Embedding Sustainability Competencies in Renewable Energy Engineering Curricula: A Gap Analysis of UNSW SOLAAH and SOLABH Programs against the Planetary Boundaries Framework

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Abstract: ***As global photovoltaic (PV) deployment accelerates toward terawatt-scale, the engineering curricula preparing future practitioners must evolve beyond technical performance to encompass full-lifecycle sustainability thinking. This paper presents a systematic gap analysis of sustainability-related competency coverage within two UNSW undergraduate engineering specialisations- SOLAAH (Photovoltaics and Solar Energy) and SOLABH (Renewable Energy Engineering)-using a structured curriculum-mapping framework derived from Wiek et al. (2011) and Brundiers et al. (2021). Seven sustainability competency dimensions are assessed across all core and elective courses in both programs using a three-tier coding scheme (Strong/Partial/Absent). Findings reveal that while both programs exhibit strong technical sustainability foundations, critical competencies-particularly normative/ethics, systems thinking within the planetary boundaries context, and integrated multi-criteria assessment-are either absent or confined to elective courses. The study identifies seven targeted micro-project interventions that can be embedded within existing courses with minimal curriculum disruption. This work contributes a reproducible, evidence-based methodology for sustainability curriculum audit and a set of actionable, PV end-of-life-focused teaching modules aligned with the planetary boundaries framework.***

Keywords: sustainability competencies, planetary boundaries, circular economy, curriculum mapping, life cycle assessment, engineering education, photovoltaics

1. Introduction

The global energy transition has elevated photovoltaic (PV) technology to a central role in climate mitigation strategy. Installed global PV capacity is projected to reach approximately 8,519 GW by 2050, representing a compounded annual growth rate of 8.9% from 2019 [1]. With this expansion, the first generation of commercial PV modules-installed in the 2000s and 2010s- is approaching the end of its operational life (approximately 25–30 years). By 2050, accumulated PV waste is forecast to reach 60–78 million tonnes globally, depending on failure and replacement scenarios [2]. This repositions solar energy from a purely 'clean' technology to a complex sociotechnical system producing substantial material outputs whose full environmental implications extend across multiple planetary boundaries.

Against this backdrop, engineering education faces a structural challenge: graduates trained predominantly in technical performance metrics-energy yield, conversion efficiency, levelised cost of energy-may be ill-equipped to navigate the full sustainability implications of the systems they design and deploy. The planetary boundaries framework [3][4], first proposed by Rockström and colleagues, defines nine Earth-system processes whose quantitative thresholds constitute a 'safe operating space for humanity'. PV end-of-life management intersects with at least three of these boundaries: novel entities (chemical pollution from polymer and trace-metal releases), land system change (waste storage, mining, recycling infrastructure), and biogeochemical flows (industrial processing emissions and soil-water contamination).

Engineering curricula, however, are typically assessed for sustainability content against relative indicators- carbon footprint, material efficiency- rather than against absolute ecological thresholds. Life cycle assessment (LCA), the dominant environmental assessment tool in the discipline, quantifies comparative burdens but does not determine whether aggregate impacts remain within Earth-system limits [5]. Circular economy (CE) frameworks are widely promoted in PV end-of-life discourse, yet the assumption that recycling equals sustainability masks material losses, energy costs, and cumulative environmental pressures that CE alone cannot resolve [6].

This paper addresses the gap between technical sustainability education and the broader competencies required for responsible practice in renewable energy engineering. Specifically, it: (i) presents a systematic mapping of sustainability competency coverage across UNSW SOLAAH and SOLABH undergraduate engineering programs; (ii) benchmarks findings against internationally established competency frameworks; (iii) identifies high-priority gaps; and (iv) proposes seven evidence-based micro-project activities that can be embedded in existing courses to address these gaps. The methodology is designed to be reproducible and transferable to other engineering programs internationally.

2. Conceptual Framework and Related Literature

2.1 Key Sustainability Competency Frameworks

The foundational reference framework for sustainability competencies in higher education was established by Wiek, Withycombe, and Redman [7], who identified five key competencies: systems thinking, anticipatory, normative/values, strategic, and interpersonal/collaboration. This framework has since become the most-cited model in Education for Sustainable Development (ESD) research. A Delphi study by Brundiers et al. [8] extended this to eight competencies, adding intrapersonal (self-awareness and reflection) and implementation (integrated problem-solving) competencies. UNESCO's 2017 Education for Sustainable Development Goals report [9] adopted this competency architecture as the global ESD standard, explicitly linking each competency to the UN Sustainable Development Goals (particularly SDG 7, SDG 12, and SDG 13). The seven-dimension framework used in this paper integrates both models.

