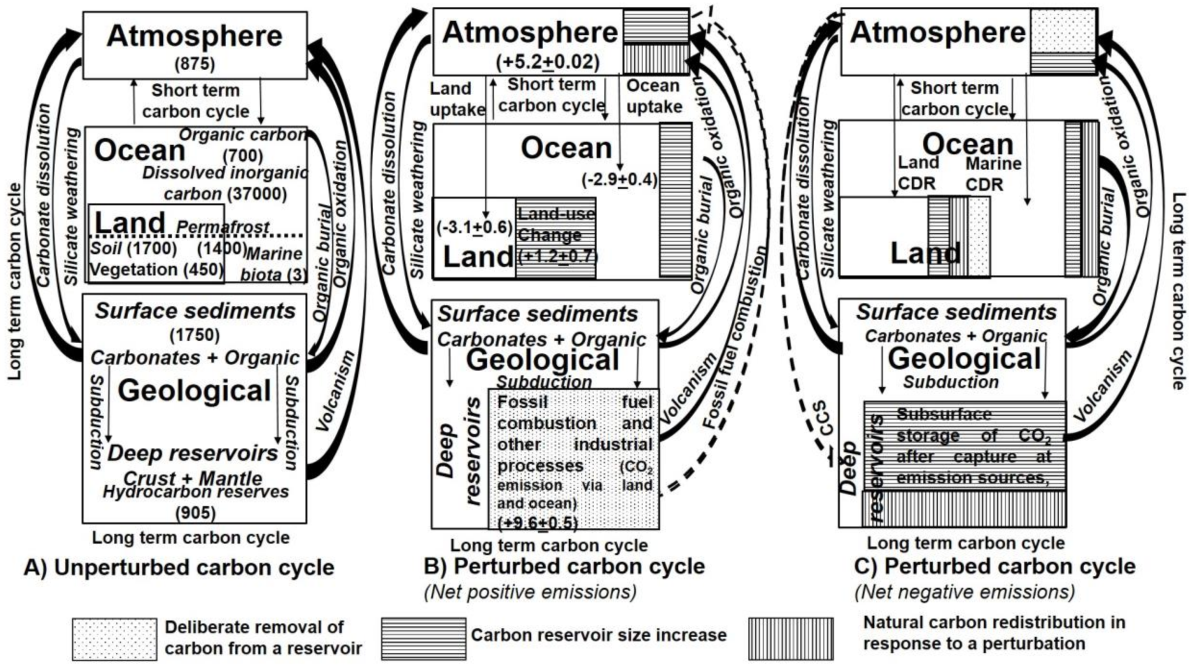

Fig. 1. The natural carbon cycle term cycles A) Unperturbed, with the carbon in stock in the main reservoirs indicated in GtC (gigatonnes of carbon) in parentheses B) Perturbed by anthropogenic activities with carbon fluxes in GtC/year averaged for the decade 2012-2021 indicated in parentheses. C) Perturbed by CO_2 removal (CDR) by enhancement of CO_2 sinks through processes such as afforestation and carbon capture and storage (CCS). Modified after Keller et al. 2018; Friedlingstein et al. 2022; Boyce et al. 2022.