2.2 Sustainability Curriculum Mapping in Engineering

Th Bury et al. [10] demonstrated a reproducible curriculum-mapping methodology applied to a Masters of Chemical Engineering at the University of Melbourne, using publicly available handbook entries and course outlines to produce a colour-coded heat map of sustainable development coverage. Their key finding-that SD inclusion was 'below an acceptable level' across the degree-and their three-tier coding (absent/weak/strong) directly inform the methodology and findings of this study. Sánchez-Carracedo et al. [11] applied a similar 'Engineering Sustainability Map' (from the EDINSOST project) across ten Spanish engineering degrees, finding that ethics-related competencies and participation in sustainability governance were the least-developed dimensions. A follow-up study [12] confirmed that 'ethics is the sustainability competency least developed in all degrees' and that universities generally lack deliberate strategies for sustainability integration. These findings provide an independent comparative benchmark for the gaps identified in this paper.

2.3 Accreditation Context

Engineers Australia Stage 1 Competency Standard [13] (Element 3f) explicitly requires graduates to demonstrate 'commitment to sustainable engineering practices.' The 2021 Washington Accord revision- noted by Bury et al. [10]- further strengthens this by referencing the SDGs, signalling that sustainability integration is transitioning from a voluntary aspiration to an accreditation-driving requirement. This forward-looking pressure strengthens the case for the curriculum interventions proposed in Section 5.

3. Methodology

3.1 Program Scope

The study examines two Bachelor of Engineering (Honours) specialisations offered by UNSW School of Photovoltaics and Renewable Energy Engineering: SOLAAH (Photovoltaics and Solar Energy Engineering) and SOLABH (Renewable Energy Engineering). Both are four-year programs leading to BE(Hons) in combination with a co-enrolled degree (Science, Commerce, or Arts). All core courses and selected electives were included, drawing from the 2026 UNSW Handbook [14] and available course outlines and education specifications [15].

3.2 Competency Dimensions

Seven sustainability competency dimensions were defined, synthesising the Wiek et al. [7] and Brundiers et al. [8] frameworks: (1) Systems Thinking- understanding complex sociotechnical-ecological interactions; (2) Anticipatory-scenario-based future orientation; (3) Normative/Ethics-values, equity, professional responsibility; (4) Strategic Action- designing and implementing sustainable solutions; (5) Interpersonal- stakeholder engagement, teamwork, communication; (6) Self-Awareness- professional reflection and identity; (7) Integrated Problem Solving- multi-criteria, cross-disciplinary assessment. These dimensions align with the Engineers Australia Stage 1 competency framework [13] and the UNESCO SDG learning objectives [9].

3.3 Data Collection and Coding

For each course, three data sources were reviewed: (i) UNSW Handbook course descriptions and learning outcomes; (ii) publicly available course outlines (where accessible via the UNSW Course Outline portal); and (iii) program-level education specifications and study plans. Each course was assessed for presence of sustainability content along each of the seven competency dimensions using a three-tier coding scheme: Strong (S)-sustainability content explicitly present in learning outcomes and assessed; Partial (P)- some sustainability content but not the primary focus; Absent (A)- sustainability content not covered in this dimension. This coding scheme follows the methodology of Bury et al. [10]. The complete mapping matrix was recorded in a structured spreadsheet (available as supplementary material).

4. Results and Discussion

4.1 Overall Competency Coverage

The mapping matrix covering 24 courses (SOLAAH) and 30 courses (SOLABH), assessed across seven dimensions, reveals a consistent pattern: strong coverage of Dimensions 1 and 4 (systems thinking and strategic action) in the technical sense, with weaker or absent coverage of Dimensions 2, 3, 6, and 7 in the context of absolute sustainability and Earth-system boundaries. Table 1 summarises the key findings at the programme level.

SOLA1070 (Sustainable Energy, Y1) is the strongest and most consistent entry point for sustainability in both programmes- covering sustainability definitions, climate change, energy security, equity, and renewable technology trade-offs, and including an explicit critical-thinking assignment. This course functions as the primary sustainability anchor for both specialisations. However, it does not engage with planetary boundary thresholds or the specific end-of-life implications of the technologies it discusses.

Table 1: Sustainability Competency Coverage Summary – SOLAAH vs. SOLABH (Core Courses)

Competency Dimension	SOLAAH Coverage	SOLABH Coverage	Priority Gap Identified
1. Systems Thinking	Partial	Partial	Absent planetary boundary framing in core
2. Anticipatory	Partial	Partial	No EoL / waste-stream scenarios in core
3. Normative / Ethics	Partial (late)	Better – SOLA5050 in core	HIGH – ethics appears only in Y4 for SOLAAH
4. Strategic Action	Strong	Strong	Circular/EoL design absent from both
5. Interpersonal	Partial	Partial	External stakeholder engagement absent
6. Self-Awareness	Partial (DESN only)	Partial (DESN only)	Reflection not embedded in SOLA courses
7. Integrated Problem Solving	Partial – LCA elective only	Better – SOLA5050 in core	HIGH – multi-criteria assessment not core

4.2 Planetary Boundary Framing- A Systemic Absence

Despite the growing importance of the planetary boundaries framework in renewable energy sustainability discourse [3][4], it is absent as an explicit analytical tool in core courses of both programmes. This is particularly significant given that PV end-of-life management intersects with three already-transgressed boundaries: novel entities, biogeochemical flows, and (indirectly) land system change [2] [16]. The dominant Life Cycle Assessment methodology taught in SOLA5051 is an elective, and even within that course, the planetary boundary LCA variant (PB-LCIA), developed by Ryberg et al. [16], is not currently the featured approach. This creates graduates who can optimise relative environmental performance but cannot determine whether their designs remain within absolute ecological thresholds- a critical distinction at terawatt-scale deployment.

4.3 Circular Economy and End-of-Life Design

Circular economy principles are addressed in SOLA5050 (Renewable Energy Industry and Policy, SOLABH core) and partially in SOLA3020 (PV Technology and Manufacturing, SOLAAH core). However, neither course explicitly integrates circular design principles- design-for-disassembly, material selection for recyclability, embedded carbon accounting- into engineering design tasks. This gap is significant because, as Kirchherr and Piscicelli [17] demonstrate, CE pedagogy requires hands-on, problem-based exercises (such as 'teardown labs' and circular design reviews) to develop actionable strategic competencies, not merely conceptual familiarity.

Furthermore, both programmes treat end-of-life management as a downstream, operational concern rather than a design-phase parameter. Leung et al. [18] have recently introduced material- and energy-circularity indicators for PV modules (from UNSW SPREE researchers), providing a technically rigorous, locally authored tool that is currently not referenced in any core course but could be directly integrated.

4.4 Ethics and Normative Competencies- Late and Thin

Ethics and normative sustainability content is concentrated in ELEC4122 (Strategic Leadership and Ethics, Y4) and DESN1000/2000 (Y1–Y2 engineering design courses).

For SOLAAH students, there is no dedicated policy/governance/ethics course in the core curriculum. This is structurally similar to the Spanish case studies reported by Sánchez-Carracedo et al. [11][12], where ethics was consistently the least-developed sustainability competency across ten engineering degrees. The equity and justice dimensions of the energy transition- differential impacts on communities in Global South countries bearing e-waste burdens, for example- are not addressed in any core course in either programme. Given that Engineers Australia Stage 1 competency Element 3(f) explicitly requires sustainability commitment across all facets of practice [13], this late and thin ethics integration represents both a pedagogical and potential accreditation risk.

4.5 Structural Difference Between SOLAAH and SOLABH

SOLABH is systematically better positioned for sustainability competency development because SOLA5050 (Renewable Energy Industry and Policy) is a core course, not an elective. This course addresses energy markets, policy instruments, environmental regulation, circular economy governance, social equity, and SDG linkages, substantially strengthening Dimensions 3 (normative) and 7 (integrated problem-solving) for SOLABH students. SOLAAH, by contrast, lacks any equivalent policy/governance course in its core sequence. This structural asymmetry- within the same school and building on many of the same prerequisite courses- represents an inequity in sustainability education outcomes between two closely related programmes.

5. Proposed Curriculum Interventions

The seven micro-project activities proposed in Table 2 are designed to address the identified competency gaps through targeted, low-disruption insertions into existing courses. Each activity is: (i) grounded in the peer-reviewed pedagogical or technical literature; (ii) scoped for completion within 2–5 hours of student time; and (iii) aligned with existing learning outcomes so that no new accreditation approval is required for initial implementation.