Earth system literacy is the interdisciplinary study of Earth's geology with aspects of biology, physics, chemistry and mathematics. It would be important for engineers to address the influence of human intervention on the functioning and interaction of the Earth systems to prevent any disruption. To reduce CO_2 emissions some direct actions for engineers would be, to consider resilience in the infrastructure they design and build, to improve energy efficiency in any good they manufacture from refrigerators to automobiles, replace carbon fuels with renewables in the manufacturing steps, and facilitate CO_2 sequestering by capturing and storing the CO_2 at the point of emission. For sustainability consideration, these approaches should be based on an understanding of environmental issues, climate change and resource depletion and the interconnected nature of these challenges, grounded on Earth system literacy. As an example, the carbon cycle consists of both short (large fluxes between relatively small reservoirs functioning at decadal scales) and long (small fluxes between enormous reservoirs accrued over thousands to millions of years) cycles, (Fig. 1A). The CO_2 is bound or converted by the ocean and terrestrial sinks and removed from the atmosphere naturally, driven by different geological processes (Table 1). However, this natural cycle can be perturbed by anthropogenic activities, leading to negative net CO_2 emissions by removal through different processes (Table 1) and positive net CO_2 emissions by combustion of fossil fuels and cement production (Fig. 1B and C). As one of the six habits of engineering defined by the National Academy of Engineering, it would be important for engineers to consider the impact of engineering on environment. The should be able to recognise any anthropogenic impact and its perturbation to a natural cycle in the context of not just the operational carbon footprint for a designed product but the embodied carbon footprint during its life cycle. Another example is the production of traction lithium-ion batteries for automobiles, where the impact of mineral resources need to be considered in the life cycle assessment. Any land disturbance due to mining activities, release of mine tailings and unused resource extraction such as copper (Kosai et al. 2021), needs an understanding of basic Earth system concepts taking into account the geological occurrences of these resources.

Table 1. Geological processes pertaining to carbon cycle and human perturbation to remove carbon dioxide from the atmosphere

Geological processes	Description (as relevant to the carbon cycle)
Carbonate dissolution	The breakdown of a carbonate rich rock (e.g. limestone) in contact with acidic water to soluable bicarbonate and CO_2.
Silicate weathering	When calcium and magnesium bearing silicate rocks break down during weathering, it produces alkalinity that can neutralise CO_2 emissions by driving the precipitation of carbonate minerals.
Subduction	When two tectonic plates converge at a plate boundary, the denser plate is driven beneath the other, transporting carbon to the Earth's interior as organic carbon and carbonates.
Organic burial	Organic carbon buried in marine sediment over millions of years serving as a net sink for atmospheric CO_2
Organic oxidation	The oxidation of organic carbon from sedimentary rocks releases CO_2 over geological timescales from long term storage.
Carbon dioxide removal processes	
Land-based	Afforestation, reforestation, carbon farming, wetland restoration
Marine based	Abiotic approaches based on the properties of the ocean (e.g. alkalinity enhancement) and biotic approaches based on photosynthetic organisms in the sea (e.g. seaweed cultivation).
Enhanced weathering	An enhancement of the natural weathering of rocks to trap CO_2 by spreading large quantities of selected, finely ground silicate rocks such as basalt on extensive land area and sea surfaces.
BECC	Bioenergy with carbon capture and storage is a process which extracts bioenergy from biomass followed by the capture and storage of the CO_2 produced during the conversion.

3 OBJECTIVES OF THE STUDY

The main objective of this study is, to assess if embedding Earth system literacy in the engineering curriculum can benefit the sustainability education of engineers, beyond the scope of conventional engineering courses. The study will First assess any gap in sustainability competencies of engineers related to only engineering skills. It will then identify the specific sustainability competences that can be developed by introducing engineering students to basic concepts on Earth systems.

4 METHODOLOGY

Sustainability competencies integrated to engineering skills are initially assessed through literature review to identify the gaps in sustainability competencies in engineering education. Two sustainability focused geology courses delivered successfully to engineering students in a London University over the last seven years in a MSc programme on natural resource are then considered to identify relevant Earth system topics for this study. The two courses focus on the extraction of Earth resources and their return of waste and pollutants to the environment, with appropriate methods adopted to deliver geology contents to engineering students (Basu 2022). The topics covered in these courses and the learning outcomes are correlated to engineering sustainability competencies to identify if any gap in the sustainability competency skills in engineering education can be addressed through Earth system literacy.

5 RESULTS AND DISCUSSION

5.1 The relevance of Earth system literacy to Engineering sustainability education

Sustainability education for engineers have focused on engineering specific skills and related cross-disciplinary competencies summarised below (Perpignan et al. 2020; Quelhas et al. 2019):

Knowledge and understanding to develop systemic and critical thinking to enable solving a complex problem, with an understanding of the environment.

Engineering analyses to enable systemic thinking and collaborative working in order to solve a complex problem, enabling engineers to identify interactions between systems and people, integrating sustainability into their performance.

Engineering design to enable solving a complex problem with consideration to sustainability, taking into account environmental, social and economic factors.

Investigations to enable critical thinking to solve a problem and, develop normative competence and self-knowledge, with an ability to recognise professional responsibilities in forwarding sustainability goals and objectives.

Engineering practice that enables critical thinking to solve a complex problem with abilities of lateral, logical and critical thinking, based on normative and strategic competencies.

Making judgements to enable critical thinking and develop strategic competence to contribute to collective action within an organisation, implementing innovative actions and rethinking of company strategies.

Communication and team working to enable collaborative working and the ability of transdisciplinary thinking.

Lifelong learning focusing on self-knowledge to reflect on the individual role in the society to advocate sustainability values and goals.

Clearly, all cross-disciplinary skills needed for sustainability education are not targeted in trainings focused on just engineering skills. While critical thinking and solving a complex problem are targeted strongly, collaboration, systemic thinking, normative competence, self knowledge and strategic competence are weakly addressed (Perpignan et al. 2020). Particularly, anticipatory competency is not addressed at all, with a lack of knowledge and abilities that enables contextualization of engineering solutions in a broader context (Perpignan et al. 2020; Quelhas et al. 2019). Also, there is a mismatch in the sustainability competencies engineering graduates possess and that required in their professional roles (Yu et al. 2022). It becomes important for higher education to consider how to better support engineering graduates to build their sustainability competencies for the work place.The eight generic sustainability competencies of relevance to skilled engineers in their professional roles are, leadership, design, professionalism, lifelong learning, technical theory, communication, problem solving and teamwork (Yu et al. 2022). There is an emphasis on interdisciplinary skills for teamwork, understanding and applying knowledge of natural sciences related to the dimension of technical theory and designing a system or process taking into account environmental constraints. Earth system literacy has the potential to develop interdisciplinary skills for engineers to enable effective collaboration with environmental insights. Based on two geological courses offered to engineering students, the contributions of Earth system literacy towards their sustainability competencies are summarised below (Table 2).

Table 2. Sustainability competency skills for engineers built on Earth system literacy

Topic	Key learning objective and UN sustainable development goals (SDGs)	Intended learning outcome(s)	Relevant Engineering sustainability competencies
Geology for Sustainable Resource Management and Energy Transition			
Rocks and minerals	Understand the importance of geological materials as resources. *Addresses UN SDG 13.*	Identify a range of rocks and minerals, relating their properties and uses. Decouple the natural decay of Earth materials, from impacts of anthropogenic activities.	Anticipatory and deeper system thinking related to gradual and catastrophic processes and impacts on natural resources.
Plate tectonics	Describe the interactions between the Earth sub-systems, within the dimension of deep time and spatial scale of geologic processes. *Addresses UN SDG 13.*	Understand the origin and alteration of rocks related to Earth processes. Locate natural resources for extraction. Provide an integrated view on how the Earth functions as a system, with interacting sub-systems.	Deep system thinking on how Earth functioned in the past to forecast how conditions might change in the future.
Subsurface energy deposits	Enable identification of hydrocarbon bearing geological structures for exploitation, recognising associated risks. *Addresses UN SDGs 6, 7, 13.*	Apply geological concepts to understand the processes of hydrocarbon formation and entrapment. Critically relate hydrocarbon extraction to any associated environmental issues.	Anticipatory, with an understanding of Earth system processes in time and space, across scales of many orders of magnitude.