Table 2: Proposed Micro-Project Interventions Addressing Key Competency Gaps

#	Gap / Competency	Micro-Project Activity	Pedagogical Basis	Target Course(s)
1	Systems Thinking – PB framing absent	Micro-lecture + MFA workshop: PV waste mapped onto planetary boundaries	Rockström et al. [3][4]; Ryberg et al. PB-LCIA [16]	SOLA3020, SOLA5051
2	Anticipatory – no EoL waste scenarios	Assignment: PV waste scenarios to 2050 under IEA deployment pathways	Weckend et al. IEA/IRENA EoL report [2]	SOLA4012, SOLA3020
3	Normative – equity / justice absent	Case study + 500-word reflection: 'Who bears the cost of solar waste?'	Sánchez-Carracedo et al. [11][12]; UNESCO SDGs [9]	SOLA5050, DESN2000
4	Strategic – no circular design task	Design brief: Circular PV Module Design Review against circularity criteria	Kirchherr & Piscicelli teardown-lab pedagogy [17]; Leung et al. indicators [18]	SOLA4012, SOLA3020
5	Interpersonal – no external stakeholder engagement	Workshop: stakeholder mapping for a utility-scale PV + EoL project	Wiek et al. interpersonal competency [7]	SOLA2051, DESN2000
6	Self-Awareness – reflection not in SOLA courses	Reflection journal (3 entries): sustainability values, trade-offs, professional responsibility	Brundiers et al. intrapersonal competency [8]	SOLA2051
7	Integrated – LCA/PB-LCIA not in core	3-lecture module + OpenLCA case study: absolute vs. relative sustainability assessment	Ryberg et al. PB-LCIA [16]; Bjørn & Hauschild carrying-capacity LCA [19]	SOLA3020 or new module

The most strategically significant intervention is Micro-Project 7: a 3-lecture module introducing absolute sustainability assessment (PB-LCIA) with an OpenLCA case study on crystalline silicon module recycling. This directly bridges the thesis topic (Yu, 2026) with the curriculum, introduces students to a globally recognised research frontier, and can utilise the PB-LCIA methodology of Ryberg et al. [16] as its technical backbone. The circular design review (Micro-Project 4) is pedagogically grounded in the 'teardown lab' approach of Kirchherr and Piscicelli [17] and can draw on the material-energy circularity indicators of Leung et al. [18], connecting the curriculum to UNSW SPREE's own active research.

Micro-Projects 1 and 3 are particularly suited for SOLAAH, where the absence of a core policy/governance course (unlike SOLABH) creates the greatest normative and systemic gaps. These can be piloted in SOLA3020 (PV Technology and Manufacturing) as a paired 2-week module without altering the course's primary technical focus. The stakeholder mapping workshop (Micro-Project 5) and the reflection journal (Micro-Project 6) require no new technical content and can be integrated into SOLA2051 (Project in PV and Renewable Energy) as additional components of an existing project assessment, adding depth to interpersonal and self-awareness dimensions without increasing workload disproportionately.

6. Conclusions

This study has presented a systematic, evidence-based mapping of sustainability competency coverage across two UNSW renewable energy engineering programs, benchmarked against internationally established frameworks and the planetary boundaries research agenda. The principal findings are: (1) both programs have strong technical sustainability foundations, anchored by SOLA1070, but lack explicit engagement with absolute ecological thresholds and planetary boundary framing; (2) Life Cycle Assessment and circular economy design remain elective or implicit rather than core competencies; (3) normative and ethical dimensions are concentrated late in the program and, for SOLAAH, are not present in any technical course; (4) SOLABH is structurally better positioned than SOLAAH due to the presence of SOLA5050 in its core sequence; and (5) seven targeted micro-projects, each grounded in the peer-reviewed pedagogical and technical literature, can address these gaps within existing courses.

The methodology developed here- a seven-dimension competency matrix applied via handbook and course outline review, using a three-tier coding scheme aligned to Bury et al. [10]- is reproducible and transferable to other engineering programs. Future work should implement and formally evaluate the proposed micro-projects using pre/post competency assessments, extend the analysis to postgraduate programs (Masters of Engineering Renewable Energy), and explore how the planetary boundary LCA approach can be more broadly embedded as a core analytical tool across the renewable energy engineering discipline globally.

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