Underground storage of CO_2 and H_2	Consider emerging CO_2/ H_2 subsurface storage technologies to tackle climate change. *Addresses UN SDGs 6, 7, 13, 15.*	Characterise the subsurface to assess the opportunities for CO_2 and H_2 storage. Address key issues around CO_2/ H_2 subsurface storage, related to fluid flow and trapping mechanisms.	System and critical thinking with a holistic understanding of the extraction of natural resources, mitigating environmental impacts.
Earth Resources and sustainability			
Mining and mining life cycle	Critically consider the protection of the environment during exploitation of mineral resources. *Addresses UN SDGs 6,13,15.*	Describe the different stages of mining for mineral extraction, considering the embedded energy and environmental footprint, during the life cycle of a mineral deposit.	System and critical thinking with a holistic understanding of the extraction of natural resources.
Types of ore deposits (e.g. magmatic, hydrothermal, surface)	Critcally consider the sustainable extraction of minerals from ore deposits. *Addresses UN SDGs 6,13, 15.*	Characterise ore deposits based on their formation. Identify potential environmental issues associated with extraction of mineral resources.	Anticipatory and system thinking, with an understanding of Earth system processes in deep time and space.
Critical metals and byproducts for green technology	Develop an understanding on the viability of sustainable extraction of critical metals from their ore deposits *Addresses UN SDGs 6, 7, 13.*	Identify ore deposits bearing critical elements for energy transition. Appraise the factors controlling the demand and supply of critical metals. Consider the availability of mineral resources and the importance of their recycling.	Strategic competence, with an integrated understanding of the technological and economic impacts of resource extraction.
Seafloor mining	Critically consider the environmental impacts during the process of deep sea mining, and the research gaps in this field. *Addresses UN SDGs 13, 15.*	Give an overview of seafloor mineralisation. Identify the technological and geologic challenges associated with exploration of deep sea minerals in the context of ore type and water depth.	Strategic competence, with an integrated understanding of the technological, economic and social impacts of resource extraction.

Environmental, social and governance issues in mining	Gain an overview of best practices and regulations for the mining sector, considering the social and environmental impacts of mining. *Addresses UN SDGs 6, 13, 16.*	Evaluate environmental and societal aspects of Earth's mineral resources. Identify best practices related to opening, operating and closing a mine.	Normative and strategic competence with a holistic understanding of environmental, economic and social aspects of sustainability.

5.2 Earth system literacy in engineering education: Challenges and opportunities

The learning outcomes from Earth system literacy courses focus on Earth processes at different temporal and spatial scales, that influence the availability and sustainability of Earth resources (Table 2). The learning outcomes from engineering courses focus on the development and design of products, processes and systems with emphasis on the technical aspects of material choice and energy consumption (Perpignan et al. 2020). The effective integration of Earth system literacy in engineering education to reflect on the learning outcomes, will require time and effort with collaboration between geoscience and engineering educators, proficient in their respective field, but receptive to the expertise of others. Earth system literacy is an ongoing process, so specific actions need to be identified to enable engineering students to gradually acquire knowledge and understanding in this area integrated to their curriculum. In this context, embedding Earth system concepts in existing engineering programmes without relying on stand-alone Earth system courses designed for engineering students would be a major challenge. This can be trialled in a selected engineering programme within its existing structure, with key outputs aligned to its core learning outcomes. A suitable programme would be one with emphasis on sustainability education, with opportunities to flexibly incorporate innovative methods of teaching. It would be very important to consider the pedagogic approaches for such implementation, noting that creating contents and designing an integrated framework for such a purpose will be challenged by students' diverse learning experiences and goals depending on their specific engineering field.

6 SUMMARY

Crossdisciplinary sustanainibility competencies including strategic, normative, anticipatory, and deeper system thinking, can be strengthened and developed in engineering education by embedding Earth system literacy in the curriculum. Basic Earth system concepts related to the formation and occurrence of different natural resources can be introduced in engineering education to expand students' understanding of sustainability with environmental insights. However, it would be challenging to embed Earth system literacy in existing engineering programmes integrated to the curriculum, moving away from stand-alone Earth system courses for engineers.

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